Summary

The Centre for Advanced Silicon Photovoltaics and Photonics incorporates the activities of the former Key Centre for Photovoltaic Engineering. The former Key Centre started in 1999, after the award of special funding from the Australian Government to promote teaching and research in the area of photovoltaics. The main initiative of this Key Centre was the establishment of the world's first undergraduate degree in Photovoltaics and Solar Energy. This was one of only eight such Key Centres awarded Australia-wide across all disciplines, demonstrating the importance of this exciting field of renewable energy. In 2003 the Key Centre and its activities were incorporated into the new Centre of Excellence, awarded to the same team at the University of New South Wales. On 1 January 2006, UNSW officially formed a new School within the Faculty of Engineering, the School of Photovoltaic and Renewable Energy Engineering, which includes the ARC Photovoltaics Centre of Excellence.

The School offers undergraduate, postgraduate and research programs encompassing a range of aspects relating to the photovoltaic and renewable energy industries. These programs have been developed in consultation with representatives from industry to ensure graduates are appropriately qualified to enter the field upon completion of their studies. Since 2003, the School has seen a total of 57 students graduate from its undergraduate programs, and 30 students from its postgraduate degrees. These graduates are now taking advantage of a range of opportunities being created in the booming photovoltaics and renewable energy industries.

During 2006, there was a considerable curriculum development and revision, particularly of the postgraduate coursework program, due to initiatives of the Faculty of Engineering which aimed at adding to the value and appeal of the engineering programs at UNSW. Throughout the year, the School continued to attract bright students to all our educational programs, and we were very excited to start a new Engineering Faculty Linkage Scholarship with Mirvac, to be offered for the first time in 2007. School Office staff also concentrated on revising existing promotional material to increase the awareness of Photovoltaics and Renewable Energy Engineering at UNSW. The higher media profile of global warming, greenhouse and energy issues in the general Australian community is helping to raise the School’s profile. Negotiations are now in the final stages to finalise the granting of a large number of scholarships for study at the School from the Australian Government, as part on the Asia-Pacific Partnership on Clean Development and Climate. Once in place, those scholarships will bring groups of undergraduate and postgraduate coursework and research students from the Asia-Pacific region to the School, starting in 2008. Another important event in 2006 was the inauguration of a new Industry Advisory Committee, especially for the teaching activities, to complement the existing Advisory Committee for the Centre of Excellence.

At the end of 2006, there were 143 undergraduate students, 5 postgraduate coursework students, and 30 research students (6 Masters by research and 24 PhD) enrolled in the Centre’s educational programs. The low postgraduate coursework numbers are expected to be rectified in 2008 by the program revisions begun in 2006 and by the Asia-Pacific scholarship students.
5.1 Undergraduate Educational Programs

The Centre offers two undergraduate coursework engineering programs, which can be taken in combination with a Bachelor of Arts, Bachelor of Science or a Bachelor of Commerce. These degrees aim to develop well-educated graduates with the basic skills, attributes and knowledge required to practise as professional engineers in the growing photovoltaics and renewable energy industries.

The Photovoltaics program draws on the expertise of Centre staff in this field and was the first of its kind internationally. The program includes education in technology development, manufacturing, quality control, reliability and life cycle applications, system design, maintenance and fault diagnosis, marketing, policy development and the use of other renewable energy technologies. It has two unique features: a project in the second year of the program, and a ‘strand’, a second area of specialisation. Since 2003, a total of 56 students have graduated from the program, as previously mentioned, and another 14 are expected to graduate in March 2007 after completing their studies at the end of 2006. At the end of 2006, a total of 93 students were enrolled in this program.

The second, broader degree program in Renewable Energy Engineering was introduced in 2003. In addition to photovoltaic devices, students in this program study solar architectural technologies, wind energy, biomass, solar thermal, and renewable energy policy as part of their core curriculum. At the end of 2006, a total of 50 students were enrolled. 2006 saw the first graduate of this program and two more are expected to graduate in March 2007.

Students usually enrol in these programs because they are both interested in working with cutting edge technology and enthusiastic about having a positive personal effect on society and the natural environment.

At the end of 2006, 24% of enrolled students were women. This is higher than is usually experienced in Engineering programs, although a slight decrease compared to previous years.

Graduates of our undergraduate programs are gaining employment within a variety of organisations, and increasingly in the area of energy efficiency and sustainable design. The interest of prospective employers for graduates with potential to contribute in that field was underlined in 2006 by the institution of a new scholarship from Mirvac. Each year a number of graduates start on a research program with our internationally recognised researchers whilst others are employed in industry by solar cell and equipment manufacturers, system design and integration companies, electricity utilities and major end users of products (such as sustainable design organisations).
5.1.1 The Strand

The strand is unique to the Photovoltaics and Solar Energy program, and is essentially a minor area of specialisation which complements a student’s study of photovoltaics. Students can take strands covering a variety of areas including computing, electronics, mathematics, physics, mechanical engineering, civil engineering, and architecture. The aim of the strand is to provide students with broader engineering backgrounds important for the cross-disciplinary nature of photovoltaic applications. UNSW’s Sunswift Solar Car project, which capped off a year of hard preparation work during 2006 by smashing the cross-continental Perth - Sydney solar car record in January 2007, is one example of the cross-disciplinary nature of photovoltaic applications, requiring the skills of mechanical, biomedical, and electrical engineers in addition to photovoltaics engineers. Since the commencement of the Photovoltaics and solar energy degree program in 2000, the Electronics and Physics strands have been the most popular, with Architecture, Mechanical Engineering and Computing also being popular choices.

Sunswift, the UNSW Solar Racing Car Team, is a student-led project with Engineering students across the Faculty involved.

5.1.2 Undergraduate Student Projects

In the second year of the Photovoltaics and Solar Energy program, students have the opportunity of undertaking a yearlong project in the photovoltaic or renewable energy areas. The main emphasis of the second year group project course is hands-on project engineering. The course has a lecture component covering project engineering skills and practice and each project has a research component, a planning component, a hands-on component and a presentation/reporting component. This course helps to prepare students for their fourth year thesis, which is undertaken by all students enrolled in both the Photovoltaics and Solar Energy and Renewable Energy Engineering undergraduate programs. As for most previous year, the project focused on developing countries applications was the most popular among students.

5.1.2.1 Biodiesel Trailer

The Biodiesel Project is constructing a small-scale, portable chemical factory to convert used vegetable oil from UNSW’s food outlets into biodiesel fuel for UNSW’s diesel vehicles. In 2006, three second-year students who undertook the Biodiesel Project worked on pneumatic controls and motors for the spark-free mixing, separation and transfer of the fluid components and solar thermal hot water supply for heating the oil to the reaction temperature. One of the key challenges was handling potentially explosive vapours and flammable liquids, and this necessitated a completely pneumatic fluid mixing and pumping system instead of the more common and cheaper electrical systems. The students spent several full days on the construction effort on campus and at the Centre’s Botany facility, learning and applying practical engineering skills.
5.1.2.2 Developing Countries

The Centre has been involved with projects in the developing countries for the last five years. The application of photovoltaics and other renewable energy technologies can make the greatest difference to people’s lives and living standards in these places. Students involved with this project in the past have installed and maintained photovoltaic lighting systems in rural locations in Nicaragua and Nepal and photovoltaics powered water purification in Sri Lanka.

In 2006, this second-year project group of nine students worked on a variety of technologies which included water pumping and general power provision for an indigenous eco-tourism camp at Malabama Beach on the Pacific coast of Cape York, Queensland. Timing of the associated trip for implementation of the project’s results is dictated by semester dates and by climatic conditions, particularly the likelihood of cyclones and monsoonal rains, and will take place in mid 2007.

Skills that the students had developed throughout the year will be put to good use in the field. Invaluable lessons were gained regarding project management of activities in developing countries, as students will need to face and overcome many technical and non-technical issues in implementing the project.

5.1.2.3 Renewable Energy Display Trailer

A new group project, launched in 2006, is the Renewable Energy Display Trailer, modelled on those built by the Queensland Sustainable Energy Industry Group (QSEIDG), and with the generous support of that Group. The School purchased a trailer shell built to the freely provided design and specifications of the QSEIDG and five students worked to design and build into it a stand-alone photovoltaic power system. Particular attention was paid to adherence to the relevant Australian Standards, especially AS4509, for system integrity and safety. The trailer had its first public display, with the students’ system supplying power to audiovisual display equipment, at the UNSW Courses and Careers Day, in September 2006. The trailer has since been used for other events on and off campus, including Orientation Week, 2007.
5.1.2.4 Thin-Film Solar Processing Equipment

This project aims to give students a broad experience in establishing and maintaining a world-class thin-film solar cell research laboratory. This is achieved through a two-stage process. Firstly, students develop a fundamental understanding of equipment and systems within the Centre’s thin-film laboratory, including vacuum systems, gas delivery systems, leak testing equipment, and plasma processing machines. The second stage involves the students integrating what they have learnt, by applying it to a specific project in the thin-film laboratory.

In 2006, two second-year students undertook this project. They worked on upgrading the gas delivery system of a reactive ion etching (RIE) machine. During the course of the project, the students designed and built a power supply and read-out box for several mass flow controllers, re-designed the RIE’s gas delivery system, mounted several mass flow controllers, and assisted in the physical modification of the gas runs. This project has given greater flexibility to mix gasses with the RIE machine and improved the reproducibility of processes performed in this machine due to the higher accuracy that mass flow controllers offer over the previously used needle valves.

5.1.3 Fourth Year Thesis

The thesis project is usually completed in the last two sessions of an engineering undergraduate student’s studies. Students undertake directed laboratory and research work on an approved subject under guidance of the Centre’s academic staff. Typically, the thesis involves the design and construction of experimental apparatus together with practical tests. Each student is required to present a seminar, submit a written report, and present a poster as part of an Open Day. It is a chance for students to demonstrate some of what they have learned throughout their studies.

Theses submitted during 2006 were again of a very high quality. The Thesis Poster Presentation Prize at Open Day in June 2006, for theses started in mid-2005 and completed mid-2006, was Chris Wilson, with his thesis on “Feasibility Study and Implementation of Solar Energy Projects in Randwick City Council”. Chris’ planning work was realised later in 2006 in the installation of a 10kW grid-connected photovoltaic array on the roof of the Council’s depot building. The topics of other presentations were: Electric Vehicle Conversion, Biodiesel from Algae - Completing the Circle, Developing novel methods of light-trapping for solar cells, and Developing countries projects in remote Australian indigenous communities.

One student, Robert Chew, built a road registered electric vehicle with roof-mounted solar modules for his thesis project, which finished in mid 2006. Robert went on to win an award from Keep Australia Beautiful, being proclaimed a Young Legend for Innovation in Sustainable Transport.
The Prize selection in November 2006 resulted in a dead heat between Ryan McCarthy for his poster about “Opportunities for Vehicle Integrated Photovoltaics” and Belinda Thorne for hers about “Photovoltaics in Developing Countries - Wakisa House”. The other topics on which theses were completed at the end of 2006 were: Wind Farm Site Selection, Solar-Powered Drip Irrigation at UNSW Ecoliving Centre; Feasibility of Space Heating Using The Sarking-Tile Space as Low-Cost, Retrofit Solar-Thermal Collector, Interconnecting Thin-Film Solar Cells Using Desktop Inkjet Printing, Production of Silicon Solar Cells in Developing Countries, Photovoltaic Up-Conversion, Monitoring of Solar Home Systems in Sri Lanka, and Solar Water Pumping at the Eco-Living Centre.


5.1.4 Dean’s Awards

In recent years the Dean of Engineering has presented awards for outstanding students in first, second and third years of study in each Engineering School.

Dean’s Award winners for study in 2005, Adeline Sugianto (2nd year) and Nicole Kuepper (3rd year). The winner for 1st year, Kai Ming Wong, was not present.
5.2 Postgraduate Programs

The School offers one postgraduate coursework program, a Master of Engineering Science, and three research programs: a Master of Philosophy, Masters by Research and a Doctor of Philosophy. These degrees are intended to provide students with an exceptional basis in advanced concepts and research in the photovoltaic area.

The one-year coursework program was developed to build on the prior education of engineers from other engineering disciplines who are currently being attracted to the photovoltaics and renewable energy industries. Students study courses chosen from the areas of photovoltaic devices, photovoltaic systems and applications, and renewable energy technologies. Enrolments in the program have continued at low numbers, with total enrolments of five at the end of 2006. There were five graduates in 2006 and four more are expected in March 2007.

At the end of 2006, the School had 30 students enrolled in postgraduate research degrees, 24 in a Doctor of Philosophy, and six in a Masters by Research. Research topics available to these students cover the entire photovoltaic sector, but with greatest emphasis on device theory, device and module design, balance of system components, and photovoltaic systems and applications. Research students play a pivotal role throughout all the Centre's activities. In 2006 the Centre saw two research students graduate, one each of Masters and PhD, and two new PhDs are expected to graduate in March 2007.

During 2006 the School was actively involved in a major Faculty-wide revision of postgraduate coursework programs. In conjunction with the rapidly expanding demand for photovoltaics production engineers in Asia, this has resulted in a well advanced plan to expand the School's MEngSc program to three semesters and to narrow the range of focus areas to photovoltaics technology. Further, all the Faculty's postgraduate coursework programs will include an emphasis on engineering management and all students will be required to take some faculty-based courses of general engineering importance. These revisions have been planned in the light of the School's expectation of a strong intake in 2008 and beyond of recipients from the Asia-Pacific region of Australian Government scholarships under the Asia-Pacific Partnership on Clean Development and Climate scheme.

5.3 Scholarships

The undergraduate programs at the Centre attract very bright students from across Australia. The UAI cut off for the programs has been approximately 80 over the last few years but was raised to 85 with the introduction of the Faculty of Engineering Admissions Scheme (FEAS) in 2006. Almost half the students admitted have had a UAI over 90 with many having a UAI over 95. The Co-Op Scholarship Program and the Faculty of Engineering's Rural Scholarship Program have helped to attract these excellent students, while the Taste of Research Summer Scholarship Program and occasional casual employment opportunities provide bright students with experience in the School's laboratories with research leaders and encourages them to pursue research careers. The Centre's very high international profile also allows it to attract high quality research students evidenced by the number doctoral students undertaking research programs at the Centre who have been awarded either of an APA or EIPRS Scholarship.
Mirvac is a leading example of the growing interest in sustainability in the construction and design industry. During 2006, the company’s Executive Director, Nicholas Collishaw, signed on behalf of the company an agreement to provide a Faculty of Engineering Linkage Scholarship for a student to study Renewable Energy Engineering at UNSW, beginning 2007. Mirvac will offer work experience opportunities for the chosen student on one or more of its many relevant projects.

5.3.1 Asia-Pacific Partnership on Clean Development and Climate (AP6)

The School applied during 2006 for scholarship funding from the Australian Government under the Asia-Pacific Partnership on Clean Development and Climate programme to bring students from the Asia-Pacific region, specifically China, India, South Korea, Japan and USA, to study photovoltaics engineering at UNSW. In January 2007, AP6 Programme investment of $5.2m was approved by the AP6 Ministers for this project. This significant grant will partly support study at UNSW by five international PhD students, starting second semester 2007, two cohorts of forty MEngSci students, starting 2008 and 2009, and three cohorts of third and fourth year undergraduate students, starting 2008, 2009 and 2010. These scholarships will address a key need for additional expertise and knowledge in the rapid expansion of the photovoltaics industry in the region and their award acknowledges UNSW’s importance in the field.

5.3.2 Co-Op Scholarship Program and New Industry Sponsor

The Co-Op Program is an industry-linked scholarship program where students obtain a year of work experience with industry sponsors as part of their undergraduate studies. In addition to their outstanding academic achievements, students are selected based on their involvement in school and community activities, their demonstrated leadership skills and their ability to communicate. Participation in this program enables students to apply the knowledge they have gained during their studies. This program is also beneficial to industry sponsors, who have access to excellent students, can observe these students in their workplace, and have the first opportunity of recruiting the best new graduates.
Two organisations, BP Solar and CSG Solar, have sponsored scholarships for the undergraduate Photovoltaics and Solar Energy program since 2001 and in 2005 the Centre gained a third industry sponsor, Suntech Power Co. Ltd., the leading Chinese photovoltaics company.

5.3.3 Rural Scholarship Program

The Faculty of Engineering established the Rural Scholarship Program in 2001 to encourage high-achieving students living in rural and isolated areas to study engineering. The scholarships are valued at approximately $8,500 per annum for four years of full-time study which eases the financial hardship of relocating to and living in Sydney. In 2006, the School again funded an extra scholarship in addition to the Faculty-funded scholarship. These students will commence studying with the Centre in 2007.

5.3.4 Taste of Research Summer Scholarship Program

The Taste of Research Summer Scholarship Program is primarily for high achieving 3rd year students and, in exceptional cases, 2nd year students may be considered. As part of the program, engineering schools offer 10 week projects for students to complete during their summer break. These projects provide students with scholarship support to gain experience working as part of a research team, for example in the world class laboratories at the Centre. From December 2006 to February 2007, the Centre hosted three students. Two worked on projects concerned with crystalline silicon thin film solar cells on glass and the other on commercial wafer-based silicon solar cells.

In addition to providing an opportunity for checking whether research is their ideal career path, participation in these projects helps students further develop their technical skills and their written and oral communication since students are required to write a report and present a poster on the outcomes of their research.

5.3.5 Research Scholarships (and EIPRS)

Through hands-on laboratory-based projects and theses, and scholarship programs, including the Taste of Research Summer Scholarship program, the Centre aims to encourage some of the best undergraduate students into research. Being an internationally recognised research organisation, the Centre attracts very high quality students to its research programs where students have the opportunity to work with leaders in this field. The fact that eight of our doctoral students are currently in receipt of very competitive APAs (Australian Postgraduate Award) or an EIPRS (Endeavour International Postgraduate Research Scholarship) is testament to the quality of these students. To be awarded an APA, the student must be a local student and ranked near the top of the first class honours graduates, while the EIPRSs are available to international students and are even more competitive than the APAs. Suntech Power also sponsors a PhD scholarship in the Centre.
5.4 Curriculum Development

Throughout 2006, students indicated through UNSW’s course evaluation process, CATEI, that they were generally satisfied with the Centre’s courses. The Faculty undertook several initiatives in 2006 to attract undergraduate students to Engineering at UNSW, each of which involving Centre staff. These include the first operation of a new flexible first year program, the initial offering of a Faculty-wide first year Engineering Design and Innovation course and of the School’s Sustainable Energy first year course, and the use of a new admissions scheme for local students.

5.4.1 Flexible First Year

In 2006, the Faculty implemented revised Engineering programs to increase flexibility for students in their first year, and ensure a broad base in mathematics, science and engineering fundamentals. Prospective students had indicated that there was value in delaying their choice of specialisation, and this revised program allows easier transfer between engineering schools at the end of first year and enables students to make a better informed choice at that stage. However, students who already know their preferred discipline of engineering can enter directly into that specialisation in their first year. The Centre’s educational programs were involved with this revision and academic and administrative staff were involved with the process that saw these modified programs implemented in 2006. The changes were well received by students.

5.4.2 New Engineering Design and Innovation Course

Along with the rationalisation of first year courses for all engineering programs for the flexible first year, a new common course on Engineering Design and Innovation was created and this was offered for the first time in 2006. Staff members from each School met periodically throughout the year to establish the aims and structure of the course, and to write a course outline. The course aims to give students first hand experience with designing and building creative solutions to problems which are limited by budget, time and resources. The key engineering skills it aims to develop in students include concept development, critical thinking and evaluation skills, clear communication, research and information literacy skills, and teamwork. Dr Jeff Cotter was one of the leaders in the development and implementation of the new course, and shared in the teaching of the course in 2006, offering a module requiring design and construction of a solar powered “space elevator”.

First year students enjoyed testing their designs in the new Engineering Design and Innovation course.
5.4.3 First Year Course on Sustainable Energy

With the introduction of the new flexible first year program and the opportunity for first year students to take electives, the Centre offered a new first year course on Sustainable Energy as part of the elective pool. This new course introduced students to energy in its different forms through a range of lectures, guest lectures from industry and demonstrations which introduced the concepts of energy storage, energy efficiency, energy conversion and sustainability. An overview of several renewable and nuclear energy sources was given with particular emphasis on photovoltaic technology including interesting case histories and fascinating mistakes and disasters. The course was offered in 2006 to all students enrolled in the Faculty of Engineering.

5.4.4 Faculty of Engineering Admission Scheme for Undergraduate Programs

Generally, admission to undergraduate programs for local Australian citizens and permanent residents is through the Universities Admissions Centre based solely on a prospective student’s UAI result as part of the Higher School Certificate. However, in 2005 the Faculty of Engineering introduced the Multiple Criteria Entry admissions scheme which recognises that there are a number of factors not measured in high school assessment, which indicate the potential of a student to succeed in engineering programs. In addition to their UAI, these factors include a student’s attitude, commitment, interest in engineering and the type of subjects taken for their HSC. Students who anticipated receiving a UAI less than 85, but higher than 75 were encouraged to apply for an interview with members of the Faculty’s academic staff. At the interview students have the opportunity to exchange information, demonstrate their suitability to engineering and ask questions of Engineering staff.

This scheme, refined and renamed as the Faculty of Engineering Admission Scheme (FEAS), was operated again in 2006. The main round of interviews for this admissions scheme was held during September, following trial HSC results, and a second, smaller round was held in the first week of January 2007, following the release of the final HSC results. Five of the Centre’s academic staff members were involved with interviews during this week.

5.4.5 Energy Efficiency Course

A course about energy efficiency, developed in collaboration with staff from the School of Electrical Engineering and Telecommunications, had been offered in trial mode previously and its success was acknowledged in 2006 by formal acceptance as a new course. This new status will make it more visible and accessible for students from other schools and additional enrolments are to be expected. A postgraduate version of the course has also been accepted into the curriculum in 2006 and discussions are underway about including it in a group of Faculty based courses from which all students will be required to select some courses.
5.5 Educational Resources

5.5.1 New Edition of Applied Photovoltaics

A revised second edition of the Centre’s book, entitled “Applied Photovoltaics” was published by the Centre in January 2006. This book was originally published by Stuart Wenham, Martin Green, and Muriel Watt in 1995, and the revisions were the result of experience teaching a course on applied photovoltaics as part of the Centre’s undergraduate and postgraduate programs and of the changes in the industry in the last decade. The book examines the characteristics of sunlight, how photovoltaic devices work, and various applications for the devices including stand-alone photovoltaic systems, grid-connected photovoltaic systems, remote area power supply, and water pumping.

The London based international publisher, Earthscan, saw the new book and approached the centre for the rights to republish it for global distribution, which was agreed. The Earthscan edition, including minor revisions and corrections, has now been published, with many pre-publication orders.

The Centre has retained rights to the Chinese translation of the book and that translation is in train. The Chinese-Australian photovoltaics manufacturer, Suntech Power Co., has donated considerable staff time towards this project and Centre students and staff are currently editing the draft translation. Publication in Chinese and distribution in China and beyond is intended to occur in 2007.

5.5.2 Outdoor Experimental Area

With support from the Faculty of Engineering, the Centre has recently gained a reserved section of new roof over an extension of the fourth floor of the Electrical Engineering building. This concrete roof area, comprising approximately 425 m$^2$, is home to a 38 m$^2$ battery room and a mounting frame for more than 4 kW of solar photovoltaic modules. Modules that were previously mounted on the UNSW property at Little Bay have been fixed to the array mounting frame and are soon to be joined by another array donated by Suntech Power Co. The arrays will be used both as a grid connected solar power station and an experimental facility and will be operated in collaboration with staff from the School of Electrical Engineering and Telecommunications. The site also hosts a domestic solar water heater, donated by Solahart Pty. Ltd., for solar thermal energy teaching and research.

The outdoor area has been used for students’ experiments and projects that require solar access and for regular community outreach activities such as the 2006 and 2007 Indigenous Australian Engineering Summer School (IAESS). The IAESS is hosted by the UNSW Faculty of Engineering each January.
Solar water heater and photovoltaic modules in the outdoor teaching area on top of the Electrical Engineering Building.

The new area on top of the Electrical Engineering Building.
5.6 PVSOC

One characteristic of the Centre which has led to the success of the educational programs is the friendly atmosphere that is engendered by being a small school with highly motivated academic and general staff. Students appreciate being able to form friendships and support networks with fellow students, as well as feeling comfortable and familiar with academic and administrative staff. PVSOC is a social committee established by the students which fosters this atmosphere with organised social events and activities to encourage student interaction. In 2006, the committee organised barbecues, pub crawls, student participation in Solar House Day (organised by ANZSES), and finally the PVSOC Annual Dinner. More than 120 students and staff attended this dinner in the Sydney CBD in November 2006 where final year students were farewelled, staff thanked, and the 2007 PVSOC committee was elected.

5.7 Promotional Activities

The Centre regularly participates in promotional activities organised by the Faculty of Engineering and Student Recruitment at UNSW. These events are important for increasing awareness and interest in the Centre's educational programs.

5.7 Print Media

The Centre increased advertising in Sydney newspapers, including Good Weekend, the Sydney Morning Herald and the Daily Telegraph in the later months of 2006 in response to the higher public profile of its focus area of global warming. Advertisements were also placed in the Earth and Environmental Science HSC Study Guide, the HSC Survival Magazine, the HSC Change of Preference Guide, and the HSC Universities Advisory and Information Day Guide. The Head of School had a lengthy “First Word” letter to the editor about the problems of nuclear energy published by the Sydney Morning Herald in May 2006 and his comments through the Australian Science Media Centre in October about the announcement of financial support for a large solar power station were widely reported around the world.

5.7.2 UNSW Information Day

Local undergraduate students must apply for admission to UNSW programs through UAC, and the 4th of January 2006 was the last day students could change their preferences for university degrees. Therefore, the university hosted an information day on the 3rd of January to assist students obtain information to finalise their preferences. School administrative and academic staff attended this event and talked to many prospective students who were unsure of their career direction. Students received information on our programs and had the opportunity to ask questions of staff. FEAS interviews were carried out on the same day and the events interacted to the extent that some students attending the Information Day were able to gain last-minute FEAS interviews after discussions with staff.

5.7.3 UNSW Courses and Careers Day

UNSW Courses and Careers Day is the annual information day, held in early September, for prospective students to obtain information about programs and student life at the university. As part of this day academic and administrative staff from the Centre attended
information desks in the Roundhouse to provide advice, and information to prospective students. During the day Dr Alistair Sproul also presented two lectures about the Centre’s programs as part of the lecture series organised centrally by the university.

In order to increase the awareness of photovoltaic technology the Centre organised other activities on the UNSW Quad Lawn, beside the Sunsprint finals. Solar cooker of various designs were used to cook simple meals on the Lawn, the Renewable Energy Display Trailer was presented by the second year students who had been working on it and a solar-powered water pump also attracted attention. Students and staff were available at the displays and in a nearby marquee to talk about our educational programs. In addition to this the Centre, in collaboration with the Energy Management Unit at UNSW, also offered tours of the inverter room for the 42kW photovoltaic array, using the Centre’s buried contact solar cell technology modules, made under licence by BP Solar, on the Quadrangle Building.

5.7.4 Faculty of Engineering Information Day for High School Students

Each year the Faculty of Engineering organises an information day to give high school students an opportunity to learn about engineering and the programs offered at UNSW. As part of the day students visit three engineering schools of their choice and engage in interactive activities aimed at demonstrating the relevant engineering area. Once again in 2006 the demand to attend this event was so great that two High Schools Days were coordinated. In 2003 59 students attended the Centre, in 2004; 40 attended; and in 2005 114 came. Due to this large number of applicants in 2006 the Centre ran three tours for the day in Semester 1 and two on the day in Semester 2. Approximately 120 students visited over the two days. As part of these tours, students competitively designed and constructed solar powered Lego® cranes to lift as many lollies as possible from the floor to a table in the set time.

5.7.5 Honeywell Engineering Summer School

The Honeywell Engineering Summer School is an event held in December and is conducted by Engineers Australia. As part of the summer school high school students from across NSW and the ACT about to enter their final year take part in a week of activities which involves industry visits and lectures / demonstrations at a number of universities. In 2006 approximately 30 students visited the Centre to participate in hands-on activities and the students were issued with information on the Centre’s educational programs.
5.7.6 Sunsprint Model Solar Car Challenge

The Centre has been running the annual UNSW SunSprint Model Solar Car Competition since 1999. This is a NSW statewide competition designed to involve high school students in project-based learning but brings with it a spirit of fun and competition. Many schools throughout NSW have allowed final year design and technology students to adopt SunSprint as their year-long major project. High school physics and science teachers have also used SunSprint as a class-based teaching project since SunSprint addresses several aspects of the curriculum.

The individual solar cars are designed and built according to specifications provided by the Australian-International Model Solar Challenge (AIMSC) ~ a national organization overseeing and linking all of the state events. These specifications provide design criteria that, when followed, allow students all over Australia to build model solar cars that are uniformly competitive with respect to cost and use of materials. The students contribute ideas, inspiration, time and money with the average vehicle costing over $600 and taking over four months to design and build.

With the success of the UNSW SunSprint events, in 2005, the UNSW Faculty of Science adopted the event, with the Centre for Photovoltaic Engineering being a co-sponsor, with each party committing an equal financial contribution to the event and each supplying similar organizational infrastructure.

In 2006, Jaycar Electronics (as in 2005) was a supporter of the UNSW SunSprint competition contributing both financial support and prizes for the event.

The 2006 SunSprint competition was placed at risk because of a school fire in Adelaide that destroyed the building housing the track nine weeks before the competition. A new 100 metre track design was adopted and was then commercially constructed at a cost of $25,000 by an industrial design facility in Sydney. The finished track was delivered to UNSW eight days before the event.

Forty-three NSW high schools registered in the event with several not being able to attend the competition for various reasons. Each school was allowed two teams comprising of up to four students each. The sky was remarkably clear for the two-day event allowing happy competitors to achieve excellent times for both the seeding on day one and the actual race on day two.
5.7.7 Minisprint

In 2005 the Centre ran the first of the annual MiniSprint competitions designed specifically for primary school children ranging from kindergarten to year eight. This event is a very much scaled down version of the SunSprint Model Solar Car Challenge with the emphasis being to keep the cost down while maximizing the fun and learning outcomes. The competition is run over a 20 metre straight course and uses nylon-fishing line for steering control. Competitors purchase a kit consisting of all of the parts needed to make a solar racecar for $65.00. The kits consist of two solar modules, a motor & switch, gears, wheels and corflute with the actual design (front/rear wheel drive, motor and wheel placement and fishing line control) being left to the student. In order to ensure a competitive competition, all entries must use the supplied solar modules and the supplied motor. Other parts or materials are also allowed. The basic kit can be assembled ready to race in an afternoon.

This year, MiniSprint was run on Saturday, 2 September 2006. The competition involved 32 primary school students with the race being run during the best sunshine of the day.

5.7.8 The 2006 AIMSC National Event

Each year the AIMSC brings together the winning teams from all of the state events with the 2006 event being jointly sponsored by the Centre and by the UNSW Faculty of Science at UNSW, 1 & 2 December 2006. Jaycar Electronics (as in 2005) contributed to the national event with both financial support and prizes.

This competition involved nearly 200 students, teachers and parents from all over Australia. The two-day event challenged the competitors by being very sunny during the time trials and seeding on the first day and having a sky filled with puffy white clouds on the race day. Puffy white clouds meant that students were actively predicting how much sunlight would be on the track during their races and were modifying the car’s gear ratios to meet this predicted light intensity. This made for a demanding time for the competitors but added greatly to the spectator’s excitement as they watch the sometimes quite unpredictable outcome of each race.
In addition to the Model Solar Car Challenge, the National Model Solar Boat Challenge was held simultaneously involving students ranging from year 1 to year 12 who had won their state competitions.

“National Model Solar Boat Challenge, 2006”.

5.7.9 Indigenous Australian Engineering Summer School (IAESS)

The Indigenous Australian Engineering Summer School (IAESS) is hosted by the UNSW Faculty of Engineering in January each year and in 2006 the School of Photovoltaic and Renewable Energy Engineering was an active participant for the first time. The IAESS brings indigenous high school students with demonstrated aptitude for science, maths and engineering to Sydney to give them a taste of engineering and to encourage an interest in the tertiary study of engineering. Centre staff and students guided the participants through a practical exercise of construction of a working stand-alone solar power system to power actual domestic loads. The IAESS Patron, former prime minister The Hon. Bob Hawke, presented the students with certificates at the graduation dinner after a week of activities.
5.8 Educational Collaboration

A range of collaborations have been established between the Centre and other educational institutions and organisations. These collaborations involve the development and implementation of educational programs and courses, the provision of support for student projects and theses, and the exchange of students and staff.

5.8.1 BP Solar Sydney

BP Solar manufactures, designs, markets and installs solar systems for residential, commercial and industrial sectors. The Australian branch of BP Solar is located at Sydney Olympic Park and staff from this company kindly donated equipment for the Renewable Energy Display Trailer, including photovoltaic modules, batteries and charge controllers.

5.8.2 Chinese Universities

In 2006 the School started discussions with four Chinese Universities in anticipation of future scholarship opportunities for enrolling third and fourth year students from those universities to study Photovoltaics and Solar Energy Engineering at UNSW and for Masters by coursework study. Suntech Power (see below) has offered scholarships for students from Jian Nan (Southern Yangtze) University and discussions have began in 2006 with three prestigious Chinese universities about sourcing students for the expected AP6 scholarships (see below).

5.8.3 Ecoliving Centre and Honeypot Childcare Centre

In 2006 two students undertook solar water pumping related projects based at the UNSW Ecoliving Centre, in close cooperation with the Manager of the Centre. When, part way through the year, the Ecoliving Centre became unsuitable to host one of the projects due to administrative changes within UNSW, the managers of the Ecoliving and Honeypot Centres cooperated to provide a new location at the childcare centre. Ecoliving Centre garden volunteers were important contributors to the success of these projects.

5.8.4 Edwards Hot Water

Edwards Hot Water produces hot water systems for domestic and commercial purposes using a variety of energy sources which includes solar. This organisation has supported the second year biodiesel trailer over the last few years and provided ongoing advice and support to students working in the project in 2006.

5.8.5 Fowler's Gap UNSW Arid Zone Research Station

In 2005, a fourth year thesis student collaborated with staff at UNSW’s Fowler’s Gap Research Station, 110 kilometres north of Broken Hill, to design and install new solar water pumping systems for stock watering and homestead supply. In recognition of the important opportunities for interesting and useful future student projects, in 2006 Dr Richard Corkish joined the Fowler’s Gap Management Committee as the representative of the Faculty of Engineering.
5.8.6 Kirrawee High School and NSW Department of Environment and Conservation

The School applied for and received in 2006 a Community Action Grant under the NSW Department of Environment and Conservation’s Climate Action Grants Program to work together with Kirrawee High School to develop a new Focus Module for the Year 11 Engineering Studies curriculum. The Unit is being developed by senior undergraduate students and staff at UNSW and was trialled at Kirrawee in late 2006. The trial is being followed by refinement of the Unit for a further trial in 2007 and subsequent web publication to enable free access for other Engineering Studies teachers to use the Unit in other schools.

5.8.7 Kyocera Solar

Kyocera Solar produces and supplies solar energy products and in 2005 donated photovoltaic module mounting frames for the fourth year thesis projects conducted in collaboration with the UNSW Ecoliving Centre.

5.8.8 Mirvac

Mirvac, as noted above, initiated in 2006 a Faculty of Engineering Linkage Scholarship for a student of Renewable Energy Engineering.

5.8.9 Murdoch University Western Australia

Scientia Professor Wenham was awarded an adjunct appointment at Murdoch University to help the university implement a new undergraduate degree in Renewable Energy Engineering which commenced in 2001. Prof Wenham still holds this appointment and is also a member of the Murdoch University Renewable Energy Engineering Board. This collaboration is important for the exchange of educational material for both institutions.

5.8.10 Queensland Sustainable Energy Industry Development Group (QSEIDG)

The Queensland Sustainable Energy Industry Development Group was formed in 2004 to enhance collaboration between government, education, industry, and community organisations involved in sustainable energy and energy efficient projects in Queensland. This organisation has developed mobile training facilities to raise awareness of sustainable energy. Each trailer has working examples of photovoltaic systems, wind energy systems, solar hot water heating and water pumping. The organisation has allowed the Centre to use their design for this trailer to build our own

Students designed and installed solar powered rainwater handling systems at the Ecoliving Centre garden and the adjacent childcare centre.
mobile display unit suitable for the annual Courses and Careers Day and for promotional events at High Schools, local government events, etc. In addition to providing the design gratis, QSEIDG has been very supportive in providing further information to help UNSW students build their own version.

5.8.11 Randwick City Council

A fourth year student worked with the Randwick City Council’s Team Leader – Sustainability through the latter half of 2005 and the first half of 2006 on the design and installation of renewable energy equipment at the Council’s depot in Maroubra. The depot roof is large and half of it is conveniently sloping towards north. The student designed, specified and sourced a solar water heater as a pre-heater for the existing water heating system for one of the two ablutions blocks in the depot building, offsetting some of the electrical load. He then drafted the tender documents for the council’s acquisition of a 10 kW grid-connected photovoltaic system on the same roof. That equipment was commissioned by Council in late 2006.

A second student is now collaborating with the council, concentrating on two of its other buildings: the library in Anzac Parade and the administration office in Randwick. Of particular interest is the application of photovoltaic modules for the dual purposes of power generation and the reduction of building heat load by window shading.

5.8.12 Santa Sabina College, Strathfield

Dr Richard Corkish made two visits on behalf of the Centre during 2006 to the Santa Sabina College, Strathfield, to speak with and demonstrate solar photovoltaic water pumping equipment to students and to investigate options for siting and funding an educational photovoltaic array at the School and integrating additional related information into the science curriculum.
5.8.13 Suntech Power Corporation

Suntech, a partly Australian-owned company operating in China, has been actively involved in assisting UNSW with the development, testing and evaluation of educational material in the PV area such as in the development, testing and evaluation of a software package called the Virtual Production Line. Significant numbers of UNSW undergraduate students also participate in industrial training at Suntech who find their time in China an extremely valuable educational and cultural experience. UNSW and Suntech carried out collaborative research on new front contact technologies in 2006 and Suntech donated translation services for the future Chinese edition of the Centre's textbook, Applied Photovoltaics. Additionally, Suntech already sponsors an undergraduate Cooperative Scholarship and a PhD scholarship and has now offered in 2006 to fund several undergraduate and postgraduate coursework scholarships for study at UNSW by students from Jian Nan University, Wuxi, China. Negotiations are underway to realise them.

5.8.14 University of Delaware IGERT

The School became in 2006 the sole non-USA partner in a collaborative project, based at the University of Delaware, known as the Integrative Graduate Education and Research Traineeship Program (IGERT) for Sustainable Energy from Solar Hydrogen. The School and IGERT will exchange students and co-develop and exchange courses.

5.9 Creation of a UNSW School

The photovoltaics group has effectively been an independent School within the Faculty of Engineering since 1999 when it was separated from the School of Electrical Engineering as an independent Centre. In the intervening years it has established its viability and grown in prominence and its recognition as an official School of Photovoltaic and Renewable Energy Engineering was passed through the UNSW governance mechanisms during 2005 and implemented on 1 January 2006. The School incorporates the teaching activities described above, the Photovoltaics Centre of Excellence and other research activities outside the scope of the Centre of Excellence.

5.10 Industry Advisory Committee

The new status conferred by the official creation of a new School of UNSW led to the formation of a new External Advisory Committee to help guide the teaching activities. This Committee is distinct from the present Advisory Committee that oversees the Centre of Excellence, which has also advised on our teaching in the past. The new committee had its inaugural meeting at UNSW on 28 July, 2006. Industry representatives in attendance were Dr Martina Calais (Murdoch University), Prof. Andres Cuevas (Australian National University), Mr Chris Dunstan (Business Council for Sustainable Energy Australia), Dr Mark Keevers (CSG Solar), Mr Christian Langen (Conergy Australia), Mr Rhys Morgan (BP Solar), Mr Bevan Pearce (Kyocera Solar Australia), Mr Simon Wild (Cundall Johnston and Partners) and, by telephone, Mr Rob Jackson (Renewable Energy Generators of Australia). The Committee received a detailed introduction to the School’s educational activities and sought further information and commented on many aspects.
When the Key Centre for Photovoltaic Engineering was awarded in 1999, it was established as an autonomous Centre within the Faculty of Engineering of UNSW, becoming independent from the School of Electrical Engineering within which the photovoltaic activities had been previously located. At that time, the Key Centre was given the same operational independence and rights as the other Engineering schools, with the Director Stuart Wenham being given the same status and authority as other Heads of Schools. With the awarding of the Centre of Excellence in 2003, the University made the commitment that the Key Centre for Photovoltaic Engineering would become the School of Photovoltaic Engineering, within which the ARC Photovoltaics Centre of Excellence would be located. This transition occurred in January 2006. The corresponding organisational relationships are shown in the upper part of Fig. 6.1.

With the revitalisation of the photovoltaic industry and the rapidly increasing interest in near-term commercial technologies, internal arrangements within the Centre were re-organised in September 2006, with the new organisation shown in the lower part of Fig. 6.1.
Within the Centre of Excellence, Deputy Directors have been appointed for each of the major strands of research as shown. Three new Deputy-Directors were appointed in 2006 to accommodate the new arrangements. These are Dr. Anita Ho-Baillie (High Efficiency), A/Prof. Thorsten Trupke (Silicon Photonics) and Dr. Allen Guo (Commercial Technologies).

The Management Committee of the Centre comprises eight Directors and Deputy Directors, along with the Head of School and the Business and Operations Manager. This committee meets fortnightly on the 1st and 3rd Fridays of each month, with each Deputy Director giving a report on the activities in his or her area over the preceding fortnight. This committee takes responsibility for decision making within the Centre that affects the Centre as a whole, while the individual Deputy Directors receive their own annual budgets to allow them to make and implement decisions that impact only their own laboratory areas and research activities.

The Advisory Committee for the Centre comprises the Centre Directors, the Head of School for Photovoltaic Engineering, leading academics from other institutions, industry leaders such as CEO’s of various companies involved in the field, and research leaders. This committee provides high level advice, feedback and recommendations in relation to the Centre’s activities and their relevance. The Advisory committee meets annually, taking into account the geographical separation of its members (Australia, USA, China, Italy, Germany), although more frequent correspondence takes place when necessary with individual committee members either by email or telephone. The membership of the Advisory Committee includes:

- Professor Stuart Wenham, Centre Director
- Professor Martin Green, Centre Executive Research Director
- Dr. Anita Ho-Baillie, Deputy Director (High Efficiency)
- Dr Jeff Cotter, Deputy Director (Buried Contact Cells)
- Associate Professor Thorsten Trupke, Deputy Director (Silicon Photonics)
- Associate Professor Armin Aberle, Deputy Director (2nd Generation PV research)
- Dr Gavin Conibeer, Deputy Director (3rd Generation PV Research)
- Dr Allen Guo, Deputy Director (Commercial technologies)
- Professor Allen Barnett: world leading academic in the field; recipient of many prestigious international prizes such as the William Cherry Award, former President of AstroPower, one of the world’s largest solar cell manufacturers, before being purchased by GE
- Dr Zhengrong Shi: CEO of Suntech-Power, another of the world’s largest solar cell manufacturers; recipient of various industry prizes; former Deputy Research Director of Pacific Solar; major collaborator of the Centre
- David Hogg: CEO of CSG Solar AC, Germany; former CEO of Pacific Solar, Australia
- Mr. David Jordan, until recently, Manager of New Technology, BP Solar International
- Prof. Andres Cuevas, ANU
- Prof. Peter Würfel, Institut fur Angewandte Physik der Universität Karlsruhe
- Dr Francesca Ferrazza, Chief Scientific Officer, Enitechnologie
Other distinguished researchers and industrialists have been co-opted to the Committee as required.

Also within the Management structure and a member of the Centre’s Management Committee is the Centre’s Business, Technology and Operations Manager Mark Silver, given the extensive involvement of Centre staff with industry, large number of collaborative research projects, and the high level of success of the Centre in generating, marketing and commercialising technology. The Head of Administrative Support for the Centre during 2006 was Jenny Hansen. Not shown in the Management Structure is the Financial Officer Julie Kwan who looks after the Centre Accounts, interfaces with the University Financial System, advises the Centre Directors and Deputy Directors on budgeting and financial matters, and generally assists with sourcing of funding, purchasing, reporting, writing grant applications, and advising on business opportunities.

A primary responsibility of the Director in the Centre is to ensure the Management structure as shown functions efficiently and effectively, with appropriate support and resources to facilitate the Centre’s achievement of its milestones and performance targets. An important aspect of this is managing the Centre’s finances to ensure suitable levels of funding are made available for supporting the major research strands, while simultaneously ensuring adequate funding is available for repair and maintenance of existing facilities and the purchasing of appropriate new infrastructure and equipment. Another important aspect relates to how the Centre has been assimilated and functions within the university system, and how the Centre interacts with industry, other research and teaching institutions, the various levels of government and the broader community. The Director also has a significant role in the appointment of new staff, the establishment and operation of the Centre’s Management Committee, and the establishment and operation of the Advisory Committee to facilitate quality feedback and guidance for the Centre’s Management Committee.

The Director works closely with the Centre’s Executive Research Director to assist in setting high level research direction and priorities for the Centre’s programs. In the teaching area, with the Key Centre for Photovoltaic Engineering and its activities being incorporated into the Centre of Excellence, the Director also takes significant responsibility in ensuring the successful development and implementation of the Centre’s educational programs, both at undergraduate and postgraduate levels. In this area, the Director works closely with Dr Richard Corkish, the Head of School.
PROGRESS AGAINST PERFORMANCE TARGETS
PROGRESS AGAINST
PERFORMANCE TARGETS

7.1 Progress Against centre Designated Milestones

In its initial application, the Centre proposed 18 challenging research milestones for its 5-year program, as well as 4 teaching milestones, 4 “linkage” milestones and 5 governance milestones. Progress towards these milestones is reported below.

Research Milestones

A.1 Efficiency improvement of standard p-type silicon cells to 26% or n-type cell to 24%.

With the growing industry interest in n-type wafers for solar cell manufacturing, the Centre has focused primarily on developing its highest performance solar cells to suit this type of wafer. Excellent progress has been made, particularly in the last 12 months, with the Centre equalling the world record of 22.7% efficiency for this type of wafer, held for more than a decade by Stanford University.

Importantly, the Centre’s new high efficiency designs for n-type wafers are still far from optimised with the expectation that the Centre will set more world records in the future, thereby establishing a clear lead over competitors internationally.

A.2 Efficiency improvement of Si cell boosted by an up- or down- converter to 28%.

This milestone is linked to A10. An increase in spectral response in the range to 1580nm (i.e. well below the band edge of Si) for a bifacial Si cell has been demonstrated representing a very small increase in current, which nonetheless represents a proof of concept.

Further work on increasing the sensitivity to light between 1250 and 1480nm, which should in turn increase this up-conversion current, continues, with some promising although inconclusive results on sensitisation by co-doping rare earth elements in an up-conversion phosphor.

A patent application has been filed on a new up-conversion approach.

A.3 Demonstration of large-area buried contact silicon solar cell of efficiency above 21% and/or multicrystalline buried contact solar cell above 18%.

Centre’s buried contact solar cell technology recently achieved this milestone with 18.1% efficiency obtained on a large area multicrystalline silicon wafer. The devices were fabricated at the University of Konstanz and the results reported by McCann et alia through an invited paper at the World PC Conference in Hawaii in May 2006.

Good progress is also being made towards achieving the designated 21% efficiency using the buried contact solar cell technology in conjunction with n-type FZ wafers. Efficiencies as high as 20% have been achieved with the devices currently being fabricated expected to increase this to 20.5% efficiency.

A.4 Demonstration of at least three new promising technologies for use in conjunction with commercial buried contact solar cells.

A.4.1. Self-Aligned Plated metallisation using laser doped interfaces

A promising variation of the buried contact approach is to incorporate dopants into the silicon nitride antireflection coating and then melt the silicon with the laser rather than ablating grooves. The dopants from the SiN create a heavily doped surface region well...
suited to being directly electrolessly plated in a self-aligned process while the SiN acts as a plating mask. Although far from being optimised, this technology has achieved voltages in excess of 650mV with efficiencies already comparable with conventional commercial devices. Considerable commercial interest is being shown in this technology.

A.4.2. Hybrid buried contact/screen-printed solar cells

An innovative emitter structure for screen-printed solar cells incorporating semiconductor fingers, has been developed in conjunction with Suntech-Power company and is described in the section on industry collaborative research in the 2005 Annual Report (pp.120-123).

Improvements during 2005/06 have increased efficiencies from 15% in 2004 to >18% efficiency, now well ahead of conventional screen-printed solar cells that are typically 16.5% efficiency. Suntech-Power has publicly announced that this new technology will enter large scale production by the end of 2006. Patent applications were filed in 2005.

This new design addresses the fundamental limitations of screen-printed metallisation schemes that have limited the performance of screen-printed solar cells for more than 30 years. The approach captures the performance advantages of buried-contact solar cells with a selective emitter, low top surface shading losses, and a well passivated and lightly diffused top surface, while simultaneously retaining the simplicity and manufacturability of screen-printed solar cells including the use of all the same equipment and infrastructure.

A.4.3. Interdigitated Rear Contact N-type Buried Contact Solar Cells

N-type CZ wafers have clear advantages over p-type CZ wafers in terms of diffusion lengths, making feasible rear junction devices with no front surface shading. A new buried contact technology has been developed for this wafer type by forming interdigitated grooves of opposite polarity on the rear surface prior to electrolessly plating the metal contacts. Efficiencies as high as 19.8% have been achieved with this approach on FZ wafers, with similar efficiencies expected once n-type CZ wafers are available. A particular strength of the technology is the excellent front and rear surface passivation and beneath the metal contacts that has facilitated the achievement of voltages approaching 700mV.

Demonstration of optical pathlength enhancement > 30 in a silicon thin-film.

Collaborative work with CSG Solar has resulted in optical pathlength enhancement above 20 in the thin crystalline layers deposited onto textured glass. Further improvement is expected in the near future.

In parallel, the AIT glass texturing method (AIT = Aluminium-Induced Texture) is being developed at UNSW. Patent protection has been sought for the AIT method (Glass texturing, International PCT patent application PCT/AU2004/000339, priority date 7/04/2003).

Demonstration of series interconnection of silicon thin-film solar cells without the use of metal interconnects and improved durability and performance for such devices.

Good progress has been made in developing new cell designs that minimise the requirement for metal contacts. Conventional cell designs require a metal grid on the light receiving surface and then another metal contact on the opposite surface, to collect
current and conduct it parallel to the cell surface to a point or region where the current is subsequently transported to the adjacent solar cell. The new cell design completely alleviates the need for such metal, with the only remaining metal being used to conduct the generated current a short distance of only 40 microns across the isolation region produced by the laser between series connected cells. This cell interconnection approach is achieved with the SAMPL, a self-aligned maskless photolithography method. Patent protection has been sought for this cell interconnection method (Thin-film solar cell interconnection, International PCT patent application PCT/AU2005/000734, priority date 4/06/2004).

The latest cell designs will aim to eliminate the final metal components by utilising doped semiconductor material to conduct the current the short distance of 40 microns between juxtaposed cells.

A.7 Demonstration of 11% efficient silicon thin-film cell deposited onto glass.

Work towards this goal progresses along two paths. One is the involvement of senior Centre staff as Consultants for UNSW’s spin-off company CSG Solar Pty Ltd (formerly Pacific Solar Pty Ltd), aiming at the improvement of the company’s CSG (crystalline silicon on glass) technology from 8.2% efficiency in 2003 to 11% by the end of 2007. Good progress is being made through this collaboration, with the best CSG Solar modules now having independently confirmed efficiencies of 9.8%.

The second path is the independent research performed in the Centre’s Thin-Film group. As outlined in Section 4.4 of the 2005 Annual Report, three novel poly-Si thin-film solar cells on glass are being developed (EVA, ALICIA, ALICE). Good progress has been made with all three cell technologies, with open-circuit voltages now in the range 440-517 mV and internal quantum efficiencies of up to 70%. The 517-mV result is, to our knowledge, a new world record for homojunction poly-Si thin-film solar cells on glass.

A.8 Demonstration of 10% photoluminescent efficiency in silicon and above 98% in GaAs, sufficient to produce device refrigeration.

This milestone is deemed to have been achieved.

The first part of this milestone was achieved in 2003. In photoluminescence (PL) testing using oxide passivated FZ silicon wafers with textured front surfaces, we have demonstrated EQE (external quantum efficiency) up to 10.2% at T = 130K and 6.1% at room temperature. [T. Trupke et al., Appl. Phys. Lett. 82, 2996, (2003)]. The IQE (internal quantum efficiency) is also estimated to be over 20%. The results of this work were also used to measure the radiative recombination coefficient B(T) [T. Trupke et al. J.Appl.Phys. 94, 4930 (2003)]. Further improvement in the PL efficiency is expected from thinning substrates with textured surfaces, and improving the light-trapping surface structures.

Progress towards the second milestone has been good with 96% efficiency for GaAs devices demonstrated in the Centre’s first year of operation (Section 5.5 of 2003 report). PL EQE measurements were carried out on an 800 nm sample of GaAs, sandwiched in a double GaInP heterojunction structure so that carriers are confined in the GaAs. Two measurements were used: a calibrated PL technique which gave 90% EQE for planar samples and a combined thermal/PL measurement that gave 92% ± 3% EQE (a reasonable agreement). Further calibrated PL measurements with the ZnSe dome to couple light out of the sample gave an increase from 90% to 96% EQE.
Further progress predicted to increase the EQE towards the 98% for GaAs was achieved in 2004, with development of the texturing technique required for the back surface. Modelling in 2004 has shown that this should bring the 96% with a ZnSe dome to a 97.5% external quantum efficiency – remarkably close to the calculated 98% required for PL cooling.

As the primary aim of this task was to improve insight into the physics and technology of improved radiative emission, rather than to achieve radiative cooling itself, no further work is planned in this milestone area.

**A.9 Efficiency improvement for a silicon based tandem cell over a single cell baseline.**

Significant progress has been made in demonstrating an enhanced band gap material for the top cell for a Si based tandem. Both Si/SiO$_2$ quantum-well (QW) and quantum-dot (QD) structures have been fabricated. These have also been grown in the multilayer structures that will be required for the superlattice structures of an enhanced band-gap material.

Photoluminescence (PL) at enhanced energies has been demonstrated. The enhancement in PL energy is in general agreement with quantum confinement calculations based on the dimensions for QW and QD structures observed in TEM (within the approximately 20% errors in the size measurements). X-ray diffraction and work on the artefacts present in TEM of such small structures is improving the quantitative validity of these calculations.

A PL energy at 1.7 eV has been observed for 1-2 nm QDs; this being the ideal band gap for an upper cell material on Si. Further evidence for quantum confinement in the Si QDs comes from the greatly enhanced PL intensity indicative of localisation in the QDs.

This work includes initial measurement of the electrical properties, with promising, although still high, resistivities. These have been reduced to about $10^3 \Omega \cdot $cm with hydrogen passivation.

Furthermore, there has been success with the fabrication of the analogous structure of Si QDs in Si$_3$N$_4$, with TEM evidence of nano-crystals by both sputtering and PECVD. The advantage of the nitride matrix is that the lower barrier height should improve conductivity for a given QD density. PL evidence for enhanced energy levels in these Si QDs in Si$_3$N$_4$ matrix has been achieved with preliminary evidence for higher energies than for similar sized dots in oxide – although this remains to be confirmed. Conductivity in these Si QDs in nitride nanostructures is also higher than in oxide, supporting the concept of a lower barrier height, although data of conductivity with temperature indicates that this is likely to be defect dominated rather than true inter-QD transport.

The technique has now also been extended to the growth of Si QDs in SiC by a similar technique of growth of alternating layers of silicon rich and stoichiometric silicon carbide. This had been achieved with both sputtering and PECVD. Physical characterisation with TEM and X-ray diffraction has demonstrated the presence of Si nanocrystals, with an increase in crystalline volume with increase in Si con concentration.

Furthermore, the technique has been extended to the growth of tin (Sn) nanocrystals in a SiO$_2$ matrix. Again TEM and XRD demonstrate the presence of Sn nanocrystals. The advantage of Sn is that it offers lower processing temperatures and the potential for band gaps below as well as above that of Si, with correct quantum dot size tuning.
Significant advances have been made in the characterisation of these nanostructures, with the problems of needing very high spatial resolution and high sensitivity for trace elements. A combination of Raman, TEM, XRD, PL, CV and IV techniques is now used.

Work on doping these nanostructures band on fabricating heterojunctions and homojunctions has now begun, in preparation for a full PV device.

**A.10 Demonstration of photon down-conversion quantum efficiency above 50% and/or up-conversion efficiency above 10% and demonstration of performance improvement in a baseline cell by either approach.**

Work to date has concentrated on up-conversion. For a luminescent phosphor, NaYF₄: 20% Er³⁺ supplied by the University of Bern, an EQE of 4% has been measured. Furthermore small improvements in below band gap photoresponse have been measured for bifacial cells with luminescent phosphors on the underside. Although only very small current increases are observed, these are very promising results for non-optimised materials. A baseline test cell has been established using bifacial cells for up-conversion comparative tests.

A small amount of work is continuing on increasing the sensitivity of the phosphor to photons below the bandgap of silicon. The concept is to absorb photons in this region, and re-emit at 1500nm where they will be absorbed by the Er atoms. This will not increase the quantum efficiency but will increase the overall efficiency. Some progress towards this has been made by co-doping Er doped phosphors with thulium (Tm). There is some tentative PL evidence that this is increasing the emission from higher energy levels in the Er, well above the band gap of Si, although it reduces the emission at the wavelength of interest, just above the Si band gap (980nm). This may be evidence for increased sensitisation, although the data is not conclusive.

Properties of down-conversion luminescent materials have been surveyed in the literature and form the subject of a review paper by authors from the Centre. For some mechanisms these can be up to 1.2 EQE, i.e., 1.2 low energy photons out for one high energy photon in, and hence useful for efficiency increase. However, in such materials there are many other mechanisms operating in parallel which bring the overall EQE to about 0.9. Nonetheless these figures are promisingly close to an EQE of 1, i.e., 50% of the ideal performance and hence close to the threshold useful for increased efficiency from down-conversion.

**A.11 Demonstration of two key elements required for hot carrier cell implementation: energy selective contacts and enhancement of radiative recombination rates relative to relaxation rates of photogenerated carriers.**

The luminescence from QDs mentioned under Milestone A.9, is consistent with enhanced band gap emission from QD superlattices. There has also been experimental evidence of resonant tunnelling in these structures. The radiative efficiency improvements for GaAs mentioned under Milestone A.8 are also relevant for improved understanding of hot carrier absorbers.

Experimental progress has been made towards selective energy contacts. This has been achieved with the demonstration of negative differential resistance (NDR) in samples containing a single layer of quantum dots sandwiched between two oxide layers (see Fig. 4.102 in 2004 Annual Report). This indicates resonance in the tunnelling current
across the two oxide barriers – this being a necessary pre-requisite for selective energy contacts. Further work on improving the quality factor of this NDR response is in progress. In addition, characterisation of these structures has been improved with two additional techniques. Firstly, a technique of optically assisted I-V has been established, which uses optical excitation of carriers rather than a bias field. This has already demonstrated more direct evidence for hot carrier generation and collection. Secondly, conductive atomic force microscopy (CAFM) in collaboration with Melbourne University, gives much greater spatial resolution of resonant tunnelling centres. The technique requires has been used to map QD locations in a sample and this has been corroborated by subsequent oxidation of these QDs. However the oxide layers used so far are too thick to allow resonant IV characteristics to be measured. Further work on a Si QD in-situ growth technique using PECVD for SiQDs in Si₃N₄ has yielded a much thinner nitride front surface and a much lower QD concentration. This should now allow the next set of CAFM measurements to detect resonant IV features, if present.

The theory of hot carrier absorbers has been extended to include a greater understanding of phononic transport and a recognition of similarities to the required properties of thermoelectric materials (see “Hot Carrier Absorbers” in Section 5.5 in 2003 Annual Report). In particular the specific mechanisms which can slow cooling by enhancing the “phonon bottleneck effect” in QW and QD superlattices are being identified. Experimental evidence of such reduced cooling in QW superlattices has been identified in the literature. This work has been extended further with modelling of the specific phonon mechanisms and quantum dot conditions that can give an enhanced ‘phonon bottleneck effect’ in QD nanostructured materials.

Further modelling in 2006 has identified the next most important mechanism in optical phonon decay once the dominant Klemens mechanism is blocked. Modelling of narrow optical phonon dispersions to reduce this new Ridley mechanism is underway both for bulk materials and for the phononically engineered QD nanostructures. In addition, the importance of interfaces between QDs and the matrix has been modelled as having a key effect on transmission of phonons in a QD superlattice.

### A.12 Demonstration of the quantum confined Stark effect in silicon as the basis of a high-speed silicon modulator.

Devices of an appropriate structure were fabricated during 2003, but silicon layers needed to be thinner to demonstrate this effect. Progress was made in the period to 2006 in reducing the thickness of these layers, that are now close to the desired value.

### A.13 Evaluation of the optical constants of quantum confined silicon SOI devices as a function of layer thickness.

Relevant data have been reported in Section 5.5 of the 2003 Annual Report and Section 4.6 of the 2004 report. Photoluminescence properties have been characterised. Conversion to optical constants requires accurate knowledge of the dimensions of the confined material. Measurement of these produces some experimental challenges, presently being addressed.

The most accurate method seems to be by identifying photoluminescence features corresponding to regions differing by the presence of one additional atomic plane in the region under test. However, finding an independent technique that is able to confirm this interpretation of the data has provided a challenge.
Other work quantifying the evidence for QDs and their dimensions is continuing. This includes analysis of HRTEM, high resolution SIMS and synchrotron XRD.

Improvement of light emission efficiency of silicon diodes above levels already demonstrated, to maintain Australian leadership and as a test bed for integrated devices.

Australia retains leadership in the bulk silicon luminescence field.

Demonstration of high light emission efficiency in silicon LEDs integrated into microelectronic chips.

Efficiencies of $2 \times 10^{-6}$ have been demonstrated, although further improvements are expected as devices become thinner.

Demonstration of high speed modulation of output of silicon light emitting diodes.

Modulation has been demonstrated, but not at high speed.

Demonstration of operational microelectronic circuits communicating at high data rates using silicon light emission and detection.

This is a target for the final year of the program. To date, we have demonstrated the targeted communication between bulk silicon devices, probably for the first time, but data rates are slow, as expected. Test structures for demonstrating this at the chip level have been designed and initial measurements completed.

Investigate the feasibility of obtaining lasing action in both bulk and quantum-confined silicon and, if feasible, demonstrate the first laser in these materials.

Several new mechanisms for demonstrating lasing in bulk silicon have been investigated.

**Teaching Milestones**

**C.1** At least 50 honours students completing their degrees by 2007.

The Centre of Excellence has performed particularly well in the educational areas with 50 students having completed their degrees and graduated with honours by the end of 2006. The Centre has achieved early what was considered a particularly ambitious milestone (due to the time-lag associated with producing the first graduates).

**C.2** At least 20 new postgraduate students involved by 2007.

The Centre has comfortably exceeded this milestone with more than 30 new postgraduate research students having enrolled in the Centre since 2003.

Importantly, the rate of enrolments have been steadily increasing since the establishment of the ARC Photovoltaics Centre of Excellence with 4 new postgraduate research students enrolling in 2003, 7 in 2004, followed by 8 in 2005, and 12 in 2006.
The involvement of at least 10 postdoctoral research fellows by 2007.

The Centre of Excellence has already achieved this 5-year target with the involvement of 15 postdoctoral research fellows since 2003. These include Dr Robert Bardos, Dr Andrew Brown, Dr Kylie Catchpole, Dr Eun-Chel Cho, Dr Gavin Conibeer, Dr Didier Debuf (Adjunct Fellow), Dr Tammy Humphrey, Dr Dirk König, Dr Kuo-lung Lin, Dr Bryce Richards, Dr James Xia, Dr Per Widenborg, Dr Thorsten Trupke, Dr Anita Ho, Dr Peter Cousins, Dr Allen Guo, Dr Avi Shalav, Dr Scott Jiang, Dr Dengy Song & Dr Shijuan Huang.

The development of at least 4 courses on photovoltaics suitable for internet-based delivery with at least 1 such internet-based course offered each year.

Four courses have now been developed for internet delivery, with two being run during session 2, 2005 and two more in 2006 and 2007.

The first course, based on the postgraduate course Photovoltaics SOLA9001, has been completed and successfully run on multiple occasions, with course enrolments from many countries.

The second is based on the undergraduate course Sustainable and Renewable Energy Engineering SOLA2053. The latter is currently being offered electronically on-line via Web CT for local students enrolling during session 2, 2005, to demonstrate suitability for internet-based delivery internationally.

A third course has been developed for on-line delivery and is based on the course Solar Cell Technology and Manufacturing SOLA9006. A CD has been produced that contains all the necessary teaching material, assignments and simulation software for project work, with this likely to be offered over the internet internationally during 2007.

The 4th course is “Energy Efficiency” and is scheduled for internet delivery in early 2007.

“Linkage” Milestones

Total Average Cash and equipment Contribution of at least $600,000 p.a. from UNSW.

As documented in the financial section within Centre Annual Reports for 2003, 2004, 2005 and 2006, UNSW has made cash contributions to the Centre of approximately $1 million each year, well above the target allocation of $600k.

In addition, with the Centre receiving “school” status, EFTSU income has been awarded to the Centre with additional earnings of close to $3 million.

Allocation of at least 70m² office space and 180m² laboratory space by UNSW.

The Centre’s space needs for new offices have been significantly greater than expected due to the growth in numbers of PhD students, post doctoral researchers and visiting Fellows/Academics associated with the Centre of Excellence. UNSW has responded well as the need has arisen, with 385m² having now been made available.
Regarding Laboratory space, an additional 200m² of space has been made available for the Centre of Excellence, primarily to accommodate the new state-of-the-art facilities at Bay St, Botany.

G.3 Support for at least 4 academic staff affiliated with the centre from EFTSU or related income.

UNSW has again exceeded its targeted support during 2006 through the provision of staff funded from EFTSU generated income or related sources. The staff supported either partially or fully are listed in the Annual Report and include: Dr J. Cotter; Dr A. Sproul; Prof S Wenham; Dr R. Corkish; Dr M. Watt; Dr A. Ho; Ms A. Bruce; and Dr G. Stephenson.

G.4 Average of at least 3 weeks per year of interchange between collaborating organisations.

This target has been comfortably exceeded as documented in the section on collaborative research in Section 4.7.

Governance Milestones

H.1 Establishment of Advisory and Management Committees during 2003.

As was reported in the 2003 Annual Report, this milestone has been achieved.

The Advisory Committee of the ARC Centre of Excellence has met annually.

The Management Committee meets fortnightly. The membership of the latter includes the Centre Director (S. Wenham), the Executive Research Director (M. Green), the 6 Deputy Directors (G. Conibeer, A. Ho, T. Trupke, A. Guo, J. Cotter and A. Aberle), the Head of School for the Centre of Photovoltaic Engineering (R. Corkish) and the Centre’s Business and Technology Manager (M. Silver).

H.2 Formation of the School of Photovoltaic and Renewable Energy Engineering and the appointment of a Head of School during 2003.

Richard Corkish officially appointed as Head of School in Aug. 2003, indicating impending recognition of School status.

UNSW Council meeting in July 2005 approved the official formation on 1 January, 2006 of the School of Photovoltaic and Renewable Energy Engineering. The School came into being on this date.

H.3 Establishment of the Management Structure of Figure H.1 of the initial application by June, 2003, with appropriate documentation of responsibilities of all staff and managers.

The Management structure was successfully established in early 2003 as was reported in Section 6 of the 2003 Annual Report. Since initially being established, the following changes have been made:
• Dr. J. Cotter has taken over as Manager of the wafer-based projects in C. Honsberg's absence, with his automatic inclusion in the Management Committee
• Head of School, Richard Corkish, was appointed August 2003
• G. Conibeer replaced R. Corkish as manager of the Third Generation strand
• T. Burns took over responsibility for School Administration
• Additional changes as documented in Section 6 of this report.

The roles and responsibilities for most staff are defined, in most cases, in their official Position Descriptions, held by Human Resources Department. These are routinely reviewed and revised at times of appointments and reappointments.

In special cases, such as for the Head of School who is responsible to the Dean of Engineering, additional documentation exists: http://www.hr.unsw.edu.au/poldoc/hos.htm. Management, staff and student responsibilities for occupational health and safety are documented by the UNSW Risk Management Unit.

**H.4 Consolidation of New Centre Strategic Plan in New Document by June, 2003.**

Following the achievement of this milestone in 2003, the strategic plan is regularly reviewed in consultation with the Head of School and Dean of Engineering.

A copy of the Centre’s Strategic Plan is held by the School of Photovoltaic Engineering.

**H.5 Document Management and Advisory Committee Meetings at least monthly and annually, respectively.**

Advisory Committee meetings have been held annually since Centre commencement.

Management meetings are scheduled fortnightly. At the latter, reports have been written for each meeting to document progress in each of the research areas.

Monthly overview meetings are also held for the entire Centre for information dissemination and the presentation of brief (nominally 6 minute) reports from each area of activity including the Lab Operations Team, External Affairs and Teaching.

In addition to the overview meetings, members of the Management team also hold meetings with the respective staff and students from their particular area in relation to the corresponding research and other activities. Such meetings are normally held either on a fortnightly or monthly basis, except for teaching meetings which involve most staff and are only held every few months.

**7.2 Progress Against ARC Designated Performance Indicators**

Subsequently to the initial application, the ARC also designated an additional set of performance indicators. Progress against these is documented below.

Quality of publications – the Centre has achieved its target of 30% of its publications in refereed journals each year. The Centre’s 2006 publications are listed in Section 9 of this report.
Number of publications – the Centre has far exceeded its target of 50 publications per year.

Number of patents per year – the Centre’s programs have led to more than the expected 1 new patent/year. In fact there were 2 in 2003, 4 in 2004, 7 in 2005 and 5 in 2006. The patents are reasonably well distributed between the three generations of PV technology with 6 in the 1st generation PV area, 8 in 2nd generation PV, 3 in the 3rd generation PV area and 1 in device characterisation area.

Invitations to address and participate in International Conferences – the Centre has easily achieved its target of 2/year with more than 60 such invitations having been received since 2003.

Invitations to visit leading international laboratories – quite a few Centre staff regularly receive invitations to visit leading international laboratories with over 30 such invited visits taking place. This is well above the target number of 2/year.

Number and nature of commentaries about the Centre’s achievements – the target number of 2 media articles per year has been well exceeded with over 100 examples of such media interaction documented.

Number of postgraduates recruited – the Centre has over 30 postgraduate students since 2003, well ahead of the target of 4 per year.

Number of postgraduate completions – the Centre has achieved 31 postgraduate completions, comprising 17 postgraduate research students and 14 postgraduate coursework students. Most of the former commenced their research degrees before the Centre commenced, with completion numbers expected to increase over the next couple of years due to the increased numbers of enrolments since being awarded the Centre. Despite this, the numbers of completions are well ahead of the target value of 3 per year.

Number of honours students – despite the challenging target of producing 10 honours students per year and the delay in producing the first graduates, the success of the Centre’s new undergraduate program has enabled it to comfortably exceed this average with 50 honours graduates to date primarily in 2004, 2005 and 2006.

Number of professional courses – the Centre on average has run more than 8 such courses per year, ahead of the target figure of 6 per year.

Participation in professional courses – there has been 34 professional courses run by the Centre since 2003. The target figure of 20 enrolments per course has been comfortably achieved with the course average being above 50.

Number and level of undergraduate and high school courses in the priority area(s) – the Centre has run a large number of undergraduate courses in the priority area. The average number run each year exceeds 16, exceeding the target number of 12 per year.

Number of international visitors – the Centre has received more than 200 international visitors in the last 3 years well ahead of the target number of 10 per year.
Number of national and international workshops – the Centre has achieved its target of 3 workshops per year with participation in 25 such workshops internationally during the period 2003-2006.

Number of visits to overseas laboratories – these were listed in chronological order in the documentation produced for the ARC during the Centre’s review in late 2005. The total number comfortably exceeds the target number of 10 per year.

Examples of relevant Social Science and Humanities research supported by the Centre – as described above, staff and students from the Centre have been actively involved in developing countries projects, providing renewable energy power sources to materially disadvantaged people who have in many cases never previously had access to electricity. Six Centre staff and more than 30 Centre students have participated in these projects including travelling to locations such as Nepal, Sri Lanka and Nicaragua to live briefly with the locals, provide technical expertise to local technicians, design and install PV systems, and train locals in their use and maintenance of the new technology. This work is usually done in conjunction with Aid Organisations or local institutions.

Number and nature of commercialisation activities – the Centre has engaged in 17 technology transfers which have in general been to companies who have licensed or purchased Centre technology, in some cases prior to the establishment of the Centre of Excellence in 2003. In addition, with the rapid growth of the PV industry, Centre staff are often also heavily involved in assisting companies in expanding or setting up new manufacturing facilities. These activities have met the Centre’s target of 4 such technology transfers per year.

Number of government, industry and business briefings – the Centre target of 2 such briefings has been exceeded with more than 30 such briefings since the commencement of the Centre. The high figure has resulted from the extraordinary rate of growth in the industry, with relatively large numbers of business briefings by Centre staff in particular being sought by the industry.

Number of Centre associates trained/ing in technology transfer and commercialisation – although the target number for this was set at 5, the diversity of Centre technology coupled with the recent high demand from the rapidly growing industry, has necessitated the Centre train additional staff and associates in the various areas where there is commercial interest in the Centre’s technologies. The Centre now has 15 staff and/or research students at a stage where they feel confident in their training for technology transfer. Those trained in technology transfer often become particularly valuable to industry and are often offered good employment opportunities. For example, two of the staff listed below have within recent months accepted offers to work for newly established companies wishing to set up new manufacturing.

Number and nature of Public Awareness programs – the Centre conducts extensive public awareness programs, particularly amongst high school students. This has been particularly important with the Centre developing and establishing the world’s first undergraduate engineering degree in Photovoltaics and Solar Energy which is only able to attract students provided students become aware of its existence and relevance. There have been well over 50 examples of activities in which the Centre has been engaged that increase the public awareness of the Centre’s program and of the photovoltaics field in general.
Annual cash contributions from Collaborating Organisations – the target of $0.5 million per year has been easily exceeded as documented in the Financial section.

Annual in-kind contributions from Collaborating Organisations – the target of $0.5 million per year has been easily exceeded with most collaborating organisations and companies preferring to make significantly larger in-kind contributions than cash contributions.

Number of new organisations recruited to or involved in the Centre – more than 50 new collaborators have been recruited to the Centre, well ahead of the target of 2 per year.

Level and quality of infrastructure provided to the Centre – the Centre’s infrastructure and facilities were already world class at the time the Centre was awarded. Since this time the Centre has further developed its infrastructure and capabilities through acquiring state-of-the-art facilities from Pacific Solar, using funding of well over $1 million from the University and State Government of NSW.

Breadth and experience of the members of the Advisory Board – the Centre’s Advisory Board comprises members recognised as industry leaders including manufacturers, end-users, academia and research institutes. In particular it includes several Heads of organisations such as CEO’s of major international companies. The membership is listed in Section 6 on Organisational Structure.

Frequency and Effectiveness of Advisory Board Meetings – the Advisory Board has met annually as planned. To be effective, a particular challenge for such an Advisory Board, with membership from 6 different countries, is to achieve adequate meeting attendance. The last meeting was held in Dresden in conjunction with one of the major international conferences. Feedback and advice from Advisory Board members have been valuable for the Centre’s Management Team in effecting improvements in some areas, particularly with regard to content in teaching programs and commercial significance of some of the research.

Quality of the Centre Strategic Plan – the Centre’s strategic plan is of high quality following several iterations, as specifically concluded by the 2005 Review.

The adequacy of the Centre’s Key Performance Indicators – the Centre’s performance criteria/milestones outlined in the original grant application are proving to be effective in guiding the research and its focus. Few, if any, have needed modification. In general they are quite challenging and ambitious. For example, the Centre has made excellent progress in developing new high efficiency solar cell technology to suit n-type wafers, with the recent achievement of equaling the world record with 22.7% efficiency. Despite this success, the aim is to achieve the ambitious 24% efficiency target by the end of 2007. Regarding the ARC designated performance indicators, their breadth and direct links to the objectives of the ARC Centres of Excellence program ensure the Centre adequately addresses all areas of importance and significance in contributing to the achieving of the program’s aims and objectives.

Measures of expansion of Australia’s capability in the priority area – the growth rate of manufacturing capacity in Australia has greatly outstripped the targeted 15% per annum in recent years, with the largest manufacturer BP Solar significantly expanding their production capability while Origin Energy is establishing new manufacturing capacity in Adelaide. The increase in capacity has been so great that locally manufactured product now exceeds demand in Australia by a factor of 5 (i.e. Australia now exports 80% of its manufactured product in this industry).
Case studies of economic, social, cultural or environmental benefits – the Centre has met its target of one such case study per year. In 2003, Centre staff were involved in a case study on Policy Support for Renewables in Australia from the perspective primarily of the social and environmental impact of photovoltaics. This case study was published in January 2004:


A second case study in which Centre staff have been involved, focused on where PV is heading in the future, and considered economic, employment, markets, social and environmental benefits. This study culminated in producing for Australia a PV Roadmap with the following publication stemming from the work in 2004:


As described elsewhere, the Centre runs projects involving the use of PV in developing countries. These projects directly impact the economic, social, cultural and environmental well-being of those being helped. For example, the Solar Sisters program specifically aims to provide PV power to facilitate new opportunities for women such as for educational radio/television, lighting at night to engage in craft work to earn income, etc. Studies have been done to identify the social and economic benefits of these projects. In 2005, these case studies were extended to the indigenous population in Australia for inclusion in the Centre’s “ Developing Countries Projects.

Another study being conducted at present by the Centre is a review by Centre staff of the Federal Government organisation Bushlight. Bushlight is also involved in studying and capitalising on the social, cultural and economic benefits able to be offered by PV and other renewable energy technologies in providing for the needs of our indigenous communities. At completion, thesis student Long Seng To, under the supervision of Dr Muriel Watt, will publish material from this case study.
Centre 2006 Income

The total income for 2006 for the Australian Research Council (ARC) Centre of Excellence in Advanced Silicon Photovoltaics and Photonics was $4.45 million. This does not include funding approaching $1.5 million from the Host Institution based on EFTSU and related income. This income has been generated by the Centre through its educational activities by virtue of the fact that it is now the basis of a School within the Faculty of Engineering. This income has been used for the development of new courses and teaching materials and to fund the salaries of most of the academic staff associated with the Centre.

The largest component of the Centre’s income was from the ARC totalling $2.65 million. The second largest cash contribution came from industry totalling almost $0.9 million with even larger in-kind contributions in excess of $1 million for collaborative research being provided. The largest industry contributor for the third successive year was Suntech-Power Company with a cash contribution of $0.51 million while also generously supporting the collaborative research at their own facilities. Including the funding of collaborative research costs, scholarships, royalties, consulting and rental of facilities, the major cash contributors to the Centre’s 2006 income were Suntech-Power Company with $512k, CSG Solar with a contribution of $217k, Toyota Motor Corporation with $90k and BP Solar with $68k. Other cash or in-kind contributions have been made by a large number of other collaborators who contribute to the Centre through the expertise and experience they offer in collaborative research areas and the in-kind support they provide through access to equipment, facilities and personnel not available at UNSW. Not included in this industry money are several other collaborative research contracts from companies in Taiwan and China such as E-Ton Solar and Nanjing PV-Tech, who have already signed collaborative research agreements each worth approaching $1 million but where the collaborative research does not commence until 2007.

The third largest cash component of income was Host Institution support, with UNSW contributing almost $0.6 million excluding EFTSU and related income discussed above. Part of the in-kind support from UNSW includes the direct funding of seven full-time or part-time academic staff who have been actively involved in the Centre’s activities.

The next largest cash component of income was $326k from the State Government with $304k being provided through the Department of State and Regional Development (DSRD). This funding is particularly important for the purchase of new equipment and the development of facilities, and has contributed significantly to the acquisition and development of the new state-of-the-art research facilities at Botany.
Other Centre contracts, consulting work and technology transfers are conducted through NewSouth Innovations, the commercial arm of the University. These are handled on behalf of the Centre of Excellence and its staff through the NewSouth Innovations accounts and are not included in this financial report.

The Centre also earns income through the sale of educational CDs, books and computer software, with a combined income for 2006 of $17k.

**Centre 2006 Expenditure of ARC Grant**

The total expenditure of ARC grant monies during 2006 was $3.1 million. This is approximately $0.5 million above the funding awarded for 2007 due to a carry-forward from 2005 of about $0.4 million resulting from purchases being delayed until the 2006 calendar year. By far the largest component of this expenditure was on salaries, with the employment of 20 full-time staff and a further 60 part-time or casual staff, including student scholarships. The combined expenditure on salaries and scholarships during 2006 was $1.8 million. This included 11 full-time researchers: P. Widenborg, A. Wang, G. Zhang, R. Bardos, G. Conibeer, X.M. Dai, K. Fisher, J-H Guo, A. Ho, H. Mehrvarz and T. Trupke. To support the research activities, 7 technical support staff were employed by the Centre during 2006, namely M. Silver, M. Griffin, L. Soria, A. Yee, J. Yang, K. Chin and R. Largent. Two full-time administrative staff were also employed by the Centre during 2006, J. Hansen and J. Kwan. The latter is the Financial Officer for the Centre of Excellence, while the former carried out secretarial, administrative and receptionist duties (see Section 10: In Memoriam).

Equipment expenditure from the Centre grant was kept relatively small for 2006 at $318k due to the support from industry, the State Government through DSRD and the host institution UNSW. The latter sources provided significant levels of funding specifically targeting major equipment and infrastructure development such as the purchase of the new Multi-beam E-beam Evaporator and the new Inkjet Printing system. This allowed the Centre funds to be used primarily for small laboratory equipment items such as hotplates, temperature controllers, pumps, an ultrasonic cleaners, small processing furnaces, specialised computing facilities, test equipment and a range of spare parts.

The total expenditure from the ARC grant on consumables and maintenance for 2006 was $748k. These costs are strongly dominated by laboratory consumables to support the device research, such as high purity gases, chemicals and general laboratory supplies.
The expenditure on travel during 2006 from the ARC grant was $243k. The primary purposes for this travel were for staff and students participating in collaborative research projects with overseas industry partners and for the attendance at international conferences such as the 4th World Photovoltaic Conference in Hawaii in May 2006 and the 10th Workshop on Crystalline Silicon solar cells and modules in Denver. Travel expenditure supporting collaborative research at the premises of our collaborators is particularly worthwhile since all the other costs of conducting such research are in general met by our collaborators.

Figure 8.3: Expenditure of ARC income by expenditure category.
9.1 BOOKS


9.2 BOOK CHAPTERS


9.3 JOURNAL PUBLICATIONS


9.4 CONFERENCE PAPERS


O. Breitenstein, P. Altermatt, M. A. Green, J. Zhao and A. Schenk, “Interpretation of the commonly observed I-V characteristics of c-Si cells having ideality factor larger than two”, 4th World Conference on Photovoltaic Energy Conversion (WCPEC), Hawaii, USA, 7-12 May 2006, pp. 879-884 (invited).


M. A. Green, “Future of Thin-Film Solar Cells”, 3rd Shanghai Environmental Energy Conference, Shanghai, October, 2006 (invited keynote speaker).


M. A. Green, Shell Roundtable Symposium on Solar Photovoltaics, Innovia Technology, Munich, April 2006 (invited).


M. A. Green, 16th International Conference on Photochemical Conversion and Storage of Solar Energy, IPS-16, Uppsala, July 2006 (invited plenary paper).


M. A. Green, “Composite Semiconductors Based on Silicon Quantum Dots”, ACUN-5 International Composites Conference, Sydney, July 2006 (invited keynote paper).


9.5 PATENT APPLICATIONS


S. R. Wenham and B. S. Tjahjono, Solar cell fabrication through the inkjet printing of dopant sources, Australian Provisional Patent Application (filed 2006).

9.6 REPORTS


Richard Corkish, “PM’s nuclear bombshell won’t stop climate change”, (letter to the editor) Sydney Morning Herald, 22 May 2006, p. 10.


In Memoriam: Jennifer Rae Hansen

After rapidly declining health during 2006, one of the Centre’s key personalities, Jenny Hansen, passed away on 25th February 2007. The following is the text of a short tribute given at Jenny’s memorial service on 2nd March 2007 by Professor Martin Green.

“Having worked closely with Jenny over the last 20 years, I appreciate the opportunity to say a few words on behalf of myself and her workmates at the Photovoltaic Centre of the University of New South Wales.

I first met Jenny in the early 1980s through our mutual friend, Beverley. Our group at the University was then small but growing very quickly. Jenny started working part-time for me from home. Fortunately she had moved to just around the corner. These were the days of the massive IBM ‘Selectric’ typewriters and I had to carry ours to Jenny, with my collection of ‘golf balls’, every time I wanted something done. After a few years, as Anna and Frank grew, Jenny started working three days a week at the University, joining full-time in 1988.

This was a dynamic period of growth for our group at the University and Jenny became key to this growth. Among other skills, Jenny was a superb typist. She once told me she had been runner-up in a state-wide speed typing competition. Jenny and I ploughed through the work. There were intense periods preparing grant applications, final reports, conference presentations, books, government submissions, letters organising this or lobbying for that. Jenny became the pivot around which the centre revolved. Some idea of the esteem in which Jenny was held is clear from a few snippets from a report I wrote for an early promotion:
“Jenny has shown the highest possible proficiency in all she undertakes - an enthusiasm for learning new skills - an excellent attitude to work and to staff and visitors - a willingness to accept responsibility. Her knowledge and experience allow even the most critical projects to be delegated with confidence.”

And on and on. A rave review! Jenny got the promotion.

Since Jenny was involved in the Centre from the start and had been crucial to its development she wheeled a lot of power within it. Jenny had an efficient, deliberately brusque manner which she used to sort out problems or get things organised.

But there was an underlying patient, soft side that came to the fore in dealing with casual enquiries, our research students and our many overseas visitors. Jenny accepted full responsibility for helping many of these through battles with visas and the Immigration Department, finding accommodation and schools for the kids and so on. Many have made it clear over the years that they remember her fondly for her efforts on their behalf and from the way she touched upon their lives.

Jenny took particular joy in her two children, Anna and Frank. She was always sharing with her workmates the latest photos and press clippings and even report cards - the good ones at least - making us all feel very much involved and part of the family.

Of her myriad activities at the Centre, I think Jenny greatly enjoyed interaction with students and visitors as mentioned. She also got great pleasure from preparing the complicated technical illustrations important in our work.

Although Jenny had no formal training in this area, she delighted in the challenge of converting a crude sketch I would do on a scrap of paper into a pristine computer image. This was a process that sometimes took days or even weeks with successive stages of refinement. Several of these illustrations are now classics - not only at the Centre but also worldwide - with drawings from a catalogue we published used in many overseas publications. The Jenny's latest promotion – 'broad banding based on new skills' in University jargon - we include a cross-section of these drawings with the paperwork, to demonstrate the sophistication of what she could do.

I would like to finish by reciting a few succinct words written by a mutual colleague, Dr Muriel Watt:

“Jenny made a huge contribution to the activities of the Centre and, of course, to so much of Martin's work. I will miss her brusque, efficient and underlying kind presence.”

This is a sentiment that I think all at the Centre share. Although we have had the last year to get used to the idea of not having Jenny around forever, her parting has left a huge gap. I extend my sincere sympathies to Jenny's family and thank you for the opportunity to say these few words.”
The Photovoltaics Centre of Excellence is a Centre of Excellence of The Australian Research Council
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Photovoltaics involve the conversion of light, especially sunlight, directly into electricity when falling upon devices known as solar cells. Silicon is the most common material used to make these cells, as well as being the material most widely used in microelectronics.

The Australian Research Council (ARC) Photovoltaics Centre of Excellence officially commenced at the University of New South Wales (UNSW) on 13th June, 2003. The Centre's mission is to advance silicon photovoltaic research on three separate fronts, as well as to apply these advances to the related field of silicon photonics. The educational activities of the former Key Centre for Photovoltaic Engineering have also been successfully integrated into the new Centre.

Photovoltaics is currently the world's most rapidly growing energy source, with markets increasing at a compounded rate of above 40% per year over the last decade, with the pace showing no signs of slacking. As evidence for the growing maturity of the industry, the electricity generating capacity of new photovoltaic product manufactured in 2006 exceeded new nuclear power capacity for the first time, with the gap expected to widen rapidly over the next decade. Most present photovoltaic sales are of “first-generation” solar cells made from silicon wafers, similar to the wafers used in microelectronics.

The Centre has a world-leading program with these “first-generation” devices, holding international records for the highest-performing silicon cells in most major categories, including that for the outright highest-performing device. First-generation Centre research addresses the dual challenges of reducing cost and improving efficiency. A key goal is to develop technology which allows silicon wafers doped with boron to be replaced by phosphorus-doped wafers. The rapid growth of the industry has also created a burgeoning interest in past and ongoing innovations of the Centre with this first generation technology. This has resulted in re-organisation and re-direction of priorities to address this greatly increased interest. As a sign of its intensity, the Centre’s “semiconductor finger” technology went into large-scale production during 2006 and several licences were signed for this and other newly developed technology.

Silicon is quite a brittle material so silicon wafers have to be reasonably thick, at least a fraction of a millimetre, to be sufficiently rugged for processing into solar cells with reasonable yields. Without this mechanical constraint, silicon would perform well even if very thin, over 100 times thinner than present wafers. Centre researchers have pioneered an approach where such very thin silicon layers are deposited directly onto a sheet of glass with the glass providing the required mechanical strength. Such a “second-generation” approach gives enormous potential cost savings since, not only are the costly processes involved in making wafers no longer required, but also there is an enormous saving in silicon material and cells can be made more quickly over the entire area of large glass sheets. The Centre is at the forefront of international research with such “second-generation”, silicon based approaches, with the first commercial product from “spin-off”, CSG Solar, appearing on the market in 2006.

The silicon thin-film approach has a large potential cost advantage over the wafer-based approach, due mainly to reduced material costs. In large enough production volumes, even these reduced material costs eventually will dominate thin-film costs. This has led to the Centre's interest in advanced “third-generation” thin-film solar cells targeting significant increases in energy-conversion efficiency. Higher conversion efficiency means more power from a given investment in materials, reducing power costs. The Centre's experimental program is concentrating on “all-silicon” tandem solar cells, where high energy-bandgap cells are stacked on top of lower-bandgap devices. The silicon bandgap is controlled by quantum-confinement of carriers in small silicon quantum-dots dispersed in an amorphous matrix of silicon oxide, nitride or carbide. Progress with this approach was recognised by the award of substantial complementary funding under the Global Climate and Energy Project managed by Stanford University and funded by a large international consortium. Cells based on “hot” carriers are also of great interest since they offer the potential for very high efficiency from simple device structures. Although their implementation poses daunting challenges, further progress on addressing these was made during 2006.
The final Centre research strand involves silicon photonics where, as mentioned, the emphasis is upon using our experience with solar cells, using light to produce electricity, to the reverse problem of engineering silicon devices that use electricity to produce light. The Centre holds the international record for the light emission performance from bulk silicon, in both electroluminescent and photoluminescent devices. Emphasis is now upon exploiting our expertise in silicon light emission to develop new techniques for silicon wafer characterisation. This area has attracted considerable international interest, as reflected by a best poster award at the 4th World Conference on Photovoltaic Energy Conversion in Hawaii in May.

In addition to these four research strands, the activities of the former Key Centre for Photovoltaic Engineering have been integrated into the ARC Centre of Excellence. The third cohort of students from the Bachelor of Engineering (Photovoltaics and Renewable Energy) program graduated during the year. This program has been enormously successful, attracting some of the best and brightest students entering the University. The first group of students have now graduated from the Centre’s second undergraduate program, leading to a Bachelor of Engineering (Renewable Energy).

The rapidly growing business interest in photovoltaics as a sustainable and increasingly marketable energy source created many commercial highlights involving the Centre during 2006. Following the success of Centre partner, Suntech Power, a largely Australian-owned and managed company operating in China, in its float on the New York Stock Exchange at the end of 2005, two other Centre-related companies completed successful initial public offerings in 2006 with a third doing so in early 2007. The combined market capitalisation of these 4 companies is now in excess of $14 billion with combined 2007 revenues expected to exceed $2 billion. As mentioned previously, Centre “spin-off”, CSG Solar, announced the first commercial sales of its highly innovative “silicon on glass” technology during 2006, with a large capacity expansion planned in 2007, and Suntech announced the commercialisation of “semiconductor finger” technology, jointly developed with the Centre.

As this report went to press, we were advised that the 2006 review of the Centre had been successful and ARC funding over the 2008-2010 timeframe would total $7.2 million.

We thank all those who contributed to the Centre’s success during 2006, particularly the Australian Research Council for its ongoing support. The present continues to be a most exciting time for photovoltaics with time drawing closer to a future where solar cells provide a significant part of the world’s energy needs, without the problems and escalating costs associated with the present mainstream options.
Market Triumphs

Following the successful float on the New York Stock Exchange (NYSE) of Suntech Power at the end of 2005 (pictured), (Suntech is a Centre partner headed by former PhD student and postdoctoral fellow Dr. Zhengrong Shi), 2006 saw two more companies with strong Centre links make their market debut. In December, Trina Solar listed on the NYSE, with former PhD student and postdoctoral fellow, Dr. Mohan Narayanan, President of Technology. Almost simultaneously, Solarfun Power Holdings listed on NASDAQ, with Fei Yun as Director of Technology. Fei was a postgraduate student and Centre researcher through most of the 1990s.

2007 looks like it is also going to be an equally exciting year for Centre-spawned entrepreneurs. In February, JA Solar listed on NASDAQ with Dr. Ximing Dai, former PhD student and long-term Centre postdoctoral researcher, as Chief Technical Officer and Director. Also featuring prominently in the company’s prospectus was Ted Szpitalak, another long-term Centre employee, up to the time when seconded to Pacific Solar. Ted sourced most of the Centre’s equipment in the ground floor laboratories. JA Solar is also to be a Centre partner in the Centre’s 2008-2010 program.

The combined market capitalisation of these companies is above $14 billion with combined 2007 revenue expected to exceed $2 billion.

“Semiconductor Fingers” Commercialised

The innovative “semiconductor finger” technology co-developed by the Centre and Suntech Power Co. overcomes the main limitation of the standard screen printing process that currently dominates solar cell production around the world. Heavily doped semiconductor lines are made in the cell top surface, instead of heavily doping the whole front surface, since this creates a surface dead layer in conventional cells. This technology may also permit the use of fewer traditional lines of metal contact strips on the top surface, thereby reducing shading from the sun to enable the cell to generate more power. Even more importantly, the new technology may allow the use of lower quality silicon to make good quality cells.
“Perhaps the most exciting part about this new technology is that it has worked particularly well with the lower-grade and poor quality silicon wafers for which we have seen increases in conversion efficiency of upwards of 17%,” according to Dr. Shi, Suntech’s CEO. “This will give Suntech the added benefit of being able to process lower cost silicon wafers at higher conversion efficiencies.”

When reporting publically on the company’s 2006 performance and 2007 plans, a company spokesman stated that the company intends to progressively convert all its production lines to this technology during 2007, unless other UNSW technology, presently in pilot-line evaluation, proves superior.

World Technology Award

Centre Director, Professor Stuart Wenham, won the prestigious 2006 World Technology Award for Energy which was presented at the historic San Francisco Town Hall. He acknowledged the contribution of the team of world class researchers at the Centre who have made UNSW achievements possible and also our industry collaborators such as Suntech-Power, CSG Solar, BP Solar, etc. for their work in commercialising our various technologies.

“Broadly speaking I think the award emphasizes the importance now being given world-wide to renewable energy technologies and more specifically photovoltaics as an important and viable energy source for our planet for the future,” said Professor Wenham. “At a more personal level the award gives great encouragement for the work we are doing at The University of New South Wales as it points to the importance and perceived value of the PV technologies we have been and are developing. This is particularly so when recognising that the nominators and judges for this award are our peers world-wide who are the recognised leaders in our field. This aspect makes the award to me particularly important and satisfying.”

Other Awards

Professors Stuart Wenham and Martin Green, Centre Director and Executive Research Director, have been ranked among the world’s best inventors in the European Inventor of the Year awards. The co-developers of the world’s most efficient solar cells were among the final top three contenders for a prize in the non-European inventors category, from a total of over 200,000 inventions that were eligible over the 1990-2000 period.

Centre researchers were also awarded the Outstanding Poster Award in the Area of Crystalline Silicon Solar Cells at the international 4th World Conference on Photovoltaic Energy Conversion, held in Waikoloa, Hawaii in May, 2006. The poster bested almost 200 other entries in the same category. Doctoral student Florence Chen, the lead author on the poster and paper, said “The project brought together my work on high-quality Silicon Nitride coatings for solar cells with the work of my colleagues on Photoluminescence Imaging techniques. It was an exciting and dynamic collaborative project between two groups at the Centre of Excellence, exactly the kind of collaborative environment that attracted me to study a PhD at UNSW”. Jeff Cotter, Thorsten Trupke and Robert Bardos were co-authors contributing to the poster and paper.
Doctoral student, Ms. Ly Mai won the 2006 Suntech Technology Innovation Award for her work on “semiconductor finger” technology. This technology is jointly owned by UNSW and Suntech and was developed as part of collaborative research between the two organisations, as earlier described.

Another highlight in 2006 was the award of a A$256,000 research infrastructure grant by UNSW to Patrick Campbell, Armin Aberle and Gavin Conibeer for a multi-beam electron-beam evaporator.

Professor Martin Green was also awarded one of this year’s prestigious ARC Federation Fellowships, making him one of the first researchers to receive this honour for the second time.

**New School, New Deputy-Directors**

In January 2006, the new School of Photovoltaic Engineering came into existence, with Dr. Richard Corkish as the inaugural Head of School. This development was one of the original organisational milestones of the Centre of Excellence.

Also during the year, the Centre appointed three new Deputy Directors, driven primarily by the growing commercial interest in Centre developed technologies and the establishment of new research activities in the areas of device innovation through ink jet technology and characterisation through photoluminescent imaging. To address the first area, Dr Allen Guo has been appointed Deputy Director responsible for PV Commercial Technologies, while Dr Thorsten Trupke has been appointed Deputy Director responsible for silicon photonics, now focussed upon photoluminescent imaging, and Dr Anita Ho-Baillie for High Efficiency PV work with particular emphasis on using inkjet technology to replace photolithographic-based processing.
Thin-Film Silicon

Good progress has been made with the Thin-Film Group’s solar cell technologies EVA, PLASMA, ALICE and ALICIA. A significant milestone achieved in 2006 was the realisation of the Group’s first poly-Si on glass thin-film solar cell with an efficiency of over 5%. Other highlights include fill factors of over 66% for 4-cm² cells, peak internal quantum efficiency values of over 86%, short-circuit current densities of over 17 mA/cm², and a boost of over 28% in the short-circuit current of a textured ALICIA cell following the deposition of a pigmented diffuse reflector onto the cell’s back surface. The Group was again active in generating intellectual property, with the filing of a provisional Australian patent application on a metallisation method for thin-film modules, a provisional Australian patent application on a method for making thin-film diode structures, and a PCT patent application for a metallisation method for thin-film semiconductor structures.

New Text Book

The School’s text book, Applied Photovoltaics (2nd Edition) is newly available in a corrected edition from London based Earthscan for the global market. The new book, by School staff Stuart Wenham, Martin Green, Muriel Watt and Richard Corkish, is an important aid to the rapidly growing renewable education sector and translation into Chinese is already underway.

The new edition (Blue Book) forms a set with three other Centre texts that have become classics in the field: “Solar Cells” (Red Book) and “Silicon Solar Cells: Advanced Principles and Practice” (Green Book) by Martin Green and “Crystalline Silicon Solar Cells: Advanced Surface Passivation and Analysis” (Orange Book) by Armin Aberle.

JA Solar and Nanjing PV Tech Collaboration, Suntech Gift

In June, UNSW signed a collaboration agreement with Chinese based solar cell manufacturer, JA Solar. The agreement will see staff and students from UNSW working on improving the production process at JA Solar, which makes screen printed wafer-based silicon cells in a new factory that was officially opened in May 2006. Early in 2007, the company successfully floated on NASDAQ, as earlier reported. JA Solar have also signed on as Centre partners in the 2008-2010 phase of Centre operation, joining Suntech Power, CSG Solar and NewSouth Innovations in this category.
In mid-year, Suntech Power Co., based in Wuxi, Jiangsu Province, China, made a $1.5m gift for research to the Centre. The CEO of the company, Dr Zhengrong Shi, is a PhD alumnus of the Centre and now leads the largest solar cell manufacturer in China and one of the largest in the world. Dr Shi has also recently offered to provide scholarships for study within the Centre, additional to those that Suntech Power already provides, and staff of the company are translating one of the Centre’s textbooks for distribution in China. The Centre greatly values its relationship with Suntech Power and especially the company’s exemplary treatment of intellectual property issues, misrepresented in the local press.

In November, a further collaborative research and licensing agreement was signed with CEEG Nanjing PV Tech. Research will focus upon adapting high-efficiency UNSW PERL cell technology to suit large-scale commercial manufacture.

High Profile Visitors

Two high-profile leaders took time out from tight schedules during January’s Asia-Pacific Partnership on Clean Development and Climate’s Inaugural Ministerial Meeting to learn more about the Centre. Amid tight security, Chinese State Councillor and Secretary General of the State Council Hua Jianmin, and US Secretary for Energy Samuel W. Bodman made separate visits to explore the Centre and to learn more about the potential of photovoltaics. The Chinese and American delegations toured the laboratories and listened to presentations highlighting laboratory achievements and plans.

Secretary Bodman, a former chemical engineer, raised well-informed questions about the merits of various photovoltaic materials and the role of subsidies in the booming field of photovoltaics. Secretary Hua, also a former engineer, took particular interest in the close relationship between the Centre and Wuxi-based photovoltaic company, Suntech, a partner in the Centre.

“We’re delighted that leaders of the two of the world’s most powerful nations recognise the leading position of the Centre and the role that solar energy is playing in the world today,” said Dr Richard Corkish, Centre researcher and Head of the School of Photovoltaic Engineering, who hosted both visits.

Later in the year, an official party led by Chinese Vice Minister of Science and Technology and Vice President of the Central Committee of Public Interest Party of China visited the Centre’s laboratories. The Vice Minister was interested to learn at first hand more about the Centre’s current and future collaborative activities with Chinese companies, universities and institutes.
New Computer Cluster

During the year, Centre researchers installed and commissioned a new high-performance computer cluster to allow simulation of quantum dots of silicon and related materials from basic principles. The 64bit Linux Beowulf type cluster consists of 10 compute nodes and one link node. Each compute node consists of four AMD Opteron CPU cores running at 2 GHz (two dual core chips) and 1.6 GHz bus clock, 4 GB DDR-ECC-RAM (400 MHz) and 400 GB HDD space. The link node has 8 GB DDR-ECC-RAM (400 MHz). Each node has a compute performance of 20 GFLOPS. The theoretical cumulative cluster performance is 230 GFLOPS.

The OS (operating system) is 64bit Rocks Parallel Linux 2.5.7. The DF-HF software is the 64bit parallel version D.01 of Gaussian03. A picture of the - rather unspectacular - cluster in Room LG26 is below. A more spectacular image shows one of the silicon quantum dots simulated.


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Photovoltaics, the direct conversion of sunlight to electricity using solar cells, is recognised as one of the most promising options for a sustainable energy future. The ARC Photovoltaics Centre of Excellence commenced in mid-2003, combining previous disparate strands of work, supported under a variety of programs, into a coherent whole addressing the key challenges facing photovoltaics, as well as “spin-off” applications in microelectronics and optoelectronics.

The Centre’s photovoltaics research is divided into three interlinked strands addressing near-term, medium-term and long-term needs, respectively. The present photovoltaic market is dominated by “first-generation” product based on silicon wafers, either single-crystalline as in microelectronics (Fig. 4.1.1) or a lower-grade multicrystalline wafer. This market dominance is likely to continue for at least the next decade. First-generation production volume is growing rapidly, with the technological emphasis upon streamlining manufacturing to reduce costs while, at the same time, improving the energy conversion efficiency of the product. Also important is the reduction of the thickness of the starting silicon wafer without losing performance, to save on material use.

The Centre’s first-generation research is focussed on these key issues. Work continues upon the “buried-contact” solar cell, originally developed by Centre researchers, the first of the modern high-efficiency cell technologies to be successfully commercialised (Fig. 4.1.1). However, several other Centre wafer-based technologies are attracting commercial interest. The Centre’s “semiconductor finger” technology went into production at Suntech Power during 2006, and several licence agreements have also been recently signed based on Centre innovations in laser and ink-jet processing.

Wafers are expensive and need quite careful encapsulation, since they are brittle and also thermally mismatched to the glass coversheet, making first-generation technology inherently material-intensive. To avoid the associated cost penalties, several companies worldwide are commercialising “second-generation” thin-film cell technology based on depositing thin layers of the photoactive material onto supporting substrates or superstrates, usually sheets of glass (Fig. 4.1.2). Although materials other than silicon are of interest for these films, silicon avoids problems that can arise with these more complex compounds due to stability, manufacturability, moisture sensitivity, toxicity and resource availability issues. CSG Solar, a partner in the Centre, has commercialised an approach pioneered by Centre researchers that is unique in that it is based on the use of the same high quality silicon used for first-generation production, but deposited as a thin layer onto glass.
As well as its collaborative activities with CSG Solar, the Centre currently maintains a largely independent program addressing alternative solutions to those adopted by CSG Solar for producing high-performance “silicon-on-glass” solar cells. The main emphasis of this program is on improving the quality of the silicon films by using thin crystallographic templates (formed by aluminium induced crystallisation) and on the development of lower-cost deposition approaches (evaporation rather than PECVD).

At the present time, second-generation thin-films are entering the market in increasing quantities. Large-scale commercialisation of thin-film product will lead to a completely different manufacturing cost structure. However, costs again are expected increasingly to become dominated by material cost as production increases, for example, by the cost of the glass sheet on which the cells are deposited.

More power from a given investment in material is possible by increasing energy-conversion efficiency. This leads to the notion of a third-generation of solar cell distinguished by the fact that it is both high-efficiency and thin-film. To illustrate the cost leverage provided by efficiency, Fig. 4.1.3 shows the relative cost structures of the three generations being studied by the Centre. This figure plots efficiency against manufacturing cost, expressed in US$/square metre. First-generation technology has relatively high production cost per unit area and moderate likely efficiencies (10-20%). The dotted lines in Fig. 4.1.3 show the corresponding cost/watt, the market metric. Values as low as US$1/watt may be feasible by increasing the efficiency while reducing manufacturing cost, but this is the likely limit of the first-generation approach (present manufacturing costs for large manufacturers are as low as US$2-3/watt).
Second-generation thin-film technology has a different cost structure as evident from this figure. Production costs per unit area are a lot lower, since glass sheets are a lot less expensive than silicon wafers. However, likely energy-conversion efficiencies are lower (5-15%). Overall, this trade-off produces costs/watt estimated as about 2 to 3 times lower than those of the wafer product, in large production volumes.

The third-generation is specified as a thin-film technology, which therefore has manufacturing costs similar to second-generation, but is based on operating principles that do not constrain efficiency to the same limits as conventional cells (31% for non-concentrated sunlight for these). Unconstrained thermodynamic limits for solar conversion are much higher (74% for non-concentrated light), giving an indication of the potential for improvement. If a reasonable fraction of this potential can be realised, Fig. 4.1.3 suggests that third-generation costs could be lower than second-generation by another factor of 2 to 3.

Of the third-generation options surveyed by Centre researchers, “all-silicon” tandem cells based on bandgap-engineering using nanostructures was selected as the most promising for implementation in the Centre’s timescale (Fig. 4.1.4). This involves the engineering of a new class of mixed-phase semiconductor material based on partly-ordered silicon quantum-dots in an insulating amorphous matrix. Photon up- and down-conversion as a way of “supercharging” the performance of relatively standard cells forms a second line of research. A third is the investigation of schemes for implementing hot-carrier cells.

Figure 4.1.4: Conceptual design of an all-silicon tandem cell based on Si-SiO$_2$ (or Si-Si$_3$N$_4$ or Si-SiC) quantum dot superlattices. Two solar cells of different bandgap controlled by quantum dot size are stacked on top of a third cell made from bulk silicon.

The fourth “spin-off” Centre strand of silicon photonics draws upon elements of all three of the photovoltaic strands. The original aim was to develop silicon light-emitting-diodes (LEDs) that can be integrated into silicon integrated circuits, with their output capable of modulation at gigahertz frequencies (Fig. 4.1.5). A by-product of this work has been the development of techniques based on silicon light-emission for characterising both completed devices, particularly solar cells, as well as silicon wafers at different stages of processing. Developing this approach to its full potential will form an increasingly large part of the Centre’s photonics program.
Figure 4.1.5: One of the concepts for an integrated silicon light-emitter/modulator investigated experimentally by the Centre. This work has led to the development of new techniques for silicon device and material characterisation based on silicon light emission.
The ARC Photovoltaics Centre of Excellence is located at the Kensington campus of the University of New South Wales, about 6 km from the heart of Sydney and close to its world famous beaches including Bondi, Coogee and Maroubra (Fig. 4.2.1).

Figure 4.2.1: Centre of Excellence location in Sydney.

Organisationally, the Centre of Excellence is located within the new School of Photovoltaic and Renewable Energy Engineering (SPREE) within the Faculty of Engineering. The Centre of Excellence has a large range of laboratory facilities (Fig. 4.2.2). These include the Bulk Silicon Research Laboratories, the Device Characterisation Laboratory, the Optoelectronic Research Laboratories, the Thin-Film Cell Laboratory, the Industry Collaborative Laboratory and Inkjet Processing Laboratory. Off campus the Centre has a Thin-Film Cleanroom facility at Botany, 5km south-west of the main campus. Another important resource is the Semiconductor Nanofabrication Facility (SNF) jointly operated by the Faculty of Science and the Faculty of Engineering.

Additional equipment commonly used for solar cell work is found at the new MicroAnalytical Research Centre (MARC) and elsewhere on the University campus. Included in this category are TEM/SEM electron and focussed ion beam (FIB) microscopes, X-ray diffraction, Raman spectroscopy, AFM and surface analysis equipment. TEM, ellipsometry and high-precision I-V equipment are also regularly accessed at Sydney University.
During 2006 the development and acquisition of laboratory equipment and infrastructure continued with specific details about significant additions found under the laboratory headings which follow.

![Diagram of laboratory layout](image)

**Figure 4.2.2: Layout of laboratories and other facilities within the Electrical Engineering Building, Kensington.**

The Centre of Excellence has two computer networks. One is used for research and general administrative purposes and the other by students enrolled in the Undergraduate Degree Courses in Photovoltaics and Renewable Energy. In 2006 the Research and Administrative network grew by 20% to consist of 6 active servers, 1 backup server, 3 Intranet servers, 2 Internet web-servers and over 107 workstations. An additional 16 computers are dedicated to the computer control of laboratory and other equipment. The Centre also has a 3 server computer controlled SCADA system and PLC network for equipment control and monitoring of the research laboratories and related infrastructure.

The computer resources are used for modelling/simulations, equipment control, general administrative purposes, document control, laboratory design support, Internet access, and maintaining the Centre’s presence on the Internet.
Each postgraduate research student is allocated a dedicated personal computer in addition to access to existing shared computers.

In 2006 a dedicated terminal server was commissioned to support access by personnel at Bay St Botany to intranet resources based at Kensington. The Centre also installed a Linux (Beowulf) 64-bit cluster with an estimated computational power of 230 Gigaflops for Density-Functional-Hartree-Fock and molecular dynamical computations.

The Student Computer network comprises of two computer laboratories of total 83 m$^2$ with 6 servers, a UNSW custom CSE computer based IPQ router and 26 workstations. Students enrolled in the Undergraduate Degree Courses use these computers for computer-related coursework and Internet access. There is also an Internet capable web-server that gathers and displays data collected from solar arrays on the roof of the building. These data can be viewed using a web browser and can be made available for Internet access.

The Laboratory Development and Operations Team develops and maintains core Centre and laboratory facilities. During 2006, the team, under the leadership of Mark Silver, comprised of an additional 5 equivalent full-time and 13 casual employees, including: electrical and industrial design engineers, a computer/network manager, electronic/computer technicians, and administrative staff.

**Bulk Silicon Research Laboratories**

The Centre houses the largest and most sophisticated bulk silicon solar cell research facility in Australia, incorporating both the High Efficiency/LED and Buried Contact Cell Laboratories. Total laboratory processing space of over 500 m$^2$ is located in the Electrical Engineering Building and is serviced with filtered and conditioned air, appropriate cooling water, processing gases, de-ionized water supply, chemical fume cupboards and local exhausts. There is an additional 540 m$^2$ area immediately adjacent to the laboratories for the accommodation of staff, research students, school office and laboratory support facilities. Off site, areas totalling 200 m$^2$ are used for the storage of chemicals and equipment spare parts.

The laboratories are furnished with a range of processing and characterisation equipment including 26 diffusion furnaces, 5 vacuum evaporation deposition systems, a laser-scribing machine, rapid thermal annealer, four-point sheet-resistivity probe, quartz tube washer, silver/nickel and copper plating units, visible wavelength microscopes, 3 wafer mask aligners, spin-on diffusion system, photoresist spinner, electron beam deposition system, TiO$_2$ spray deposition, belt furnace, manual and automatic screen printers and a laboratory system control and data acquisition monitoring system.

In 2006, one of the 4 inch wafer mask aligners was replaced with a newer more reliable unit and new improved mass flow controllers for better control of gas delivery were installed on the furnaces in Room G27.
The laser scribe tool, shown in Figure 4.2.3, has a 20 watt Nd:YAG laser for infrared operation (1064 nm) and an optional frequency doubler for green operation (532 nm). The work stage is CNC controlled allowing 1 micron positional accuracy and table speeds approaching 25 cm/second across an area of 15 cm by 15 cm. The tool is used primarily for Buried Contact solar cell fabrication, cutting 35-micron wide laser grooves as deep as 100 microns into silicon wafers. It can also be used to cut other suitable materials, such as stainless steel.

Device Characterisation Laboratory

This laboratory is located on the lower ground floor of the Electrical Engineering Building. Associated with it is the Optoelectronic Research Laboratories, reception area, seminar room, offices for Centre staff interacting with the public and industry, including the Business & Technology Manager, External Relations and Design Assistance Division Manager and computer workstations for the device modelling activities of the Centre.

The Device Characterisation Laboratory houses characterisation equipment including “Dark Star”, the Centre’s station for temperature controlled illuminated and dark current-voltage measurements, the Centre’s Fourier-transform infrared spectroscopy system (FTIR), frequency dependent impedance and analyser, ellipsometer, Sinton photoconductance lifetime equipment, wafer probing station for SOI LED work, open circuit voltage versus illumination measurement system (Suns-Voc), 4 point resistivity probe, spectral response system and spectrophotometer with integrating sphere.

Optoelectronic Research Laboratories

This facility has six optical benches and several visible and near-infrared semiconductor diode lasers along with other optical and electrical instrumentation. The facility is used for photoluminescence and electroluminescence measurements in the visible and infrared spectral range up to wavelengths of 2500 nm, luminescence experiments with simultaneous two-colour illumination, quasi steady state photoluminescence lifetime measurements and Sinton lifetime testing with the conventional flash-light replaced by a high-power light emitting diode array. An area separate from the Device Characterisation Laboratory was necessary in order to meet stringent standards for laser use. It shares cryogenic cooling equipment with the Device Characterisation Laboratory.
In 2005, the world’s first photoluminescence imaging system was installed along with a silicon CCD camera (for sensitive PL measurements) and a second spectroscopic PL system. In 2006, the PL imaging system was further upgraded to make it more user friendly and available for less experienced users. Also commissioned was a new PL lifetime measurement unit. The spectroscopic PL system was upgraded with a new cooled CCD camera and setup commenced on an LBIC measurement system.

**Thin-Film Cell Laboratory**

This 40 m² laboratory is equipped with a range of equipment for thin-film deposition and patterning, including a plasma-enhanced chemical vapour deposition (PECVD) system, a sputtering system, larger area plasma etcher, a reactive ion etcher (RIE), a resistively heated vacuum evaporator and an optical microscope with digital image acquisition system. Also used by the laboratory is an electron-beam vacuum evaporator for silicon which is physically located within the Bulk Silicon Research Laboratory. This Si evaporator is also equipped with an ionizer unit and a sample heater, enabling fast-rate Si homoepitaxy at temperatures of about 500-600°C by means of ion-assisted deposition (IAD). Other equipment of use in thin-film projects is located within the Semiconductor Nanofabrication Facility.

The PECVD system, shown in Fig. 4.2.5, has a 40x20 cm² process platen and can handle large-area silicon wafers as well as smaller pieces. Two types of plasma excitation (remote microwave and direct RF) are available. The machine is used for the low-temperature deposition of thin dielectric films (silicon nitride, silicon dioxide) and of amorphous silicon. The dual-cylinder, remote microwave plasma source produces excellent-quality silicon nitride and silicon dioxide films, with precise control over the stoichiometry at temperatures up to 500°C. Amorphous and microcrystalline silicon films can also be deposited in the system.

In 2006, the RIE was upgraded with additional mass flow controllers to support the controlled mixing of gases including CF₄, SF₆, O₂, and Ar hence expanding the range of materials that can be etched, e.g., the new SF₆/O₂ mix allows for the rapid etching of silicon carbide.
Industry Collaborative Laboratory

This 120 m² laboratory houses equipment needed for many of the industry-collaborative research activities including the Buried-Contact Solar Cell group. The laboratory equipment includes a belt furnace; a state of the art laser micromachining tool; a new PECVD deposition system (located in the adjacent thin film solar cell laboratory); a TiO₂ spray deposition station; a high temperature semiconductor muffle furnace, manual screen printer and a fully automatic production scale screen printer.

Inkjet Processing Development Lab

This laboratory, new in 2005, houses the Centre’s inkjet printing development systems. The laboratory is used to develop solar processing “inks” (chemical solutions) and for printing them onto a solar wafer under computer control. The aim is to develop low cost processing techniques for creating fine structures in solar cells. It is anticipated that the inkjet printing is capable of replacing processes such as laser scribing and photolithography for forming fine patterns for contacting but at a cost of at least 10 times cheaper. In 2006 a second ink jet material deposition printing system, capable of depositing a wide range of materials onto different substrates, was added to the laboratory.

Semiconductor Nanofabrication Facility

The Centre also owns equipment within, and has access to, the Semiconductor Nanofabrication Facility (SNF) at the University. This is a joint facility shared by the Faculties of Science and Engineering and houses a microelectronics laboratory and a nanofabrication laboratory for e-beam lithography. A collaborative project continues with the SNF to e-beam pattern a photonic crystal on the surface of the Centre’s SOI LED.
structures for enhanced optical emission. The SNF provides an Australian capability for the fabrication of advanced nanoscale semiconductor devices and their integration with microelectronics. SNF research projects form an integrated effort to fabricate innovative semiconductor nanostructures using the latest techniques of electron beam patterning and scanning probe manipulation. A major applied objective of the facility is the development of a prototype silicon nuclear spin quantum computer. The capabilities of this facility will be further expanded with recently secured NCRIS funding to develop an Australian National Nanofabrication Facility.

**Thin-Film Clean Room facility in Bay Street, Botany**

During 2003 the Centre added a 120 m² cleanroom facility in Bay Street, Botany to its infrastructure, greatly improving its experimental capabilities in the area of thin-films. This cleanroom is equipped with several fume cupboards, two tube furnaces, an electron-beam vacuum evaporator, a thermal vacuum evaporator, a glass washing machine, a rapid thermal processing (RTP) machine and a 5-chamber cluster tool. The cluster tool presently features four plasma-enhanced chemical vapour deposition (PECVD) chambers and one lamp-heated vacuum annealing chamber. The PECVD chambers enable the low-temperature deposition of dielectric films (silicon oxide, silicon nitride, etc) and amorphous silicon films (either n- or p-doped or undoped). Furthermore, samples can be hydrogenated by PECVD using a hydrogen plasma at substrate temperatures of up to 480°C. During 2004, the Centre purchased a low-pressure chemical vapour deposition (LPCVD) system, an infrared NdYAG laser scriber and a box furnace for sample annealing. The LPCVD system is capable of depositing doped crystalline silicon on glass and with its additional remote plasma source is currently engaged in hydrogenation work. The NdYAG laser is used for scribing silicon films and other suitable metal and dielectric materials.

During 2006, a state of the art multi-target sputter machine was installed. This vacuum tool has four separate targets, with provision to accommodate more, able to be operated independently of each other, allowing users to cosputter a thin film from more than one target and deposit multilayers without breaking vacuum. Three power supplies are available with substrate biasing. The custom made system can handle substrates up to 150mm x 150mm. Excellent film purity is assured as the system incorporates a load-lock. Computer control can be used for most operations, including substrate heating, allowing precise multilayers to be deposited repeatedly. Also installed was an additional double sized fume cupboard with generous under-bench storage. The unit has a timer allowing it to automatically shut down after hours, saving energy and reducing external noise.
Figure 4.2.7: Bay St Clean Room Sputter Machine.

Figure 4.2.8: New Fume Cupboard at Bay St Clean Room.
FIRST GENERATION: WAFER BASED PROJECTS

4.3.1 High Efficiency Cells

University Staff
Dr. Anita Ho-Baillie (group leader)
Dr. Hamid Mehrvarz
Prof. Martin Green
Prof. Stuart Wenham
Assoc. Prof. Jianhua Zhao (to June, 2006)
Dr. Aihua Wang (to June, 2006)

Technical Staff
Jules Yang

The Centre holds the world record of 24.7% for silicon solar cell efficiency using p-type wafers. Last year it equalled the world record of 22.7% for n-type wafers using PERT solar cells. The group sees the potential for further improving the performances of these devices. In particular, the group is keen to demonstrate the performance potential of n-type Czochralski-grown (CZ) substrates over their p-type counterparts. This necessitates new ways of identifying losses in high efficiency cells to gain new insight at overcoming these loss mechanisms.

Table 4.3.1.1: Performance of n-type rear emitter PERT cells

<table>
<thead>
<tr>
<th>Material</th>
<th>Cell Area (cm²)</th>
<th>Resistivity (Ωcm)</th>
<th>Thickness (µm)</th>
<th>V_OC (mV)</th>
<th>J_SC (mA/cm²)</th>
<th>FF (%)</th>
<th>Eff (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FZ</td>
<td>22</td>
<td>1-2</td>
<td>170</td>
<td>702</td>
<td>40.1</td>
<td>80.5</td>
<td>22.7*</td>
</tr>
<tr>
<td>FZ</td>
<td>22</td>
<td>1-2</td>
<td>170</td>
<td>706</td>
<td>40.1</td>
<td>79.1</td>
<td>22.4*</td>
</tr>
<tr>
<td>FZ</td>
<td>22</td>
<td>1-2</td>
<td>400</td>
<td>696</td>
<td>39.1</td>
<td>77.4</td>
<td>21.0*</td>
</tr>
<tr>
<td>CZ</td>
<td>22</td>
<td>4.5-5.5</td>
<td>200</td>
<td>659</td>
<td>39.9</td>
<td>78.7</td>
<td>20.8*</td>
</tr>
<tr>
<td>CZ</td>
<td>22</td>
<td>4.5-5.5</td>
<td>180</td>
<td>660</td>
<td>39.3</td>
<td>79.7</td>
<td>20.7*</td>
</tr>
</tbody>
</table>

*Confirmed by Sandia National Laboratories under the standard 100mW/cm², AM1.5 global spectrum at 25°C.
*Tested at UNSW referenced to cell measured by Sandia National Laboratories

Figure 4.3.1.1: Results from PC-1D simulations showing variations of (a) J_SC, (b) V_OC, and (c) cell efficiency with substrate thickness for 1Ωcm n-type rear emitter device.
Defects introduced by in-house wafer thinning for n-type rear emitter devices

Both simulations (see Figure 4.3.1.1) and experimental devices (see Table 4.3.1.1) indicate the benefits of using thin substrates for rear emitter structures to bring the collecting junction closer to the top surface for short wavelength light and to take advantage of reduced bulk recombination.

This necessitates in-house chemical etching and mechanical polishing to be performed on the wafers prior to cell processing. This is due to the lack of supply of such thin and polished wafers in the market and the need to determine experimentally the optimum thickness for devices fabricated on different materials (CZ vs FZ) with different background doping levels.

It has been anticipated that the in-house polishing can cause damage to the wafers, but the location, extent of this damage and in particular, its effect on final cell performance have been difficult to characterise.

One of the very powerful characterisation tools developed recently within the Centre, photoluminescence (PL) imaging, has been very effective at locating damage introduced by the in house polishing. Figure 4.3.1.2 (a) shows the micro-cracks in the wafer and damage near the edge at the bottom of the wafer, introduced by inappropriate polishing conditions. This damage subsequently led to breakage (see Figure 4.3.1.2 (b)).

![Figure 4.3.1.2: Photoluminescence image of a wafer (a) with dark marks indicating damage introduced by poorly controlled mechanical and chemical polishing. Brighter regions at the bottom of the wafer are due to non-uniformity of another process. The wafer (b) later broke as it underwent subsequent processes.](image)

![Figure 4.3.1.3: Photoluminescence image of a wafer after mechanical and chemical polishing with improved conditions.](image)

Through the use of the PL imaging tool, the group has been able to improve the polishing process to ensure uniformity (see Figure 4.3.1.3) and minimise damage. By examining each polished wafer prior to cell processing, wafer breakage and effects of any damage on final cell performance can be predicted, allowing decisions to be made on whether wafers should progress to the next stage of fabrication.
Defects introduced by Diffusion Processes

It has been known that diffusion processes (boron and phosphorus but more so in the former case) can generate dislocations in the wafer reducing its effective carrier lifetime. However these crystalline defects cannot be easily observed or located unless aided by chemical etching. Such etching etches defects intersecting the surface faster than the surrounding crystal making defects deep underneath the surface difficult to observe without prolonged etching. This destructive method of delineating the defects makes the wafers unsuitable for subsequent processes causing wastage and is especially not desired for wafers that required extensive preparation (e.g., in-house thinning and polishing) prior to cell processing.

For the first time, the high efficiency group has been able to observe physically the effects of different diffusion processes on wafer quality. Figure 4.3.1.4(b) shows a wafer that has gone through 2 diffusion processes typically used to fabricate high efficiency solar cell revealing damage at the top of the wafer caused by the boron diffusion and at the bottom caused by the phosphorus diffusion. These crystalline defects (e.g. those that run along the [010],[001] directions) are particularly severe at the edge of the wafer where it makes physical contact to the quartz boat during the diffusion process. These regions follow the thermal cycle of the quartz material which is different from the rest of the wafer (especially towards the top). Together with the already high levels of stress experienced by the wafer as high concentrations of dopants are being deposited and diffused putting the wafer surface under tension while the bulk experiences compression, defects or misfit dislocations (according to earlier work reported by the Centre [Cousins et.al., IEEE Trans. Elec. Devices, Vol. 53, No. 3, March 2006]) get generated and propagate through the wafer.

Figure 4.3.1.4: Photoluminescence image of a planar oxidised wafer (a) before and (b) after diffusion processes.
Through careful control of the diffusion processes, the group has been successful at eliminating such damage, see Figure 4.3.1.5. These results are particularly useful for n-type rear emitter devices since the structure requires full area diffusions on both the front (as front surface field) and rear (as rear junction) surfaces where high carrier diffusion lengths are essential.

Figure 4.3.1.5: Photoluminescence image of a textured (in the active cell areas) and oxidised wafer after diffusion processes ready for metallisation.

The improved insight into the optimal processing conditions allowed by rapid characterisation using photoluminescence holds the promise of steady improvement in cell efficiency beyond the record values already demonstrated.
4.3.2 Buried Contact Solar Cell Group

University Staff:
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Project Scientists and Technicians:
Kate Fisher
Brett Hallam
Anahita Kapour

Research Fellows:
Dr. Malcolm Abbott (since June 06)
Dr. Allen Guo (until May 06)

Affiliated Researchers:
Dr. Robert Bardos
Dr. Tom Puzzler
Dr. Alistair Sproul

Postgraduate Students:
Malcolm Abbott (until June 06)
Jonathan Bocking
Florence Chen
Matthew Edwards
Kate Fisher
Andrew Li

Undergraduate Thesis Students:
Yong Heng (Andy) So
Hong Hua (Bruce) Wang

The Buried-Contact Solar Cell Group aims to develop new solar cell structures and novel process technologies specifically for commercially relevant silicon wafers. The group has a broad spectrum of research and development activities that address the evolving nature of commercial silicon solar cells. The Group's main activities are focused on developing high-efficiency, thin-wafer Buried Contact solar cells, developing of low-cost processing technologies and related device designs, and transferring BC and related technology to industrial and technical collaborators.

4.3.2.1 Screen Print Selective Diffusions for High Efficiency Industrial Silicon Solar Cells

Screen print diffusion pastes present an industrially applicable alternative to conventional techniques of dopant deposition. Commercially available screen print dopant pastes from Ferro and Filmtronics were assessed for their suitability in forming heavy selective diffusions for use under metal contacts in solar cells. Pastes were assessed in terms of their ease of application, their ability to form heavy diffusions with low sheet resistances, and their ability to maintain high post-diffusion wafer lifetimes. Potential for the use of dopant...
pastes in high efficiency solar cell devices was investigated using photoconductance measurements and photoluminescence images. It was found that under certain conditions, screen print dopant pastes, particularly phosphorus paste, have potential to form effective selective diffusions without significantly compromising performance in high-efficiency solar cells.

**Printing and Drying of Dopant Pastes and Paste Dynamics**

All of the pastes used had similar appearance and viscosity. A slow print stroke (around 20 mm/s) was found to minimise the occurrence of air bubbles in the printed films, and provides a film of uniform thickness. Visual inspection and microscopy of the diffused regions after oxidation revealed useful information about the paste-diffused regions (see Figure 4.3.2.1). The oxidation rate is enhanced in more heavily doped regions, resulting in a thicker oxide and an observable difference in oxide colour. Inspection under the microscope showed that some samples exhibited “mud-crack” patterns due to stresses developed in the film during drying, with lower doping apparent along the cracks of the pattern. Also, local regions of apparently lighter doping were observed, perhaps as a result of macroscopic contamination on the wafer surface or the presence of tiny air bubbles in the printed film. These lightly diffused regions are potentially problematic if, when coated with the metal contact, they lead to localised shunting or recombination leakage currents.

![Figure 4.3.2.1: Micrographs of Ferro phosphorus diffused wafers after oxidation, showing a) border between diffused and undiffused region, magnified 5 times, b) “mud-crack” pattern observed on some samples due to stress on film during drying, magnified 10 times, and c) small region of lighter doping, magnified 20 times.](image)

**Influence of Drive-In Time and Temperature on Final Sheet Resistance of Diffusion**

Figure 4.3.2.2 shows sheet resistance of diffusion of Filmtronics phosphorus paste as a function of temperature. For 90 minute drive-ins at 950°C or more, resistances of less than 10 Ω/□ were easily achievable with deviations of sheet resistance across both wafer and batch 10% or less under these conditions. A clear trend in decreasing sheet resistance with increasing drive-in temperature was observed, and uniformity of diffusion across both wafer and batch improved with increasing temperature, as expected.
Figure 4.3.2.3 shows sheet resistances for Filmtronics boron paste. Results indicate that higher temperatures and drive-in times are necessary for the diffusion of boron paste compared to those of phosphorus paste to achieve the same sheet resistance. Sheet resistances are difficult to control even at higher temperatures and drive-in times.

Minority Carrier Lifetime Following Heavy Diffusion

One key requirement of diffusion pastes for high-efficiency applications is maintaining high lifetime in the bulk regions and low recombination in the diffused regions. Float-zoned (FZ) wafers with dopant paste applied to a large area, were diffused to produce sheet resistances of about 10 Ω/□. For phosphorus paste, drive-in was carried out at 950°C for 90 minutes, and for boron paste drive-in was carried out at 1100°C for 150 minutes. The diffused layer was then removed by etching with NaOH, and the surface of the wafer was passivated with a light phosphorus diffusion and thermal oxidation.

Figure 4.3.2.4 shows photoluminescence images and photoconductance lifetime curves for wafers diffused with phosphorus screen print paste. For wafers printed with Ferro phosphorus paste driven-in in an N₂ ambient, photoconductance lifetimes were quite variable, ranging from 26 to 163 µs. Photoluminescence images of some samples indicate low bulk lifetime in the area where paste is printed. In these samples, the PL image shows a dark square where the square dopant paste print was made. The probable cause of this is contamination from the dopant paste itself. However, many of the samples exhibited high lifetime in the region where paste was printed (see Figure 4.3.2.4). In these samples, electronically dead regions were clustered outside the region where paste was printed.
Table 4.3.2.1: Photoconductance lifetime data (bulk lifetime fit and implied $V_{oc}$) for wafers in Figure 4.3.2.4.

<table>
<thead>
<tr>
<th></th>
<th>Bulk Lifetime (µs)</th>
<th>Implied $V_{oc}$ (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Ferro Phosphorus in 100% N₂</td>
<td>58</td>
<td>618</td>
</tr>
<tr>
<td>b) Ferro Phosphorus in 80% N₂, 20% O₂</td>
<td>285</td>
<td>659</td>
</tr>
<tr>
<td>c) Filmtronics Phosphorus in 80% N₂, 20% O₂</td>
<td>519</td>
<td>672</td>
</tr>
</tbody>
</table>

Lifetimes that were both higher and more consistent were achieved using a baseline gas mixture of 20% O₂ – 80% N₂ during drive-in. Bulk lifetimes of n-type wafers with Ferro phosphorus paste ranged from 150 to 330 µs with implied open-circuit voltages of up to 663 mV. It should be noted that lifetimes were still unacceptable on p-type samples, with implied voltages not exceeding 600 mV. For Filmtronics phosphorus paste, lifetimes on n-type wafers were as high as 550 µs (implied $V_{oc}$ of 673 mV). These results indicate some degradation of wafer lifetime during the printing and diffusion process, visible as dark spots in the photoluminescence images, but that at least for n-type wafers diffused in 20% O₂ – 80% N₂ gas mixture, screen print phosphorus paste meets the requirements for use in high efficiency devices.

For boron pastes, high bulk lifetimes reached only 63 µs (implied $V_{oc}$ of 621 mV), even for wafers diffused in 20% O₂ – 80% N₂ gas mixtures. More work is necessary to improve post-processing lifetimes for boron to allow its use in high-efficiency devices.

4.3.2.2 Surface Passivation of N-type Surfaces Using Hydrogenated Amorphous Silicon

High-quality surface passivation is required for making high-efficiency n-type solar cells. It involves reducing the recombination of electron-hole pairs via defects at the surface. Surface recombination is typically evaluated by the value of the effective surface recombination velocity ($S_{eff}$) where a lower value of $S_{eff}$ is better.

Previously, we have achieved very good passivation of various surfaces for n-type solar cells using PECVD silicon nitride (SiN). In the last few years, research has shown that PECVD hydrogenated amorphous silicon (a-Si:H) also has the potential to achieve good surface passivation, with advantages such as lower processing temperatures. The first part of this work investigates the ability of PECVD a-Si:H to passivate n-type silicon surfaces. The second part of this work investigates the thermal and light-soaking stability of the a-Si:H surface passivation.

Planar N-type Silicon

Implied open circuit voltages as high as 739 mV and $S_{eff}$ as low as 2.4 cm/s were achieved using various deposition parameters, showing that excellent surface passivation can be achieved on the planar 1 Ωcm FZ n-type silicon surface using PECVD a-Si:H.
Boron-Diffused Emitters

Boron-diffused emitters with sheet resistances varying from 50 and 300 Ω/cm² were formed on both sides of the 1 Ωcm FZ n-type silicon using diffusion. Various deposition parameters were used to deposit a-Si:H on both sides of the symmetrical p⁺/n/p⁺ test structure. The best deposition parameters have yielded implied open circuit voltages of ~645 mV and S_eff of ~100 cm/s across the range of sheet resistances. This is better surface passivation than that achieved by as-deposited SiN, however, the surface passivation achieved by the a-Si:H is not as good that achieved by thermal oxides. Further improvement is required before a-Si:H becomes a competitive option for the surface passivation of boron-diffused emitters.

Thermal Stability

Figure 4.3.2.5 shows the S_eff at Δn = 10¹⁵ cm⁻³ provided by the a-Si:H layers on the n-type silicon over annealing time. The different symbols represent the different deposition temperatures, while the different colours represent the different annealing temperatures.

We observe that the a-Si:H surface passivation is more stable with lower annealing temperatures. The passivation is clearly unstable at the annealing temperature of 450°C, degrading to ~270 cm/s after only 20 mins of annealing. At 350°C and 330°C, it is also unstable but degrades much more slowly to ~200 cm/s and ~70 cm/s respectively after 3 hours. At 300°C and 200°C, the a-Si:H surface passivation degrades initially and then appears to stabilise to ~23 cm/s and ~14 cm/s respectively after 3 hrs. As highlighted by the guidelines, the thermal stability of the a-Si:H surface passivation is strongly dependent on the annealing temperature. While there appears to be a small dependence on the deposition temperature, it is negligible in comparison to the dependence on the annealing temperature.

Thus any further processing after the deposition of the a-Si:H films should occur at very low temperatures (<200°C) and should only reach a maximum temperature of 300°C.

![Figure 4.3.2.5: S_eff of a-Si:H passivated 1 Ωcm, FZ, n-Si wafers deposited at 200°C, 250°C, 300°C and 400°C and annealed at 200°C, 300°C, 330°C, 350°C and 450°C. Dashed guidelines have been added to highlight the trends at the different annealing temperatures.](image1)

![Figure 4.3.2.6: Measured S_eff of a-Si:H passivated 1 Ωcm, FZ, n-Si wafers over 48 hours of light-soaking.](image2)
Light-Soaking

A difference in the $S_{eff}$ before light-soaking and after 48 hrs of light-soaking is observed. However, we observe in Figure 4.3.2.6 that the surface passivation quality of the a-Si:H films is quite stable overall. The final $S_{eff}$ after 48 hrs of light-soaking appears to be related to the initial $S_{eff}$ immediately after deposition and there is no apparent dependence on the deposition temperature. While there is some degradation, the $S_{eff}$ at $\Delta n = 10^{15}$ cm$^{-3}$ only increases by a factor of two at most after 48 hours. As the $S_{eff}$ are still ~12 cm/s after 48 hours of light-soaking, the excellent surface passivation quality of the a-Si:H films is maintained. Thus, there does not appear to be any significant degradation problems with the exposure of the a-Si:H films to light.

4.3.2.3 A Contact-less Technique to Quantify the Edge-junction Recombination in Solar Cells

Edge recombination can play a significant role in limiting silicon solar cell performance, especially for very high efficiency devices, where other sources of recombination have been minimized; and very small area devices, where the perimeter is proportionally high. For example, edge recombination has been identified as one of the main loss mechanisms at the maximum power point in SunPower’s 149 cm$^2$ pilot-line 22% silicon solar cells, with a loss of 0.5 mA/cm$^2$ attributed to edge recombination [4.3.2.1]; small-area, high-efficiency laboratory solar cells that demonstrate efficiencies of 21% or 24%, for example, are not removed from their host wafer in order to avoid the detrimental effects of edge recombination [4.3.2.2, 4.3.2.3].

There are two types of edge recombination that can affect the performance of a solar cell. Edge-bulk recombination, $J_{0eb}$, denotes recombination where the quasi-neutral regions of the device intersect the solar cell’s edge; and edge-junction recombination, $J_{0ej}$, denotes recombination where the space-charge regions intersect the solar cell’s edge, as illustrated in Figure 4.3.2.7. $J_{0eb}$ has an ideality factor (n) of approximately 1 and can have a significant effect on open-circuit voltage and light-generated current, whereas $J_{0ej}$ has an ideality factor of approximately 2 and can have a significant effect on fill factor and open-circuit voltage. The difference in the ideality factor allows the two edge-associated recombination mechanisms to be separated in the analysis presented here.

![Figure 4.3.2.7: Cross section of a partially finished solar cell used in the experiments.](image-url)
In 2006, we developed a method to quantify edge-junction recombination based on the extended analysis of quasi steady state photoconductance (QSS-PC) or quasi steady state photoluminescence (QSS-PL) lifetime data. In the extended analysis, we use a freeware student version of PSPICE9.1 to construct an equivalent circuit of a lifetime test device. PSPICE9.1 has a good graphical-user-interface that allows circuit layouts and simulations to be set up quickly and provides fast and flexible numerical solutions to complex, non-linear circuits. The equivalent circuit consists of a current source and a diode with $n=1$ is used to model an ideal solar cell. Parasitic effects are modeled by adding additional circuit elements to the main circuit at the appropriate location in the circuit. The simulated inverse effective lifetime graph is produced by converting the simulated $J_G$ versus $V$ data into $1/\tau_{\text{eff}}$ versus $\Delta n$ data.

Because both QSS-PC and QSS-PL measurements are contactless, the method presented here can be applied on partially finished cells, allowing fast and reliable quantification of edge-junction recombination caused by various isolation techniques, or allowing a comparison between various methods of passivating the edge of a solar cell. This can be relevant to industrial solar cells since they usually require edge isolation by laser or by plasma etching, and in some cases the isolated edges are not passivated, causing a reduction in cell efficiencies.

In this work, a batch of six high-lifetime, n-type, float zoned, 1 ohm.cm wafers were saw damage etched and RCA cleaned. A 135 ohm/sq oxide-passivated boron emitter was diffused on the front side of the samples, and a 100 ohm/sq oxide-passivated phosphorus high-low junction was diffused on the rear surface. A Nd:YAG laser was used to scribe a square isolation trench through the boron emitter to define the device active area and isolate it from the physical edges of the wafer. This isolation trench was etched with NaOH to remove laser damage and slag, and passivated with an oxide-passivated, 100 ohm/sq phosphorus diffusion.

Next, an additional laser-formed trench was introduced in the central region of each wafer, through the p-n junction, to deliberately introduce an artificial edge. This was followed by an etch in NaOH to remove slag and laser damage, thereby exposing the space charge region of the p-n junction to a clean, well-prepared edge, as illustrated in Figure 4.3.2.7. The length of the laser-formed trench was varied on each wafer, ranging from 0.463 cm to 2.778 cm, resulting in a total artificial edge length ranging from 0.926 cm to 5.556 cm. The depth of the trench was kept constant at approximately 30 microns. The injection level dependent carrier lifetime curves were determined by the QSS-PC and QSS-PL techniques after each processing step. We use QSS-PC to measure high injection level data because we have a very bright light source for this technique, and we use QSS-PL to measure low injection level data because it is not affected by artifacts such as trapping or the DRM effect.

The extended analysis technique was first used to model the data taken on samples before the introduction of the artificial edge ($L = 0$) in order to extract the baseline recombination parameters of the wafer and the surface diffusions ($J_{0d} = 130 \text{ fA/cm}^2$; $\tau_{\text{bulk}} = 0.3 \text{ ms}$). Some localized recombination was also observed in the baseline case; however it is only a small effect, and does not affect this experiment in a significant way. The localized recombination is modeled by an additional circuit network in parallel with the main diode. This network consists of a diode with series resistor ($J_{\text{localized}} = 70 \text{ fA/cm}$; $n = 1.0$; $R_{\text{localized}} = 1000 \text{ ohm cm}^2$). The modeled fit of the baseline case ($L = 0$) is shown in Figure 4.3.2.8.
The extended analysis was then repeated using additional recombination parameters to model $J_{0eb}$ and $J_{0ej}$ introduced by the artificial edge, while keeping all of the baseline parameters fixed. From $J_{0ej}$ (which has a unit of $A/cm^2$), the per length edge recombination ($J_{02}$) can be calculated by $J_{02} = J_{0ej} * A / L$, where $A$ is the effective device area and $L$ is the edge length. A similar calculation can be made for $J_{0eb}$.

Figure 4.3.2.8 shows the modeled fits for the various cases of edge length varying from $L = 0.926 \text{ cm}$ to $5.556 \text{ cm}$ after the NaOH etch of the artificial edge. A very good fit was achieved for all cases by varying only $J_{0ej}$ while keeping all other recombination parameters fixed ($J_{0ej} =$ variable; $n_{ej} = 2.0$). Figure 4.3.2.9 shows $J_{0ej}$ plotted against the artificial edge length, $L$. The clear linear relationship between $J_{0ej}$ and $L$, with an intercept of $J_{0ej} = 0$ at $L = 0$, indicates that the extracted values of $J_{0ej}$ correspond well to edge recombination. The ideality factor of 2 required for a good fit suggests that the extracted values of $J_{0ej}$ correspond to edge-junction recombination. The calculated value of $J_{02}$ was $1.72 \times 10^{-9} \text{ A/cm}$.

Figure 4.3.2.8: QSS-PC and QSS-PL data of samples with various artificial edge lengths and the modeling fit. The $J_{0ej}$ value is varied while the rest of the parameters were kept constant ($J_0e = 130 \text{ fA/cm}^2$; $\tau_{\text{bulk}} = 0.3 \text{ ms}$; $J_{\text{localized}} = 70 \text{ fA/cm}^2$; $R_{\text{localized}} = 1000 \text{ ohm.cm}^2$).

Figure 4.3.2.9: The relationship between extracted $J_{0ej}$ and the introduced artificial edge length. The dash line is guide for the eyes.

Figure 4.3.2.10 shows a typical modelled fits for the cases of before and after the NaOH etch was applied to remove laser damage and slag from the artificial edge. The extracted $J_{02}$ before the NaOH etch was around $1.9 \times 10^{-8} \text{ A/cm}$, which is in good agreement with the reported value of $\sim 10^{-8} \text{ A/cm}$ on finished cells in 4.3.2.3. The $J_{02}$ improved by a factor of ten after the NaOH etching. With a proper edge passivation technique, such as phosphorus diffusion and oxidation, the $J_{02}$ can be further reduced to less than $\sim 10^{-11} \text{ A/cm}$.
Figure 4.3.2.10: QSS-PC and QSS-PL data of a typical test device at various stages of the experiment: (a) no introduced artificial edge, and (b) with an introduced artificial edge before NaOH etch, and (c) after NaOH etch.

These results show that extended analysis of QSS-PC and QSS-PL is a reliable and easy method to extract the information about edge-junction recombination on partially finished devices. On the other hand, the quasi-neutral regions of the artificial edges used in this work did not introduce a significant amount of recombination and could not be extracted. Modification to the test device structure would be required (for example, by making the laser-formed artificial edges very deep) to extract further information on quasi-neutral region edge recombination.

Finally, the experiment was repeated with boron-diffused emitters of sheet resistances varying between 50 to 220 ohm/sq. No strong correlation between extracted values of per-length edge-junction saturation current and emitter sheet resistance was found.

4.3.2.4 Laser Doped Selective Emitter Solar Cells

The buried-contact group has previously reported efficiencies over 19% on textured FZ wafers using the interdigitated backside buried contact (IBBC) structure and efficiencies over 16% on planar CZ wafers using the double-sided buried contact (DSBC) structure. However, the lengthy and expensive processing involved presents a barrier to industrial manufacturing of these devices. Formation of the contact regions on the IBBC and DSBC devices takes up an estimated 50% of the total fabrication time and requires several high-temperature processing steps and a difficult groove deglazing step. Laser doping offers good potential to simplify the processing of high-efficiency silicon solar cells that incorporate selective emitter contact regions.

To improve the manufacturability of these devices laser doping has been investigated as an alternative process to form the contact regions. Pulsed lasers are used to locally melt silicon, incorporate dopant atoms in the recrystallized melt and remove a surface dielectric to define a mask for electroless plating. This process occurs at the substrate at room temperature and greatly simplifies the fabrication of IBBC and DSBC solar cells by removing two high temperature furnace diffusions, associated chemical cleaning and etching steps and removes the need for a masking oxide and deglazing process. In 2005 the laser doping process was developed and applied to planar DSBC solar cells with good initial solar cell results. The results of this investigation were presented as an oral presentation at the 2006 world conference. In 2006 the process was applied to textured surfaces and to the all back contact structure of the IBBC cell. The process was found to work on these structures, however further optimisation of the cell processing is required to improve the efficiency.
Several issues were identified as limiting the application of the technique to these cell structures. Replacing the deep grooves with flat laser doped contacts results in adhesion problems with the copper plated fingers. Figures 4.3.2.14 demonstrates how poor adhesion leads to the lifting of copper fingers and total cell failure. A further problem exists in the nickel sintering step required to improve the adhesion. This process, particularly when applied to contact pads, has been identified as the cause of a “bump” in the dark IV curves of finished cells which limits the FF of these devices.

Figure 4.3.2.11: Champion cell results for laser doped selective emitter, textured, double-sided solar cell.  
Figure 4.3.2.12: Champion cell results for laser doped selective emitter, textured, interdigitated back contact solar cell.

Several issues were identified as limiting the application of the technique to these cell structures. Replacing the deep grooves with flat laser doped contacts results in adhesion problems with the copper plated fingers. Figures 4.3.2.14 demonstrates how poor adhesion leads to the lifting of copper fingers and total cell failure. A further problem exists in the nickel sintering step required to improve the adhesion. This process, particularly when applied to contact pads, has been identified as the cause of a “bump” in the dark IV curves of finished cells which limits the FF of these devices.

Figure 4.3.2.13: Issues identified with electroless plating of laser doped contacts evident in dark IV curves of cells with “bump” that reduces fill factor.  
Figure 4.3.2.14: SEM and optical images of copper plated contacts demonstrating adhesion problems.
4.3.2.5 Laser Isolation of Shunted Regions

In a solar cell production line, shunted cells significantly reduce average efficiencies, result in modules with poor low light performance and reduce the total yield. This problem is particularly pronounced in cells fabricated on cheaper forms of silicon where material induced defects present many different sources of shunting and is therefore expected to become worse in the future given the current shortage in silicon feedstock. In many cases, the source of low shunt resistance is highly localized, one example is conductive SiC inclusions which are typically only 5-10 µm in size. Although the shunted region itself is highly localized, the lateral conductive path formed by the emitter and by metal contacts generally causes much larger areas of the solar cell to be affected.

In this work, we developed a technique to mitigate the influence of localized shunted regions by isolating them from the majority of the cell with a laser groove. In doing so we demonstrate a technique that can be used to greatly improve the performance of industrial solar cells and reduce the yield loss due to shunting.

The application of the process is shown in the figures below. In Figure 4.3.2.15, PL imaging is used to detect the location of shunted regions on the solar cell. In Figure 4.3.2.16 laser scribes are cut around these regions, disconnecting them from the majority of the device. After application of laser processing the electrical characteristics, shown in Table 4.3.2.2, are greatly improved. Further work is now being done to improve the technique through better localisation of shunted regions and more optimal laser settings.

Table 4.3.2.2: Summary of one Sun IV characteristics before and after application of the laser isolation process.

<table>
<thead>
<tr>
<th>Laser Process</th>
<th>( V_{DC} ) (mV)</th>
<th>( J_{SC} ) (mA/cm²)</th>
<th>FF (%)</th>
<th>( \eta ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>590</td>
<td>30.76</td>
<td>53.1</td>
<td>9.6</td>
</tr>
<tr>
<td>Final</td>
<td>605</td>
<td>30.00</td>
<td>72.9</td>
<td>13.3</td>
</tr>
</tbody>
</table>

Figure 4.3.2.15: PL image of a 156 cm² silicon solar cell before laser isolation of shunted regions.

Figure 4.3.2.16: PL image of a 156 cm² silicon solar cell after laser isolation of shunted regions.
4.3.2.6 References


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4.4 Second Generation: Thin-Films

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4.4.1 Summary

Thin-film polycrystalline silicon (poly-Si) on glass solar cells are developing rapidly and are expected to lead to enormous reductions of the cost of PV electricity. The presently maturest poly-Si on glass thin-film PV technology is that of CSG Solar AG where a 1.5 µm thick PECVD-deposited a-Si precursor diode is crystallised at 600°C using solid-phase crystallisation (SPC). The CSG technology achieves mini-module efficiencies of up to 9.8% and is now entering mass production in Germany, with estimated manufacturing cost of about 1.5 €/Watt [4.4.1].

Independent research in the Centre’s Thin-Film Group (or “Second-Generation Group”) is exploring a range of alternative poly-Si on glass PV technologies. One aim is to establish potentially cheaper silicon deposition methods than PECVD (~30 €/m² for 1.5 µm thick SPC poly Si films [4.4.2]) for such cells, with particular emphasis on silicon deposition by electron-beam evaporation. Another aim is to realise polySi films with better electronic quality (larger grain size, longer diffusion length, etc) compared to the existing technologies, enabling higher cell efficiency. Cell thickness is generally in the range of 1 to 5 µm. Our R&D work over the past years has led to innovative solutions for the key steps of the solar module fabrication process, including glass texturing, Si deposition, grain size improvement, light trapping, and solar cell metallisation and interconnection.

In 2006 we have continued to combine the individual process steps, enabling functional solar cells. Glass texturing is realised by a thermally activated chemical reaction between the glass and a thin, sacrificial Al film (AIT, “Aluminium-Induced Texture”). The antireflection coating is an about 70 nm thick SiN film deposited by PECVD. Silicon deposition onto the SiN film is performed by either PECVD or electron-beam evaporation. The Si film is either deposited in amorphous form and then crystallised, or it is immediately deposited as crystalline material using “ion-assisted deposition” (IAD) at 600°C. Next follows rapid thermal annealing (RTA) at about 900°C, hydrogenation at about 600°C, and then metallisation. To obtain a larger grain size, some of the solar cell structures under development receive a poly-Si seed layer. These seed layer solar cells are termed ALICE and ALICIA (seed layer made by Al-induced crystallisation) and SOPHE and SOPHIA (seed layer made by solid-phase crystallisation). The cells without a seed layer are termed PLASMA (Si deposited by PECVD) and EVA (Si deposited by e-beam evaporation). The fabrication sequences of the six solar cell structures under development in the Thin-Film Group are outlined in Fig. 4.4.1.
Figure 4.4.1: Process sequence of the six poly-Si on glass thin-film solar cells under development in the Thin-Film Group. All cells are designed for the superstrate configuration (i.e., the sunlight enters the cell through the glass).

The scientific innovation in our work lies in the use of alternative and innovative approaches for the key solar cell fabrication steps compared to approaches known in the literature (CSG, etc.). Silicon deposition is realised by PECVD (industry standard, but low deposition rate) and e-beam evaporation (high deposition rate). Due to its high deposition rate (up to several μm/min), electron-beam evaporation appears to enable an in-line Si deposition process, which would provide substantial cost savings in a factory compared to today's PECVD batch systems. Large-grained seed layers on glass are formed by aluminium-induced crystallisation (AIC) of a-Si. The relevance of our R&D work is considerable as it could lead to the world’s first poly-Si thin-film solar cells on glass deposited with an in-line silicon deposition machine.

Structural results presented in this report include AFM (atomic force microscope) images of our AIT-textured glass substrates and TEM (transmission electron microscope) images of textured EVA solar cells. Silicon deposition results reported include details on the contamination levels in electron-beam evaporated Si films. Electrical results reported include 1-Sun fill factors of over 66% for 4-cm$^2$ cells, peak IQE (internal quantum efficiency) values of over 86%, short-circuit current densities of over 17 mA/cm$^2$, and 1-Sun cell efficiencies of over 5% for 4-cm$^2$ devices.

The results obtained in 2006 confirm that good progress is being made by the Thin-Film Group towards the realisation of efficient poly-Si thin-film solar cells on glass. Each of the investigated Si formation methods (solid phase crystallisation SPC, solid phase epitaxy SPE, ion-assisted deposition IAD) has been shown to be capable of producing device-grade Si material, with voltages in the 450-520 mV range. Fill factors of over 60% are now routinely obtained, using interdigitated cell metallisation schemes. The best cells now have efficiencies of over 5% and are improving rapidly. By thoroughly optimising the Si deposition processes, the post-deposition treatments, the metallisation processes and light trapping, we are optimistic we can achieve cell efficiencies of over 10%.
The Thin-Film Group was again active in generating intellectual property, with the filing of a provisional Australian patent application on a metallisation method for thin-film modules, a provisional Australian patent application on a method for making thin-film diode structures, and a PCT patent application for a metallisation method for thin-film semiconductor structures. Furthermore, the Group has published one book chapter, seven journal papers and seven conference papers in 2006.

4.4.2 Details of Solar Cell Fabrication Processes

Six different solar cells are being investigated by us: EVA, PLASMA, ALICE, SOPHE, ALICIA and SOPHIA. Figure 4.4.1 shows the process sequence of the investigated thin-film solar cells. The substrates are 3 mm thick planar borosilicate glass sheets obtained from Schott AG, Germany (Borofloat 33). Both planar and textured glass substrates are investigated. The texture on the Si-facing surface of the glass aims to reduce reflection losses and improve light trapping in the Si film. The texture is realised with the UNSW-developed AIT method (aluminium-induced texture [4.4.3]) and consists of irregular, sub-micron sized dimples. This texture is realised by depositing a thin (~100 nm) Al film onto the glass, followed by thermal annealing at about 600°C for 30 min and subsequent wet-chemical etching of the Al and the reaction products. The next step is the deposition of an about 70 nm thick SiN film by PECVD at about 400°C glass temperature. This SiN film acts both as an antireflection coating and a barrier layer for contaminants from the glass. For EVA and PLASMA cells, an amorphous silicon n^+pp^+ precursor diode is then deposited by either e-beam vacuum evaporation (EVA) or PECVD (PLASMA), followed by solid-phase crystallisation (SPC) during 24 hours at 600°C in a nitrogen atmosphere.

The process for the four other cells involves the fabrication of a thin (~100 nm) poly-Si seed layer on the SiN. This seed layer is either formed by AIC of an intrinsic a-Si layer at about 500°C (AIC seed) or by SPC of a heavily doped a-Si layer at about 600°C (SPC seed). The heavily doped a-Si layer (n^+ or p^+) is formed by either e beam evaporation or PECVD, whereas the intrinsic a-Si layer is formed by dc magnetron sputtering or PECVD. Details on the AIC and SPC seed layers can be found elsewhere [4.4.4, 4.4.5]. In the case of ALICE and SOPHE cells, the next step is the deposition of a pp^+ or nn^+ a-Si structure onto the heavily doped seed layer, followed by crystallisation of the a-Si structure by SPE, post-deposition treatment of the samples (RTA, hydrogenation), and metallisation. In contrast, in the case of ALICIA and SOPHIA cells, poly-Si double layers (nn^+, pn^+, np^+ or pp^+) are epitaxially grown on the heavily doped seed layer by ion-assisted deposition (IAD) at about 600°C, followed by post-deposition treatments (RTA, hydrogenation) and metallisation. The RTA process uses a lamp-based system that rapidly heats the samples to the desired temperature (900-1000°C), maintains the peak temperature for a certain time, and then lowers the sample temperature in a controlled manner to values below 200°C. The entire RTA process, from loading to unloading, takes about 20 minutes. Hydrogenation is performed at a maximum sample temperature in the range of 500 to 620°C, using a remote plasma tool.

The main advantage of EVA and PLASMA cells is their simplicity, since no seed layer is involved in the fabrication process. However, this simplicity comes at a price as the grain size of the resulting poly-Si films is quite small (typically 1-2 µm) and hence their electronic properties (effective carrier lifetime, lateral conductivity, etc) are significantly affected by grain boundary effects. The seed layer solar cells offer the advantage that the properties of the seed layer and the remainder of the solar cell can be independently optimised. This allows the realisation of larger-grained and/or more heavily doped materials. For example, seed layers formed by the AIC process have a grain size of the order of 20 µm.
4.4.3 Glass Texturing

We are aiming at producing poly-Si thin-film solar cells on a glass superstrate, with evaporation as a possible silicon deposition method. Thus, a glass texturing method that produces a surface morphology that is compatible with “line-of-sight” silicon deposition is an advantage. Use of a textured transparent conducting oxide (TCO) is ruled out because of the high temperatures involved in our cell fabrication process. We are using Schott Borofloat 33 glass because its thermal expansion matches that of silicon quite well. Recently we have developed a glass texturing process called Aluminium-Induced Texture (AIT), in which an Al film evaporated onto planar glass is annealed in an inert atmosphere [4.4.3]. High temperature transfers oxygen in a redox reaction from the glass, largely as SiO$_2$, to the aluminium. A surface texture is imparted to the glass according to the nucleation conditions provided during this anneal. Finally, a wet-chemical etch consisting of hydrofluoric acid and nitric acid is used to remove the Al and the reaction products. Our previous work had shown that considerable freedom is available for varying conditions used in the AIT process, and that these conditions affect the morphology of the resulting texture. Prime determinants are the Al layer thickness, the anneal temperature profile, as well as the HF-nitric acid ratio and the immersion time.

During 2006, we have used atomic force microscopy (AFM) to analyse the morphology of AIT-textured glass as a function of the Al thickness. Typical results are shown in Fig. 4.4.2. As can be seen, the size of the texture features increases significantly with increasing Al thickness. Importantly for our work, the AIT method is capable of producing average feature sizes of the order of 1 $\mu$m, as required for poly-Si thin-film solar cells. The measured surface roughnesses of the textured glass sheets are shown in Fig. 4.4.3. As can be seen, intermediate Al thicknesses of about 200 nm produce the highest surface roughness.

The glass texture provided by the AIT method is well compatible with the solid-phase crystallisation (SPC) method of amorphous Si, for a-Si deposition by either PECVD or e-beam evaporation. As an example, Fig. 4.4.4 shows an AFM image of a 1.5 $\mu$m thick poly-Si film made by SPC from evaporated a-Si. A rough Si surface with rounded sub-micron features becomes evident, which is well suited for scattering light and hence should provide good light trapping in the poly-Si film.

![Figure 4.4.2: AFM images of glass surfaces textured with the AIT method. Each image covers an area of 10 $\mu$m x 10 $\mu$m. The z axis (“height”) is magnified by a factor of 4 compared to the x and y axes. The Al thicknesses used in the AIT process were 40, 145 and 225 nm, respectively.](image)
The optical absorbance of poly-Si films made on SiN-coated AIT glass has been measured using a spectrophotometer with an integrating sphere. As an example, Fig. 4.4.5 shows the results obtained from two 1.5 µm thick EVA poly-Si films. The Al thickness in the AIT process was 40 nm and 145 nm, respectively. Clearly, the glass surface textured with the thicker Al film provides much better optical absorption in the poly-Si film. Considering that c-Si can convert photons with wavelengths of up to 1100 nm, the absorbance curves of Fig. 4.4.5 correspond to maximum possible short-circuit currents of 25.0 and 19.0 mA/cm², respectively, under the standard solar spectrum (AM1.5G). From these currents it follows that the AIT texture can boost the short-circuit current of poly-Si thin-film solar cells on glass by more than 30%.
4.4.4 Cell Metallisation

In 2006, we have further refined and optimised our interdigitated solar cell metallisation method. A schematic representation of the metallisation scheme is shown in Fig. 4.4.6. Evaporated aluminium is used for contacting the emitter and the BSF layers. The method involves formation of a comb-like air-side electrode, followed by removal of the silicon in the openings of the air-side electrode by means of plasma etching. Using PLASMA solar cell material, a large number of 4-cm² solar cells with fill factors FF of over 60% have been realised in 2006 using this method. The best FF value achieved so far is 73%.

4.4.5 EVA Solar Cells

EVA solar cells are made by “solid phase crystallisation of EVAporated silicon”. The deposition of the amorphous silicon occurs at about 200°C in a non-ultra-high vacuum environment (10⁻⁷ - 10⁻⁸ Torr) onto silicon nitride (SiN) coated Borofloat33 glass. To realise the desired dopant profiles, phosphorus and boron are added in-situ (i.e., during the deposition) via high-temperature effusion cells. After the silicon evaporation, the amorphous structure is crystallised during 24 hours at about 600°C in a nitrogen-purged tube furnace. A schematic of a crystallised EVA cell is shown in Fig. 4.4.6b. A rapid thermal anneal (RTA) process at about 900°C for several minutes activates dopants and anneals point defects, and a hydrogen passivation (at about 600°C for about 15 minutes) decreases the defect density drastically both inside the grains and at grain boundaries, thereby significantly enhancing the electrical performance of the solar cell.
Structural properties

Transmission electron microscope (TEM) images reveal that EVA solar cells are of good structural quality and that their grain size is of the order of 1 µm. Figure 4.4.7(a) is a TEM picture of one of our first EVA cells – it was made on planar glass and the p-type doping was realised with gallium. The grain growth appears to have started at random locations within the device, as can be seen from the grain boundaries that cross the cell horizontally as well as vertically. In contrast to this, Fig. 4.4.7(b) shows a TEM image of a recent EVA cell which was made on AIT-textured glass and which uses boron for p-type doping. The textured EVA cell shows preferential grain boundary orientation from the front to the back of the Si film, indicating preferential nucleation from either the bottom or the top heavily doped surface layer. This grain structure is preferred since charge carriers on their way to the p-n junction do not have to cross grain boundaries where the rate of recombination is higher than within the grains.

![TEM images of EVA solar cells](image)

Figure 4.4.7: TEM images of EVA solar cells made on (a) planar glass and (b) on AIT-textured glass. The images were taken by Yidan Huang, the Centre's TEM expert.

Contaminants

The total thickness of our present EVA solar cells is in the range of 1.5 to 2 µm. The thickness of the p-doped base layer is mainly limited by the achievable diffusion length $L_n$ of the minority-carrier electrons in this layer, which is presently about 1 µm for EVA devices. Carriers that are created in a region significantly further away from the p-n junction than the distance $L_n$ cannot be collected effectively and thereby do not contribute significantly to the device performance. This is why we are trying to enhance the electronic quality of our EVA poly-Si films via improvements in the silicon evaporation process as well as the crystallization process of the deposited films.

The amorphous silicon deposition itself plays an important role with respect to the crystal quality of the finished device. Since the Si source material is of very high purity, the main contaminants within the evaporated Si film stem from the residual background gasses in the vacuum chamber. This in turn means that the chamber pressure during the Si evaporation process and the Si deposition rate are crucial parameters for the contamination levels, and hence the electronic quality, of the finished devices. Figure 4.4.8 displays the results of SIMS (secondary ion mass spectroscopy) measurements on a 1350 nm thick intrinsic silicon film evaporated at a rather low rate of 150 nm/min, using a glass temperature of
about 200°C. Graph (a) shows the results from the as-deposited (i.e., amorphous) sample, while graph (b) shows those from the crystallised sample. The contaminants nitrogen and carbon are present at levels (~$10^{17}$ cm$^{-3}$ and ~$10^{18}$ cm$^{-3}$, respectively) that seem compatible with thin-film solar cell fabrication, despite the relatively low Si deposition rate. Oxygen is present with a density of about $5\times10^{18}$ cm$^{-3}$, which seems a bit high for solar cell work. Since the oxygen density in the Si film scales approximately reciprocally with the Si deposition rate, it is recommended to deposit the EVA cell absorber layer with a rate of at least 300 nm/min, reducing the oxygen density to an acceptable level. A comparison of the two graphs in Fig. 4.4.8 shows that no increase of the contamination levels occurs during the solid-phase crystallisation step, i.e. the furnace anneal does not introduce additional quantities of the profiled contaminants into the Si film. It can also be noticed that significantly more hydrogen is present in the as-deposited film as compared to its crystalline counterpart.

Figure 4.4.8: SIMS measurements on an evaporated intrinsic silicon film (a) before and (b) after solid-phase crystallization. The measurements were done by Bob Reedy from the National Renewable Energy Laboratory (NREL) in USA, as part of an ongoing SPC study with Paul Stradins from NREL.

Metallisation

While the electronic quality of EVA poly-Si films seems sufficient for PV applications (we regularly obtain voltages in the 450 to 500 mV range), the realisation of non-shunted metallised cells has proven more difficult than expected. The reason is small holes ("pinholes") in the EVA films that seem to be an inherent feature of poly-Si films made by SPC of evaporated Si. Figure 4.4.9(a) shows an optical microscope image of a pinhole in an EVA film. The pinholes are typically 5-20 µm wide and irregularly shaped, with a density of about 0.1-1 per mm$^2$. If a blanket metal film is deposited onto an EVA cell, the metal deposited into the pinholes will create a low-resistance path between the two heavily doped layers (emitter, BSF) of the diode, shunting the solar cell.

Figure 4.4.9: (a) Optical microscope image (transmission mode) of a pinhole in an EVA poly-Si film on glass. The pinhole is about 9 µm wide. (b) Optical microscope image (transmission mode) of the four different point-contact patterns used to contact the rear surface of EVA solar cells. Each bright dot has a diameter of about 30 µm.
One way to overcome this problem is to add a process step that locally deposits a nonconductive material (such as an oxide) into the pinholes prior to metal deposition ("pinhole filling"). Another method is to replace the full-area metal contact by a point-contact scheme through an insulator with small local openings. Clearly, by limiting the metallised area to a small percentage of the cell’s rear surface, the risk of hitting a pinhole with the metal film is greatly reduced. Point contacts are a feasible option for EVA solar cells because of the good sheet resistances of the heavily doped layers (emitter ~150 Ω/□; BSF ~1,000 Ω/□).

In 2006, point-contact experiments were conducted on EVA cells using the photomask shown in Fig. 4.4.9(b). Sputter-deposited silicon dioxide was used as the insulating film. The openings have a diameter of about 30 µm and were realised by photolithography and wet-chemical etching. Table 4.4.1 summarises the electrical results (open-circuit voltage, shunt resistance, pseudo fill factor) obtained on EVA cells before and after metallisation of the rear surfaces with four different point-contact patterns. These results were obtained with the Suns-Voc method. As can be seen from the Table, a fractional coverage of 3% or less does not significantly reduce the electrical parameters of the cells, whereas the reduction is severe for fractions of 15% or more. A rear-surface metallisation fraction of 3% is well compatible with 1-Sun solar cell work, and research is in progress to implement this point-contact pattern into our standard metallisation scheme.

Table 4.4.1: Average values (of 3 cells, respectively) of V_{oc}, R_{sh} and pFF of EVA cells with a point-contacted rear electrode and four different dot densities. Also shown (second row) are the results obtained on the unmetallised EVA material used in this experiment.

<table>
<thead>
<tr>
<th>fractional coverage (%)</th>
<th>avg. V_{oc} (mV)</th>
<th>R_{sh}(W/cm²)</th>
<th>avg. pFF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>before metallisation</td>
<td>459</td>
<td>1180</td>
<td>70.0</td>
</tr>
<tr>
<td>0.5%</td>
<td>460</td>
<td>1401</td>
<td>70.1</td>
</tr>
<tr>
<td>3%</td>
<td>454</td>
<td>1404</td>
<td>70.2</td>
</tr>
<tr>
<td>15%</td>
<td>447</td>
<td>902</td>
<td>62.2</td>
</tr>
<tr>
<td>~99%</td>
<td>352</td>
<td>376</td>
<td>44.8</td>
</tr>
</tbody>
</table>

4.4.6 PLASMA Solar Cells

Due to the low absorption of near-infrared light in c-Si, an effective light trapping scheme is essential for thin-film poly-Si solar cells (i.e. Si thickness of < 10 µm). One effective way to obtain light trapping is to texture the substrate. The most efficient poly-Si thin-film solar cells made as yet at low temperature on foreign substrates were all deposited on textured substrates and were made by solid phase crystallization (SPC) at about 600°C of hydrogenated amorphous silicon (a-Si:H). Energy conversion efficiencies in the range 9-10% on a textured metal substrate (9.2%) [4.4.6] or a textured glass superstrate (9.8%) [4.4.1] are reported in the literature.

In 2006, we fabricated PLASMA solar cells to investigate the potential of our AIT (aluminium-induced texturisation) glass texturing method for poly-Si thin-film solar cells on glass. The poly-Si material was made by solid phase crystallisation (SPC) of PECVD-deposited a-Si:H.
Experimental details

A conventional 13.56-MHz parallel-plate PECVD system was used for depositing a SiN layer (used as a diffusion barrier and antireflection coating) and doped a-Si:H layers onto 15x15 cm² glass substrates from Schott AG (Borofloat33, 3.3 mm thick). Gas mixtures of pure silane with 0.5% phosphine in silane, 100 ppm diborane in hydrogen, and 0.5% trimethylboron in hydrogen were used for the deposition of n⁺, p and p⁺ doped a-Si:H films, respectively. The total silane gas flow was kept fixed at 40 sccm, the total pressure was about 800 mTorr, the substrate temperature about 400°C, and the RF power about 25 mW/cm². The SPC anneals were performed ex-situ in a conventional nitrogen-purged atmospheric pressure tube furnace. The SPC anneals were performed at about 600°C for 19 hours, followed by a RTA process at about 900°C for 5 min and a high-temperature hydrogenation treatment. The hydrogenation was performed in a cold-wall vacuum system featuring an inductively-coupled remote plasma source (Advanced Energy), using a glass temperature of 610-625°C during 15-30 min, a plasma power of 3200-3500 W, a hydrogen gas flow of 200 sccm, and an argon gas flow of 60 sccm. The samples were then metallised with our interdigitated metallisation process. Each glass piece has an area of 5x5 cm² and features four solar cells with dimension 1x4 cm². It is noted that no diffusive back reflector is currently incorporated in our metallisation process; instead, the entire rear surface of the Si film is directly in contact with the aluminium metal.

Results

Currents of over 17 mA/cm² and efficiencies of over 5% have been obtained for 3 micron thick PLASMA solar cells on AIT-textured glass, as shown in Fig. 4.4.10. These results confirm that the AIT glass texturing method has great potential for efficient poly-Si solar cells on glass. The internal quantum efficiency of PLASMA cells now has peak values of over 86% (see Fig. 4.4.11), which is an excellent result for poly-Si thin-film cells on glass. EQE and I-V measurements show that the AIT texture increases the Jsc by about 17% and boosts the EQE response at 800 nm by about 35% compared to a planar sample. While significant, these improvements are substantially lower than what was expected from the absorbance measurements on metal-free samples. Simulations with PC1D and the analysis of absorbance measurements both indicate that the aluminium back reflector performs poorly in terms of light trapping.

Figure 4.4.10: One-Sun current-voltage and power-voltage curve measured at UNSW on a 4cm² textured p type PLASMA cell (100 mW/cm², 25°C cell temperature, approximated AM1.5G spectrum). The cell is 3.2 µm thick and has the following parameters: Jsc = 17.3 mA/cm², Voc = 458 mV, FF = 66.5%, Eff = 5.3%.

Figure 4.4.11: Measured EQE and IQE of a 3.2 µm thick planar PLASMA sample (glass/ SiN/n⁺pp⁺). The peak IQE is 86.7%. Based on the EQE curve, a short-circuit current of 14.9 mA/cm² is expected under 1-Sun illumination (AM1.5G).
4.4.7 ALICE Solar Cells

a) Hydrogen-induced emitter neutralisation of ALICE

The best ALICE cells reported so far are based on PECVD-deposited a-Si:H and have a low level of parasitic $n=2$ diode recombination and a 1-Sun open-circuit voltage ($V_{oc}$) of up to about 420 mV. The hydrogenation of these solar cells was performed at a temperature of about 480°C for 75 min in a conventional 13.56-MHz parallel-plate PECVD machine, using a rf power of 70 W (0.3 W/cm$^2$). Interestingly, solar cells of the structure glass/SiN/n$^+$p$^+$ made by the SPC method (PLASMA cells) and utilising similar PECVD a-Si:H deposition parameters, crystallisation anneal, RTA and hydrogenation parameters as the ALICE solar cells, achieved a significantly higher $V_{oc}$ of about 460 mV. This result was surprising, given the fact that characterisation of the films with Raman and UV reflectance measurements showed that the crystal quality of the ALICE diodes is clearly superior to that of the PLASMA diodes.

During 2006, a detailed investigation was performed into the reasons why n-type PECVD ALICE solar cells, despite their better structural material quality, exhibit lower voltages than p-type PLASMA companion cells. Since it is generally believed that a hotter hydrogenation process improves the electronic quality of poly-Si thin-film materials, the hydrogenation in this study was performed at a relatively high temperature of 610°C. Surprisingly, the voltages of n-type PECVD ALICE cells completely collapsed as a result of this hot hydrogenation process.

In an attempt to improve the Suns-$V_{oc}$ curve of a hydrogenated ALICE sample, it was subjected to successive 30-minute heat treatments at increasingly hotter temperature (275°C, 310°C, then 350°C). As can be seen in Fig. 4.4.12, these bakes significantly improved the Suns-$V_{oc}$ curve, resulting in a 1-Sun $V_{oc}$ of close to 400 mV after the 350°C bake. It is noted that these Suns-$V_{oc}$ curves were all measured using the original corner etch as the p-type contact pad. Interestingly, when a new corner etch process was performed on the 350°C baked sample and this corner-etched region was used as the p-type contact pad, the measured Suns-$V_{oc}$ curve (see curve labelled “350°C – new corner etch” in Fig. 4.4.12) showed a similarly poor behaviour as that measured on the unbaked sample.

Figure 4.4.12: Suns-$V_{oc}$ curves measured on an ALICE sample after hydrogenation (no bake) and after successive 30-minute bakes at 275°C, 310°C and then 350°C, using the original corner etch as the p-type contact pad. Also shown is the Suns-$V_{oc}$ curve of the 350°C baked sample that was measured after the formation of a new corner etch and using the new corner etch as the p-type contact pad. Only the two curves on the right can be fitted with the 2-diode model using fixed ideality factors of 1 and 2 (the fits are not shown for the sake of clarity).
To further investigate this effect, sheet resistance profiling on a hydrogenated PLASMA sample (SPC-H) and three hydrogenated ALICE samples (SPE-H) was performed. The results are shown in Fig. 4.4.13, whereby the x axis shows the remaining thickness of the devices after each plasma etching step. The PLASMA cell displays the expected sheet resistance profile of a poly-Si p-n diode with an intermediate sheet resistance (~1900 $\Omega/\square$) at the original surface due to the BSF (which was confirmed by hot-probe measurements to be p-type), a gradual increase in the absorber region, a pronounced peak in the p-n junction space charge region, and a declining sheet resistance due to the exposure of the emitter. Hot-probe measurements conducted during the sheet resistance profiling experiment confirmed that the emitter of the PLASMA cell is n-type. By combining the sheet resistance and hot-probe measurements, it follows that the n-type emitter of this particular PLASMA cell has a sheet resistance of about 500 $\Omega/\square$ and a thickness of about 300 nm.

In contrast to the PLASMA cell, the investigated ALICE samples all have a sheet resistance profile that is untypical for a p-n diode. As can be seen from Fig. 4.4.13, the sheet resistance is low at the exposed surface due to the BSF (which had an n-type polarity), but the peak in the p-n junction space charge region is very weak or even completely missing. Furthermore, the sheet resistance does not decrease when the AIC poly-Si emitter becomes increasingly exposed but increases to extremely high values of well over 20,000 $\Omega/\square$. Hot-probe measurements revealed that the polarity of the ALICE samples changes from n-type to p-type in the thickness range 250-270 nm in Fig. 4.4.13.

Figure 4.4.13: Sheet resistance profiling of a PLASMA cell (SPC-H) and three ALICE cells (SPE-H) after hydrogenation. The horizontal axis displays the remaining thickness of the devices after each plasma etching step.

Upon completion of the sheet resistance profiling experiments, the thinned samples were subjected to a 1-hour bake at 350°C to determine how this additional treatment changes the sheet resistance (or its reciprocal value, the sheet conductance). Also included in this bake were two thinned samples which only had an RTA as a post-crystallisation treatment (one PLASMA and one ALICE sample). It is noted that all thinned ALICE samples had a thickness that was less than the original AIC poly-Si seed layer thickness and hence the AIC poly-Si surface of the ALICE samples was exposed to the lab oven’s atmosphere during the 1-hour bake at 350°C. For both PLASMA samples, no statistically significant change in sheet conductance occurred. The same conclusion applies to the ALICE sample that did not receive a hydrogenation. In contrast to this, a huge conductance change of over 300% occurred for the thinned hydrogenated ALICE diodes.
It is well known in the literature that p-type doping in c-Si is prone to become neutralised when exposed to atomic hydrogen. It is also known that the neutralisation effect of shallow acceptors in c-Si can be reversed by thermal annealing. One hypothesis that could explain the anomalous Suns-Voc curves and sheet resistance data of our hydrogenated ALICE samples is that the buried p-type AIC poly-Si seed layer absorbs such a large amount of atomic hydrogen during the hot hydrogenation process that it becomes essentially neutralised. If this hypothesis is correct, hydrogenated ALICE samples will have a very highly resistive (i.e., very lowly doped) p-type AIC poly-Si layer upon hydrogenation. As discussed above (see Fig. 4.4.13), our experimental PECVD ALICE samples exactly show this behaviour. Furthermore, the reactivation energy of hydrogen-neutralised Al acceptors in c-Si is about 1.9 eV, indicating that a thermal anneal at temperatures above 300°C will reactivate a significant fraction of the neutralized Al acceptors and thus will strongly increase the AIC seed layer’s conductance. This theoretically expected behaviour is also fully confirmed by our experiments which showed that the conductance of the AIC poly-Si seed layer increases by more than 300% due to a 1-hour bake at 350°C. Thus, in combination, the sheet resistance results and the conductance data provide very strong support for the hypothesis that the buried AIC poly-Si seed layer in PECVD ALICE solar cells is largely neutralised following our hot and intense remote-plasma hydrogenation process.

Since the Suns-Voc curves of our unbaked hydrogenated ALICE cells cannot be fitted with the 2-diode model with fixed ideality factors, we believe that the neutralised, highly resistive p-type AIC poly-Si layer forms an opposing Schottky diode with the metal probe of the Suns-Voc tester, causing abnormally low 1-Sun open-circuit voltages (< 100 mV) and super-steep Suns-Voc curves. The fact that baking the diodes at temperatures above 300°C improves the Suns-Voc curves so much that they can be fitted with the 2-diode model using fixed ideality factors of 1 and 2 is consistent with the experimental finding of a significant re-activation of Al acceptors during 350°C baking of exposed AIC seed layers. It is noted that the re-activation of the AIC seed layer during baking requires that the AIC seed layer is exposed to atmosphere (i.e., is not buried under a silicon film), as can be seen from the poor Suns-Voc curve labelled “350°C – new corner etch” in Fig. 4.4.12. Re-activation of the AIC seed layer by baking does therefore not seem to be an option for PECVD ALICE solar cells, as this would almost certainly lead to hydrogen concentrations in the absorber and BSF regions of the solar cell that are too low for efficient passivation of defects.

A neutralised emitter has many severe consequences for the electrical performance of a p-n junction solar cell. First of all, the built-in potential of the junction is reduced, lowering the Voc capability of the cell (note that the built-in potential of a p-n junction diode is determined by the active doping concentrations on both sides of the junction). Furthermore, the emitter’s low active doping concentration (i.e., high sheet resistance) makes it impossible to form low-resistance ohmic contacts. In combination with the emitter’s high sheet resistance (well over 20,000 Ω/□ in our case), this contact resistance problem causes poor fill factors of the cell’s current-voltage curves. Schottky barrier formation at the emitter contacts further distorts the current-voltage curves. It is thus plausible that the paradox of better crystal quality but lower Voc for n-type ALICE diodes (glass/SiN/p+/nn+) compared to p-type PLASMA diodes (glass/SiN/n+/pp+) is due to the neutralisation of the p-type emitter of the ALICE diode during hydrogenation.
One strategy to overcome the problem of a neutralised buried p-type AIC poly-Si seed layer is to add an extra boron or gallium-doped p+ layer into the device structure, thereby creating a p+ emitter that is more robust against neutralisation by hydrogen. This approach is being used in our ALICIA poly-Si solar cells where the solar cell is epitaxially grown on an AIC-seeded glass substrate by ion-assisted deposition at about 600°C and where open-circuit voltages of up to 441 mV have been realised so far. Another strategy is to use an n-type AIC poly-Si layer, as described in the following section.

b) ALICE cells with n-type AIC emitter and p-type base

Given the inertness of n+ emitters against neutralisation by hydrogen, several amorphous silicon precursor diodes of the structure n+pp+ were deposited by PECVD onto cleaned, H-terminated AIC poly-seed layers on SiN-coated glass sheets, followed by crystallisation via SPE and the two standard post-crystallisation treatments (RTA, hydrogenation). These p-type ALICE samples with the intended structure of glass/SiN/n+pp+ were then analysed by Suns-Voc measurements and sheet resistance profiling. As can be seen from the sheet resistance profile in Fig. 4.4.14, these solar cells exhibit the typical behaviour expected for a p-n junction diode. The heavily doped region near the glass has a very low sheet resistance of 160 Ω/□, and hot-probe measurements confirmed that it is of n-type polarity. This shows that the polarity of the AIC poly-Si seed layer has been successfully converted from p to n-type during the solar cell fabrication process. Figure 4.4.15 shows the measured Suns-Voc curve of one of the fabricated p-type ALICE samples, together with the fitted 2-diode model curve and the associated fit components. As can be seen, the 1-Sun Voc of this planar solar cell is 476 mV and is dominated by n=1 recombination.

Figure 4.4.14: Measured sheet resistance profile of a hydrogenated PECVD ALICE diode with p-type base and n-type glass-side emitter.

The best Voc achieved in the course of this study was 480 mV, which is the highest Voc reported as yet for a solar cell made on low-temperature glass featuring an AIC poly-Si seed layer. It is emphasised that the Voc of these p-type ALICE solar cells is more than 20 mV higher than that of p-type companion cells (PLASMA) that were made with the SPC method using similar experimental conditions. Given the fact that the number of p-type ALICE cells made so far is small in comparison to the number of fabricated p-type PLASMA and n-type ALICE cells, we expect that the voltage difference between p-type ALICE and PLASMA cells will increase in the future.

Figure 4.4.15: Measured Suns-Voc curve of a planar hydrogenated PECVD ALICE cell with glass-side junction and p-type base. The solid line is a fit to the measured data using a 2-diode model with fixed ideality factors of 1.0 a 2.0 and a shunt resistance. The dashed lines are the three components of the solid-line fit (n=1 diode, n=2 diode, shunt resistance).
4.4.8 ALICIA Solar Cells

ALICIA stands for “ALuminium-Induced Crystallisation Ion-Assisted deposition” [4.4.7]. The idea behind the patented ALICIA solar cell technology is to directly (i.e., epitaxially) grow the crystalline absorber layer on a hydrogen-terminated seed layer made by Aluminium-Induced Crystallisation (AIC) on glass. The AIC precursor structure is glass / SiN (∼75 nm) / Al (∼200 nm, evaporated) / a Si (∼300 nm, sputtered). This structure is annealed for 12 hours at about 450°C in a tube furnace at atmospheric pressure and then the Al and the excess Si are removed. The resulting average grain size is about 10 to 20 µm. For low-temperature Si epitaxy we use IAD (Ion-Assisted Deposition) because this method is capable of high-rate Si growth at low (i.e., borosilicate glass compatible) temperatures of about 600°C. In recent years we have developed an IAD process that is capable of achieving good-quality epitaxial Si in a non UHV environment [4.4.8]. This makes IAD Si epitaxy potentially suitable for the PV industry. Figure 4.4.16 schematically shows a Mesa-type ALICIA solar cell. The two IAD-grown poly-Si layers have a combined thickness of about 2 µm and are deposited at a rate of several hundred nanometres per minute.

Figure 4.4.16: Schematic of a Mesa-type ALICIA solar cell realised by shadow-mask epitaxy (not to scale).

For the results reported below, planar Borofloat33 glass panes (5x5 cm², 3 mm thick) from Schott AG, Germany were used as substrates. The absorber and back surface field (BSF) layers were grown using ion-assisted deposition of e-beam evaporated Si and in-situ doping from effusion cells of gallium (Ga) and phosphorus (P), giving the following structure: Glass (planar) / SiN (75 nm) / p⁺ (AIC, 200 nm @ 1x10¹⁹ cm⁻³ Al) / p⁻ (IAD, 50 nm @ 1x10¹⁷ cm⁻³ Ga) / n⁻ (IAD, 1000 nm @ 4x10¹⁸ cm⁻³ P) / n⁺ (IAD, 100 nm, N_surface ~ 1x10¹⁹ cm⁻³ N). The samples in this study are nominally identical, with three mesa structures (two 1x15 mm² strips and one 15x15 mm² square) per glass substrate that all receive the same processing. During the growth of the absorber and BSF layers a mask was used to cover parts of the seed layer, forming a mesa structure via shadow-mask epitaxy. Al can easily be deposited onto the exposed n⁺ and p⁺ type layers (both contacts done in one or two depositions using a mask). A point to remember is that these mesa solar cells are planar and hence, despite the Al back reflector, feature poor light trapping.

A post-deposition treatment (rapid thermal anneal, then hydrogenation) is crucial for ALICIA solar cells. Figure 4.4.17 shows the effect on V_{OC}, V₁ and V₂ from the RTA plateau time at 1000°C before and after hydrogenation. RTA times at 1000°C plateaus are: no RTA, 1, 10, 15 and 30 sec. As might be expected, the V_{OC} increases, reaches a plateau and then falls off. It can be seen that at 30 sec the device is drastically affected both before and after hydrogenation, most likely due to Al diffusion along grain boundaries, causing shunting and drastic smearing of the junction. At around 10 sec the V_{OC} maximizes to an average value of 235 mV and 425 mV before and after hydrogenation, respectively.
Figure 4.4.17: Averaged $V_{oc}$, $V_1$ and $V_2$ after RTA and after hydrogenation as a function of the RTA plateau time at 1000°C. The lines are 3rd-order polynomial fits.

The variation in $V_1$ and $V_2$ has some interesting characteristics that provide insight into what the limiting defects in the cell are and how well these defects are annealed and passivated. Before hydrogenation $V_{oc}$ is typically $n=2$ dominated, as seen by $V_2$ being smaller than $V_1$ (except in the extreme case of a 30-sec RTA). Following hydrogenation $V_2$ is still smaller than $V_1$ for 0 and 1 sec RTA. However, after a 10 and 15 sec RTA $V_2$ is greater than $V_1 + 18$ mV, indicating $n=1$ dominance at $V_{oc}$. Due to better fill factors of the I-V curves, this is the preferred situation for p-n junction solar cells.

The effect of 10 and 15 sec 1000°C RTA plateau time on the IQE as compared with the best measured as-grown device is shown in Fig. 4.4.18. Since these are planar thin-film diodes there are interference fringes in the EQE and reflectance data. The increase in total response, hence minority carrier lifetimes in base and emitter, is quite large over the entire wavelength range of 300 to 1050 nm. Some of the response above ~500 nm (where interference sets in) is an effect of light reflecting off of the back contact and can be used to determine the back surface reflectance. This effect is easily seen in the as-grown curve in Fig. 4.4.18. Shifting of the peak wavelength from around 430 nm to around 470 nm, and broadening of the peak response, provides some idea of the smearing of the junction deeper into the absorber region. Of course this broadening also indicates a large increase in minority carrier lifetimes in emitter and base. The increase in $J_{sc}$ (as determined from EQE) is from 1.91 mA/cm² (in the best as-grown device) to 5.97 mA/cm² and 6.11 mA/cm² for a 10- and 15-sec RTA, respectively.

Figure 4.4.18: Measured IQE of ALICIA cells before and after the 1000°C RTA process step. RTA plateau times are 10 and 15 sec.

Smearing the junction deeper into the absorber region through an RTA can be beneficial. The AIC layer’s interface to the absorber region has been shown through SIMS analysis to have a higher concentration of contaminants than the rest of the cell. By moving the junction away from this region, carrier lifetimes are increased. The optimal balance between this beneficial effect and the smearing of the junction profile must be determined to maximize the cells’ performance. This is further complicated by faster dopant diffusion along grain boundaries.
Following hydrogenation for 15 min at 620°C, the increase in IQE from a peak of 40% to over 70% is seen in Fig. 4.4.19 and good improvement over all other wavelengths is also seen. Lifetime in the absorber region is drastically improved with an RTA. Even a 1-sec RTA 1000°C plateau significantly improves the device’s quantum efficiency. Looking at the peaks of the 1, 10 and 15 sec curves, it can be seen that the curves are equivalent in magnitude above a wavelength of 600 nm while below this point the 1-sec RTA curve diverges much lower in magnitude. This, along with the peak moving to longer wavelengths and broadening, indicates that the longer RTA greatly improves the defect density within the junction region.

Figure 4.4.19: IQE of ALICIA cells as a function of the 1000°C RTA plateau time. RTA plateau times are 1, 10, 15 and 30 sec. Also shown, for comparison, are the IQE of the as-grown cell and a hydrogenated cell that did not receive a RTA step.

Comparing the best as-grown device (no RTA or hydrogenation) with a hydrogenated device without an RTA, a dramatic increase in the peak IQE from 16% to 41% is seen. The effect on the absorber region is quite interesting in that the lifetime is drastically improved and seems to be limited by defects near the junction region. Hydrogenation alone has at least as much impact on the quantum efficiency of ALICIA solar cells as defect annealing, although a combination of both gives the greatest benefit obviously.

A summary of the effect on peak IQE, J_{sc} (determined from the EQE curve) and the V_{OC} as a function of RTA plateau time at 1000°C is shown in Table 4.4.2. The impact on J_{sc} from only the hydrogenation is enormous, from 1.91 mA/cm^2 to 6.43 mA/cm^2, a gain of over 3, while the V_{OC} doubles. With only a 1 sec RTA plateau time the majority of gain in J_{sc} is achieved, yet to maximize V_{OC} a much longer RTA plateau time is needed. As seen from the table, the optimal RTA time for this solar cell structure is between 10 and 15 sec to provide the best gain in J_{sc} and V_{OC}. The best V_{OC} measured within this study is 430 mV, which was obtained with a 10-sec RTA. Note that natural cooling also results in the best IQE and J_{sc}, most likely due to slightly less time above 1000°C.

Figure 4.4.20 shows the evolution of the minority carrier lifetimes in ALICIA cells due to a 15-sec RTA treatment at 1000°C and subsequent hydrogenation, as determined by PC1D analysis of measured IQE curves. Also shown, for comparison, is the carrier lifetime of a hydrogenated sample that received a 10 sec RTA at 1000°C (dashed line). As can be seen from these PC1D results, the 1000°C RTA process improves the minority carrier lifetime in the base region of the investigated cells by about 2 orders of magnitude. Subsequent hydrogenation provides a further one order of magnitude improvement of the minority carrier lifetime to a value of about 1 ns, which corresponds to a lower bound for the diffusion length in the base region of about 1000 nm.
Table 4.4.2: Electrical characteristics of ALICIA cells as a function of the RTA plateau time at 1000°C.

<table>
<thead>
<tr>
<th>RTA time (sec)</th>
<th>Peak IQE (%)</th>
<th>J_{sc} (mA/cm²)</th>
<th>Average V_{oc} (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A (as-grown)</td>
<td>16</td>
<td>1.91</td>
<td>119</td>
</tr>
<tr>
<td>N/A (no RTA, hydrogenated)</td>
<td>41</td>
<td>6.43</td>
<td>247</td>
</tr>
<tr>
<td>1, controlled cool</td>
<td>61</td>
<td>10.50</td>
<td>329</td>
</tr>
<tr>
<td>10, controlled cool</td>
<td>67</td>
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<td>425</td>
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<tr>
<td>15, natural cool</td>
<td>71</td>
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<td>416</td>
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<td>68</td>
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<tr>
<td>30, controlled cool</td>
<td>3.6</td>
<td>0.56</td>
<td>213</td>
</tr>
</tbody>
</table>

Figure 4.4.20: Evolution of the minority carrier lifetimes in ALICIA cells due to 1000°C RTA treatment.

4.4.9 Oxygen Study in Evaporated Si Films by Infrared Spectroscopy

Oxygen is typically the most abundant impurity in crystalline silicon. Fortunately, the most common form, interstitially bound oxygen, is not detrimental for c-Si's electronic quality. However, if present in SiO$_2$-like clusters or B-O complexes the electronic quality is severely affected. In 2006, we used Fourier transformation infrared (FTIR) spectroscopy, available in the Centre’s Characterisation Lab, to study the oxygen contamination of evaporated silicon films at various stages of their processing sequence. FTIR not only allows us to detect trace amounts of oxygen and carbon in a c-Si film, but also to assess the properties of an amorphous Si film prior to crystallization. The amorphous Si films were evaporated onto Si wafer substrates and then thermally crystallised at about 600°C by SPE (solid-phase epitaxy).

Figure 4.4.21 shows the infrared absorbance spectra measured on a c-Si film evaporated onto a Si wafer substrate. Graphs (a) and (b) are the spectra before and after, respectively, a chemical clean of the sample to remove the surface oxide. The following conclusions can be drawn:

- Most of the bonded oxygen present after the SPE crystallization step is removed by the chemical clean and hence does not affect the electronic quality of the c-Si film.
- The deposition rate and the base pressure in the Si evaporator are the main factors determining the oxygen content in the crystallised c-Si film.
• If a sufficiently high deposition rate is used, in this study 300 nm/min, the bonded oxygen is mainly present in an interstitial configuration in c-Si. From solar cells made on Cz-grown Si wafers it is known that this type of oxygen contamination is not detrimental to the solar cell performance.
• For low deposition rates (< 100 nm/min), detrimental SiO$_2$ clusters are detected in the c-Si film.
• The infrared refractive index of the evaporated amorphous Si, which is related to the density of the amorphous film, increases with increasing Si deposition rate.
• Both a rapid thermal anneal and a hydrogenation step do not seem to significantly increase the bonded oxygen content in the c-Si film.

Figure 4.4.21: Differential absorbance spectrum of (a) a crystalline silicon film directly after crystallization and (b) of the same sample after an additional Piranha clean and HF dip. Fortunately, the detrimental SiO$_2$ absorption visible prior to the clean is completely removed and only interstitial oxygen can be detected after the clean. The difference in the Si-Si peak (at 610 cm$^{-1}$) can mainly be attributed to a small difference in the thickness of the c-Si substrate.

4.4.10 Back Reflector Study on Thin-Film poly-Si Solar Cells

Thin-film silicon solar cells offer many advantages over traditional wafer-based solar cells, such as low silicon usage and direct fabrication on a transparent glass pane which simultaneously serves as the required front cover of the solar cells. With these advantages come some challenges: one of the primary being limited light absorption due to the minimal silicon thickness. In very thin silicon films, a large fraction of the sunlight hits the back surface of the solar cell. The greatest fraction of useful energy from the sun for a silicon solar cell comes in the wavelength range from 600 nm to 800 nm, and for these wavelengths over half of the incident light hits the rear of the solar cell. Figure 4.4.22 illustrates the fraction of light which hits the rear of a thin-film silicon solar cell with a thickness of 1.3 µm.

To obtain a high short-circuit current, light that is not absorbed during the first pass through the silicon relies on a good back surface reflector. For a single pass, the limiting current for a 1.35 µm thick silicon solar cell is shown in Table 4.4.3, for three different reflection scenarios at the front surface of the solar cell. Also shown is the case assuming total light absorption.
During 2006, we have experimentally examined several back surface reflectors on silicon thin-film solar cells on glass. A metal film is the simplest back reflector and simultaneously provides a low-resistance ohmic contact to the cell’s back surface. We have used aluminium as it is the most common metal in the photovoltaics industry and is fairly cheap.

Using a dielectric film between the silicon and the rear metal film is a good method to increase the rear reflectance, and this method is commonly used in high-efficiency silicon wafer solar cells. The high reflection is caused by the large drop in refractive index between the silicon \((n \approx 3.5)\) and the dielectric \((n \approx 1.5-2.5)\), causing total internal reflection for photons that arrive at the rear silicon surface at an angle that is larger than the critical angle (“escape cone”). As dielectric we used a TCO (transparent conducting oxide) film with a refractive index of 2.0. The metal was again a thin, evaporated aluminium film.

Pigmented diffuse reflectors (PDRs) are reflectors which scatter light [4.4.9]. White paint is a good example; it is made of small pigment particles suspended in a binder material. Light which enters the PDR is scattered randomly by the pigments, and most of the scattered light is then returned to the silicon with a semi-random direction. A schematic representation of a silicon thin-film solar cell with a PDR on its back is shown in Fig. 4.4.23. The effect of scattering the light at the rear surface of the silicon film is two-fold: Firstly, the light travels a longer path in the silicon before it hits the front surface (where it may escape), enhancing absorption in the silicon during the second pass. Secondly, due to the oblique path of the light, the fraction of photons totally internally reflected at the front surface is increased, in effect trapping the light in the silicon and hence further enhancing the absorption in the silicon.
A planar and a mildly textured ALICIA thin-film silicon solar cell were selected as test vehicles for the analysis of the optical performance of the three back surface reflectors under investigation. The cells are Mesa-type and of a bifacial nature, enabling the deposition of the back surface reflector in the metal-grid-free regions of the back surface. The thickness of each cell is about 1.5 µm. The experimental procedure consisted in the deposition of a particular back surface reflector, the measurement of the external quantum efficiency (EQE) of the solar cell, followed by the removal of the back surface reflector. This procedure was conducted for each of the three investigated back surface reflectors. Since the different back surface reflectors were applied to the same solar cell, the measured EQE curves are directly comparable and highly reproducible.

The experimental EQE results are shown in Fig. 4.4.24. As can be seen, for both the planar and the textured ALICIA cell, the EQE at infrared wavelengths is best for the pigmented diffuse reflector, intermediate for the TCO/Al reflector, and worst for the Al reflector. Using the EQE curves from Fig. 4.4.24, the short-circuit current densities of the solar cells can be determined by combining these measurements with the AM1.5G solar spectrum. The results are shown in Table 4.4.4. From these results it follows that, compared to the standard aluminium reflector, the pigmented diffuse reflector provides a current boost of 20% for the planar cell and an even larger boost of about 29% for the textured cell. A PDR is thus extremely promising for improving the efficiency of poly-Si solar cells on glass.

<table>
<thead>
<tr>
<th>Back surface reflector</th>
<th>Current density (mA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Planar cell</td>
</tr>
<tr>
<td>Aluminium</td>
<td>6.93</td>
</tr>
<tr>
<td>TCO</td>
<td>7.85</td>
</tr>
<tr>
<td>PDR</td>
<td>8.31</td>
</tr>
</tbody>
</table>

Figure 4.4.23: Schematic representation of the operating principle of a Pigmented Diffuse Reflector (PDR) behind a silicon solar cell.

Figure 4.4.24: The EQE of (left) planar and (right) textured ALICIA solar cells with different back reflectors.

Figure 4.4.24: The EQE curves are directly comparable and highly reproducible.
4.4.11 References


Third Generation Strand – Advanced Concepts

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The major focus in 2006 has been on Si nanostructure tandem cells (the “all-Si” tandem cell) with continued funding on the Global Climate and Energy Project (GCEP), Stanford University, program. This has allowed a significant increase in the activities both on fabrication and on characterisation of Si nanostructures. This has included full commissioning and implementation of the multi-target sputtering machine for growth of the various Si nanostructures, including transfer of the Si QD technology in SiO$_2$ and Si$_3$O$_4$ matrices to a silicon carbide matrix; initial nanostructure doping studies; and transfer of the technology to tin (Sn) QDs in SiO$_2$. Characterisation has broadened into a wide range of X-ray techniques, development of TEM preparation, electron diffraction and TEM modelling; and significant improvement in electrical testing methods, including C-V and resistivity with temperature.

The next largest effort has been on Hot Carrier cells, with further improvements in characterisation of selective energy contacts (SECs) and development of carrier cooling theory. The SEC work has been supported by the parallel project with Toyota on high efficiency energy conversion, which was successfully completed in 2006.

There has also been development in the subsidiary project areas of Up-conversion, with investigation of co-doped rare earth species to enhance the spectral response and Plasmon coupling, with further enhancements in light emission.

4.5.1 Third Generation Photovoltaics

“Third generation” approaches aim to achieve high efficiency for photovoltaic devices but still use “thin film” second generation deposition methods. The concept is to do this with only a small increase in areal costs and hence reduce the cost per Watt peak [4.5.1]. Also, in common with the silicon based second generation thin film technologies, these will use abundant and non-toxic materials. Thus these “third generation” technologies will be compatible with large scale implementation of photovoltaics. The approach differs from “first generation” fabrication of high quality and hence low defect single crystal photovoltaic devices, which have high efficiencies that are approaching the limiting efficiencies for single band gap devices but which use energy and time intensive techniques. Third Generation aims to decrease costs to below US$0.50/W, potentially to US$0.20/W or better, by dramatically increasing efficiencies but maintaining the economic and environmental cost advantages of thin film deposition techniques (see Fig. 4.1.3 describing the three PV generations) [4.5.1]. To achieve such efficiency improvements such devices aim to circumvent the Shockley-Queisser limit for single band gap devices that limits efficiencies to the “Present limit” indicated in Fig. 4.1.3 of either 31% or 41% (depending on concentration ratio). This requires multiple energy threshold devices such as the tandem or multi-colour solar cell. The Third Generation Strand is investigating several approaches to achieve such multiple energy threshold devices [4.5.1, 4.5.2].
The two most important power loss mechanisms in single-bandgap cells are the inability to absorb photons with energy less than the bandgap (1 in Figure 4.5.1), and thermalisation of photon energy exceeding the bandgap (2 in Figure 4.5.1). These two mechanisms alone amount to the loss of about half of the incident solar energy in solar cell conversion to electricity. Multiple threshold approaches can utilise some of this lost energy. Such approaches do not in fact disprove the validity of Shockley-Queisser limit, rather they avoid it by the exploitation of more than one energy level - in some form – for which the limit does not apply. The limit which does apply is the thermodynamic limit shown in Figure 4.1.3, of 67% or 86.8% (again depending on concentration).

There have been proposed three families of approaches effectively for applying multiple energy levels [4.5.2]: (a) increasing the number of bandgaps; (b) capturing carriers before thermalisation; and (c) multiple carrier pair generation per high energy photon or single carrier pair generation with multiple low energy photons. Of these, tandem cells, an implementation of strategy (a), are the only ones which have as yet been realised with efficiencies exceeding the Shockley-Queisser limit.

In the Third Generation Strand, we are implementing strategy (a) by fabricating a tandem cell based on silicon and its oxides, nitrides and carbides using reduced dimension silicon nanostructures to engineer the band gap of an upper cell material. We are also tackling strategy (b) by investigating the “Hot Carrier solar cell” in which carrier cooling is slowed such that carriers can be extracted before thermalisation. This requires both an absorber with slowed carrier cooling properties and collection of carriers over a limited range of energies, such that cold carriers in the external contacts do not cool the hot carriers. Finally we are investigating implementation of strategy (c) by up-conversion in a layer behind the Si cell. Rare earth doped phosphors in the up-converter absorb below band gap photons and up-convert two or more to above band gap photons which are then incident on the Si cell.

Hence all Third Generation approaches are based on tackling one or both of the “below band gap” or “thermalisation” loss mechanisms mentioned above, as detailed below.
4.5.2 Si nanostructures

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A major impetus for this work in 2006 has been the continuation of the Global Climate and Energy Project work on fabrication of an “all-Si” tandem cell.

4.5.2.1 The “all-Si” Tandem cell

Silicon is a benign readily available material, which is widely used for solar cell fabrication. Silicon also has a bandgap which is close to optimal not only for a standard, single p-n junction cell (a little too low) but also for the bottom cell in a 2-cell or even a 3-cell tandem stack (a little too high). The radiative efficiency limit for a single junction silicon cell is 29%. This increases to 42.5% and 47.5% for 2-cell and 3-cell tandem stacks respectively. The optimal bandgap of the top cell is 1.7 eV ~ 1.8 eV for a 2-cell tandem with a Si bottom cell and 1.5 eV and 2.0 eV for the middle and upper cells for a 3-cell tandem, see Fig. 4.1.4.

Our approach is to produce a material with an engineered band gap using small nanocrystals of Si embedded in a silicon dielectric matrix, with the nanocrystal size approaching the Bohr radius. The resultant quantum confined energy levels will give an increase in the effective band gap of the nanostructure as compared to bulk Si. By restricting at least one dimension of silicon to the Bohr radius of the bulk crystalline silicon (5 nm or less), quantum confinement cause its effective bandgap to increase. Our early experiments involved carefully thinning the thin silicon layer (50 nm thick) in commercially available silicon-on-insulator wafers [4.5.3] and showed clear PL evidence for a quantum-confined bandgap increase up to 1.7 eV for layers about 1 nm thick. Also demonstrated was an increased strength of optical processes due to the localisation of electron-hole pairs – which is important for solar cell applications. This work was developed further by constraining Si in all three dimensions in nanocrystals to achieve a much stronger quantum confinement effect.

We are now investigating Si QDs in SiO$_2$ and analogues in other silicon dielectrics, and also other group IV analogues such as Sn QDs in SiO$_2$. We have adopted a threefold strategy for this work. Firstly we are model the materials and structures with respect to their quantum confined properties, doping potentials and suitability as wide band gap photovoltaic materials. We then try to fabricate these nano-structure materials using thin film deposition techniques, including: sputtering, PECVD and e-beam evaporation. These are then characterised with respect to their physical, optical and electronic properties with a high spatial resolution and sensitivity. Results from these are modelled interpretively before feeding into the next stage of modelling, fabrication and characterisation.

4.5.2.2 Fabrication

Thin film techniques are used for nanostructure fabrication. These include and plasma enhanced chemical vapour deposition (PECVD). The deposition is a variation of the multi-layer alternating ‘stoichiometric dielectric / Si rich dielectric’ process described below, followed by an anneal during which Si nanocrystals precipitate. The most successful and
hence most commonly used technique is sputtering, because of its large amount of control over deposition material, deposition rate and abruptness of layers. This uses a new multi-target remote plasma sputtering machine with two independent RF power supplies as well as additional DC power supplies.

RF magnetron sputtering is used to deposit alternating layers of SiO$_2$ and SRO of thicknesses down to 2nm. [SRO refers to Si rich oxide, formed by co-sputtering Si and SiO$_2$.] Deposition of multi-layers, consisting typically of 20 to 50 bi-layers, is followed by an anneal in N2 from 1050 to 1150°C. During the anneal the excess silicon in the SRO layer precipitates to form Si nanocrystals between the stoichiometric oxide layers according to the following reaction, Eq.(1):

$$SiO_x \rightarrow \frac{x}{2} SiO_2 + \left(1 - \frac{x}{2}\right)Si$$  \hspace{1cm} (1)

Experimental results have shown that the size of the QDs can be quite well controlled by selecting an appropriate thickness for the SRO layer and the density of the dots can be varied by the composition of the SRO layer. This control is possible for layer thicknesses less than about 7nm, within which Si migration to nucleating sites is dominated by a 2D rather than a 3D diffusion regime. Fig. 4.5.2 shows typical transmission electron microscope (TEM) and high resolution TEM (HR-TEM) images of Si nanocrystals grown using this method. TEM evidence indicates that these nanocrystals tend to be spherical - as surface energy minimisation would dictate - and at this scale would have energy levels confined in all three dimensions and hence can be considered as quantum dots (QDs).

[4.5.4-5] This technique is adapted for solar cells from that of Zacharias [4.5.6].

(a)                                               (b)

Figure 4.5.2: TEM image of Si quantum dots in a SiO$_2$ matrix with low magnification (a) and HRTEM image showing Si (111) lattice planes.

The main challenge for a nanostructure engineered material for a tandem cell is to achieve sufficient carrier mobility and hence a reasonable conductivity. For a nanostructure this may require formation of a true superlattice with overlap of the wave function for adjacent quantum dots; which in turn requires either close spacing between QDs or low barrier height. This is discussed further in the next section.

Another requirement for a PV cell element is the presence of some form of carrier separation of photo-generated carriers. This is usually achieved with a grown or diffused p-n junction or a p-i-n junction. For a superlattice cell this would either require doping of p- and n-type
superlattice regions or fabrication of p- and n- layers with the superlattice as the i-region. The latter requires careful control of the work functions (and therefore doping) of the p and n-regions but also means that it is not essential for the i-layer superlattice to be doped.

More generally carrier separation can be achieved by any method of filtering electrons in one direction and holes in the other. Hence other approaches could involve modification of the work function by control of the electron affinity in different superlattice regions of the cell to form an an-isotype junction. Ab-initio modelling work indicates that this may be possible using Si QD superlattices in different dielectric matrices. Alternatively a p-n junction can be formed not by doping the quantum dots but by doping the matrix, in such a way that free carriers ‘flow’ into the QDs – so called “modulation doping”, widely used in QW superlattices [4.5.7, p660].

The final challenge for a tandem cell is the inter-cell connections between adjacent cells. These must connect the valence band of one cell to the conduction band of the other. This can be achieved with an interband tunnel junction or with a metallic type, defect dominated, high recombination junction. This could be achieved with a quantum dot material, with very small QDs, or a nanocrystalline Si based material.

**Alternative matrixes for Si quantum dots [4.5.8-10]:**

As discussed above, transport properties are expected to depend on the matrix in which the silicon quantum dots are embedded. As shown in Figure 4.5.3, different matrixes produce different transport barriers between the Si dot and the matrix, with tunnelling probability heavily dependent on the height of this barrier. Si$_3$N$_4$ and SiC give lower barriers than SiO$_2$ allowing larger dot spacing for a given tunnelling current.

![Figure 4.5.3: Bulk band alignments between crystalline silicon and its carbide, nitride and oxide.](image)

The wave function of an electron confined to a spherical dot penetrates into the surrounding material. The barrier to tunnelling between quantum dots is reduced for a lower barrier height material, because the tunnelling probability for a square potential well is given by, (e.g. [4.5.7], p244):

\[
T_e = 16 \exp\left(-d \frac{8m^*}{h^2} \Delta E\right) \tag{2}
\]

where $m^*$ is the bulk effective mass in the respective band of the matrix, $d$ is the spacing between dots and $\Delta E$ is the energy difference between the CB edge of the matrix and the confined energy level of the quantum dots ($\Delta E = E_c - E_n$). Hence the important parameter in determining the degree of interaction between quantum dots is $m^*\Delta Ed^2$. As barrier height decreases the barrier thickness for a given probability increases, thus requiring
lower dot density for a given conductivity or higher conductivity for a given dot density. In addition as dot size decreases $\Delta E$ also decreases, thus increasing $T_e$ and enhancing the effect further for smaller quantum dots [4.5.7]. Following this line of argument, the results suggest that dots in a SiO$_2$ matrix would have to be separated by no more than 1-2 nm of matrix, while they could be separated by more than 4 nm of SiC. The same type of calculation allows the effect of fluctuations in spacing and size of the dots to be investigated. It is found that the calculated Bloch mobilities do not depend strongly on variations in the dot spacing but do depend strongly on dot size within the QD material [4.5.11].

Hence, transport between dots can be significantly increased as the barrier height decreases with alternative matrixes. The spacing of dots would have to be closest in the oxide, nitride and carbide, in that order. Similar deposition and quantum dot precipitation approaches should work for all.

**Si quantum dots in a silicon nitride matrix**

For the above reason we have explored transferring the technology of Si QDs in SiO$_2$ to the growth of Si nanocrystals in silicon nitride by both sputtering and PECVD [4.5.12]. For sputtering, growth parameters are very similar to the oxide. In addition, two separate PECVD systems – a remote plasma and a parallel capacitor machine - have been used for the growth of Si nanocrystals by depositing alternate Si rich and stoichiometric nitride layers. Annealing is carried out again at 1100°C but with a pre-annealing at 500°C to drive off hydrogen incorporated from the PECVD process. Again HRTEM images showing even clearer nanocrystals have been obtained. To the best of our knowledge this is the first time layered Si QDs in nitride have been demonstrated [4.5.12].

We have now also extended the layered Si QDs in nitride technology to gas-phase in situ deposition. Fig. 4.5.4 shows in situ Si QD dispersed in a nitride matrix. A stoichiometric Si$_3$N$_4$ layer and an in situ Si QD layer are alternately deposited on a Si substrate. This technique allows QDs to form during deposition without the need for a subsequent anneal. We are actively studying this technique because it is a low temperature process and potentially lends itself to doping of Si QDs.

![Figure 4.5.4: Gas phase in situ Si QDs dispersed in a Si$_3$N$_4$ matrix: (a) low magnification TEM and (b) high resolution TEM.](image)
Si QDs in silicon carbide

SiC nanocrystals of a few nm diameter in a SiO$_2$ matrix were produced by silicon and carbon implantation into thermal oxide [4.5.13]. However, to our knowledge, little has been reported on the experimental properties of Si QDs embedded in a SiC matrix.

A Si-rich amorphous silicon carbide precursor layer can be achieved by control of the sputtering parameters of Si and carbon containing targets (e.g. pure carbon, silicon carbide, boron carbide etc). One way to fabricate Si-rich silicon carbide is co-sputtering from silicon and carbon containing targets. Alternatively small chips of carbon attached to a silicon target can produce a Si-rich silicon carbide precursor layer. A high temperature anneal (800-1200°C in an inert gas or in vacuum) of a silicon rich carbide carbide precursor layer precipitates Si and/or SiC nanocrystals depending on its chemical composition as follows:

\[
Si_{1-x}C_x = x \cdot (SiC) + (1-2x) \cdot Si \quad (3)
\]

Raman, TEM and XRD spectra for a silicon-rich Si$_{0.75}$C$_{0.25}$ precursor layer grown on a quartz substrate with subsequent annealing are shown in Fig. 4.5.5. There is clear evidence for the formation of nano-crystalline Si at an anneal temperature greater than 1000°C. This is shown in the Raman peak at ~ 508 cm$^{-1}$ (redshifted from 520 cm$^{-1}$ due to a nanocrystalline folded Brillouin zone dispersion in k-space); TEM lattice fringe spacing consistent with \{111\} Si planes; and XRD peaks at 2\(\theta\) = 28.4° with peak broadening indicating nanocrystal of 3-7nm (estimated using the Scherrer equation). [It should be noted that the nanocrystal size determined by TEM is, in our experience, slightly smaller than that determined by XRD.]

![Figure 4.5.5: Silicon-rich SiC precursor layer: (a) Raman spectra for various annealing temperatures; (b) Cross-sectional HRTEM image; and (c) X-ray diffraction.]

Other Si and C concentrations were tried. As the concentration of C in SiC$_x$ is increased to the nearly stoichiometric Si$_{0.495}$C$_{0.505}$, Raman evidence for the stretching vibration modes of Si-C and C-C bonds can be easily identified. With increasing annealing temperature showing increasing intensities of both TO and LO bands, indicating the formation of crystalline SiC during annealing. In addition there is a dramatic decrease in the intensity of Si-Si vibration modes indicating the formation of far fewer Si nanocrystals. There is also evidence for free carbon at ~1400 cm$^{-1}$ in as-deposited film, splitting into two bands.
at ~1360 (D band) and 1590 cm\(^{-1}\) (G band) after annealing above 1000°C, indicating formation of amorphous graphitic carbon [4.5.14].

HRTEM data shows crystallites with lattice fringes corresponding to \(\beta\)-SiC \{111\} planes, with a mean crystallite size in the range of 3 - 10 nm. However, in contrast to the spherical Si nanocrystals in the silicon-rich SiC precursor (see Fig. 4.5.5), SiC nanocrystals are irregular with some nanocrystals joined together to form an extended crystal. XRD results show SiC peaks for \(\beta\)-SiC \{111\}, \(\beta\)-SiC \{220\} and \(\beta\)-SiC \{311\} planes, with a very weak peak at \(2\theta = 28.3^\circ\) from Si \{111\} planes. A Scherrer equation estimate of SiC nanocrystal size gives 7.3 ± 0.4 nm.

The difference of nanocrystal shapes from silicon-rich SiC and near-stoichiometric SiC is due to the differing mechanisms for nanocrystal formation. For the Si rich carbide precursor, nanocrystals precipitate to nucleating sites, due to an excess of Si in the matrix, with surface energy minimisation favouring the formation of spheres. For the near-stoichiometric composition, SiC nanocrystals formation does not depend on precipitation and hence random shapes occur, dependent more on local concentration variations.

For an intermediate composition (SiC\(_{0.5}\) to SiC\(_{0.8}\)) evidence for a mixture of Si and SiC nanocrystals is observed. Raman spectra for SiC\(_{0.71}\) have peaks around 490 cm\(^{-1}\) associated to the stretching vibration mode of the Si-Si bonds and two broad bands centered at ~740 and ~940 cm\(^{-1}\) similar to \(\beta\)-SiC peaks. A shift to lower frequency of both bands with respect to crystalline SiC is probably due to the small crystallites and presence of the amorphous SiC phase. The intensity of peaks increases with annealing temperature, indicating an increased fraction of SiC crystalline phase with a higher annealing temperature. There is also evidence for C-C vibration modes at higher energies. XRD spectra for SiC\(_{0.71}\), annealed at 1100°C, show two strong peaks at \(2\theta = 28.3^\circ\) and 35.9° due to diffraction from Si \{111\} and \(\beta\)-SiC \{111\} crystalline planes, respectively. With additional weak peaks are diffraction from Si \{311\}, \(\beta\)-SiC \{220\} and \(\beta\)-SiC \{311\} planes. The estimated nanocrystal size is around 7.5 ± 0.5 nm and 5.1 ± 0.4 nm, respectively.

Hence the best data so far for Si nanocrystals in a SiC matrix are obtained for a Si\(_{0.75}\)C\(_{0.25}\) precursor composition. In order to control the size of Si nanocrystals multilayer structures, based on this concentration, have been fabricated, as shown in Fig. 4.5.6. Optical measurements of optical band gap and absorption coefficient are being carried out on these layers and indicate an optical gap increasing from 1.4 to 1.6 to 2.0 eV for as-deposited and 800 and 1100°C annealed material. Further measurement is underway.

![Figure 4.5.6: TEM images of SiC/Silicon-rich SiC multilayer (a) as-deposited and (b) annealed at 1100°C for 20 minutes.](image)
Sn QDs in silicon oxide

The work on Si QDs in dielectric matrices involves a high temperature anneal (except for the in-situ Si QDs in Si$_3$N$_4$ work). Furthermore, such technology can only ever increase the band gap of an engineered nanostructure, not decrease it. Hence we are also considering other group IV elements as QDs in a dielectric matrix. Both Sn and Ge are likely to precipitate at lower temperatures in an appropriate analogue material. Also, as Sn and Ge also both have lower bulk band gaps, they can produce a QD nanostructure with effective band gap below that of Si. This could be useful for fabrication of a nanostructure cell to stack below a Si cell in a tandem stack.

We are currently concentrating on Sn as it is a much more readily available material than Ge. Although the bulk value of the Sn band gap is lower than that of Si, it increases more rapidly with decreasing size and exceeds that of Si for very small sizes. The electron effective mass of Sn is 0.0236 $m_o$ and its Bohr radius corresponds to 40 nm. Semi-empirical tight binding calculation indicates an effective bandgap of 0.4 eV for 20 nm dots and 2.5 eV for 5 nm dots [4.5.15]. Fig. 4.5.7 shows the theoretical bandgap of Sn nanocrystals due to quantum confinement [4.5.16].

Sn has two polymorphic structures: The semi-metallic $\alpha$-Sn (diamond cubic Sn) and truly metallic $\alpha$-Sn (double body-centred-tetragonal). $\alpha$-Sn has conduction band minima below the point of the valence band and is a semi-metal with bandgap of 0.08 eV at 300°K. A phase transition from $\alpha$-Sn to $\alpha$-Sn occurs at 13.2°C [4.5.17].

Our first experiments on a Sn nanostructure have involved Sn precipitation from a SiO$_2$ matrix. Whilst this is a more complex system, it is a more direct analogue of our existing technologies and we can build on our existing knowledge of the SiO$_2$ processing parameters.
The Sn-rich precursor layers were prepared by magnetron co-sputtering of Sn and SiO$_2$. With the intention of forming Sn nanocrystals of uniform size, a multilayer structure of Sn-SiO$_2$ alternating with a stoichiometric SiO$_2$ layer was deposited. This was annealed at the relatively low temperature of 600 °C.

Figure 4.5.9 shows a plan-view TEM image of a single layer of Sn QDs embedded in SiO$_2$. By annealing the sample at 600 °C in N$_2$, a very uniform size of Sn QDs of 3.5±0.6 nm was obtained. The density of the quantum dots and inter-dot spacing can be readily controlled by changing the Sn content.

Further chemical, structural and optical characterisation is underway along with further investigation of deposition properties and possible photovoltaic application.

4.5.2.3 Density Functional ab-initio modelling using Gaussian03:

Researchers:
Dirk König, James Rudd, Daniel Mansfield

Gaussian03 is a Density Functional – Hartree-Fock (DF-HF) based ab-initio program for calculating basic thermodynamic, electronic and phononic properties of atomic clusters in the quantum mechanical regime, and, to some extent, in the molecular dynamic regime. In contrast to many ab-initio programs like Abinit, Gaussian computes the molecular orbitals (MOs) of the atomic cluster in real space and thus delivers a spatial picture of respective states as a function of energy in real space. Thermodynamic optimisations (cumulative binding energy of the cluster $\rightarrow$ Max.; variational principle) deliver the thermally relaxed configuration of the cluster. The cluster with a maximized cumulative binding energy is the starting point for calculating its MO energies, delivering the density of states as a function of energy, DOS(E). The energetic difference between the highest occupied MO (HOMO) and the lowest unoccupied MO (LUMO) can be seen as a band gap. Another relevant feature - particularly for the Hot Carrier cell project - is the capability of Gaussian to calculate the phonon spectra. This will be a property for investigation on a medium term base.
First computations were carried out on H-terminated Si clusters ranging from just one Si atom (SiH₄; Silane) to Si₁₇₂H₆₄ (corresponding to a QD of d_QD = 14 Å, assuming a perfectly spherical shape). As an MO basis set we used G6-31G(d) in the B3LYP exchange energy functional approach and Troullier-Martins atomic pseudo potentials.

The optimisation shows that there is an intrinsic tendency of the Si QDs to align towards a spherical shape so as to minimise the ratio of the number of Si atoms at the surface of the QD to those in the QD volume. This is due to the surface Si atoms not being as thermally relaxed as the more bulk-like Si atoms of the QD interior. For larger clusters the effect is quite significant.

Another result of the single point energy (single point referring to the maximum of the cumulative binding energy of the cluster atoms in state space of energy) is the computation of the MO eigen energies and the spatial distribution of the MOs within the cluster. With these results, areas of spatial overlap of occupied and unoccupied MOs under the constraint of selection rules for carrier generation can be found. This is interesting especially when investigating foreign atoms in a host cluster like a Si QD. If a pair of MOs which fulfils the selection rules (eigen-energy, sign of MO wave function) has a large spatial overlap, a radiative recombination of an electron hole pair is more likely. This is useful in considering photon recycling. Alternatively, if the spatial overlap of the pair of MOs is rather small, the relative probability of a non-radiative recombination increases, because the probability of phonon emission increases with the carrier displacement required for recombination (mean free path). With the electronic band structure of small Si QDs approaching the direct band gap regime, the investigation of these MO pairs becomes even more significant.
The integration of the conjugate complex square all occupied MOs gives the electronic charge density. The C atom has a higher ionisation energy, electron affinity and electronegativity compared to Si. Therefore it is negatively charged, while the remaining electrons are distributed evenly between the Si atoms.

Figure 4.5.12: Electronic charge density of the Si$_{34}$(CH)$_{36}$ cluster, seen along the <111> direction (left). Thereby the view to the C atom in the central position is not obscured. The DOS(E) of an Si$_{26}$H$_{32}$ cluster with a Gaussian broadening of the MO eigen states corresponding to $kT = 1200$ K (right).

The sum of all MOs presents the DOS(E) of the cluster. The MOs are broadened by a Gaussian distribution with the full width half maximum corresponding to the thermal energy $kT$, because we investigate the QDs at finite temperatures. The example below shows the DOS(E) of a Si$_{26}$H$_{32}$ cluster at a temperature of $T = 1200$ K. It is quite remarkable to see that even at elevated temperatures the DOS(E) is low within certain regions of the bands.

Figure 4.5.13: HOMO (EV) and LUMO (EC) energies of H-terminated Si clusters as a function of QD diameter (left) and as a function of the number of Si atoms in the respective cluster (right).

The HOMO and LUMO levels as well as the band gap are maximum values for realistic Si QDs since the computed clusters are free of any defects. The H termination effectively renders the Si QDs embedded in vacuum; a dielectric matrix like SiO$_2$ surrounding the Si QDs has a significant impact on the band structure.
Further computations on Sn and SiC clusters, are under way. In order to address the required
demand for computation power, a Linux cluster of 11 dual core Opteron computers is
being established. This should enable us to compute larger clusters, equivalent in size to
QDs which have been characterised experimentally by PL, TEM and XRD. The modelling
of QDs embedded in a surrounding dielectric matrix and the computation of clusters
with Born – von Karman periodic boundary conditions will soon become feasible with
this increased computing power, as are investigations of the impact of foreign atoms on
respective clusters or their dielectric matrix.

Simulation of HRTEM

Researchers:
Tom Puzzer, Giuseppe Scardera

Nanoscale structured materials and systems play a central role in the development of
Third Generation solar cell structures. The physical parameters determining the ultimate
nanoparticle properties are the elemental composition, size, external shape and internal
structures. Characterising these materials and their nanostructures is an essential part of
the research project. Although other techniques such as X-ray diffraction and selected-
area electron diffraction, can provide accurate structural information (averaged over the
excited sample volume), they are incapable of providing information on the structure of
individual nanoparticles. The information contained in the diffraction pattern, however,
extends much further in reciprocal space than is accessible to HRTEM. Since the various
types of microscope aberrations do not influence electron diffraction, high resolution
electron diffraction data can be obtained without imaging artefacts.

Despite the difficulties involved with HRTEM, it remains the most powerful technique to
examine these materials at sub-nanometre resolution. It is important to remember, however,
that the image formation system of the TEM is not perfect. The contrast transfer function (see
Fig. 4.5.14) contains zeros and inversions meaning that some spatial frequencies present
in the sample are not observed in the images and other spatial frequencies are imaged
with reversed contrast. Therefore, there is a problem with unambiguous interpretation
of individual high-resolution images and only under well-defined conditions may high-
resolution images be naively interpreted in terms of the projected potential of the atomic
columns aligned along the beam direction.

![Figure 4.5.14: Contrast transfer function at the Scherzer defocus (maximum passband). Si low index planes are indicated by the blue vertical lines. The Si(111) is in the main passband; Si(220) is at a point of zero contrast; Si(311) is in a passband with a positive contrast [4.5.18].](image)

In order to model which nanocrystals are likely to be observable above the noise level in
HRTEM images, a 3nm QD is modelled in a range of low index plane configurations, see
Fig. 4.5.15.
The numbers on each nanocrystal indicate the number of atoms in projection for each atomic column in the particle. Hence if this number exceeds the average number of atoms in the amorphous phase then contrast is expected. The modelling proceeds by embedding the simulated nanocrystals in an amorphous background. To model the latter a simple model based on determining the smallest cell that contains a SiO molecule is used and randomly placing 1 Si and 2 O atoms in this cell. This gives the number of projected atoms per square Å. For a 3nm thick SiO$_2$ layer in this model, the mean number of Si and O atoms are 4.3 atoms/Å$^2$ and 8.5 atoms/Å$^2$, respectively. This results in a random arrangement of “columns” of atoms in the amorphous phase with the number of atoms varying from 3 to 8 atoms.

Hence only those nanocrystals with columns of 6 or more atoms would be expected to have good contrast. These are the [110] and [111] orientations. Add to this the fact that the usual mode of operation is to focus the TEM around the Scherzer defocus and it can be seen from Fig. 4.5.14 that of these planes only the [111] will be in a pass band. Thus it is not surprising that one tends to only resolve [111] planes in HRTEM images and that this does not indicate a lack of nanocrystals with other orientations.

4.5.3 Hot Carrier cells

Researchers:
Chu-Wei Jiang, Santosh Shreshtha, Chris Flynn, Eun-Chel Cho, Dirk König, Martin Green, Gavin Conibeer

Hot carrier solar cells offer the possibility of very high efficiencies (limiting efficiency 65% for unconcentrated illumination) but with a structure that could be conceptually simple compared to other very high efficiency PV devices – such as multi-junction monolithic tandem cells. For this reason, the approach lends itself to ‘thin film’ deposition techniques, with their attendant low costs in materials and energy usage and facility to use abundant, non-toxic elements.

The concept underlying the hot carrier solar cell is to slow the rate of photoexcited carrier cooling, caused by phonon interaction in the lattice, to allow time for the carriers to be collected whilst they are still at elevated energies (“hot”), and thus allowing higher voltages to be achieved from the cell [4.5.1, 4.5.20, 4.5.21]. It thus tackles the major PV loss mechanism of thermalisation of carriers (loss (2) in Figure 4.5.1 and strategy (b) discussed above in Section 4.5.1). In addition to an absorber material that slows the rate
of carrier relaxation, a hot carrier cell must allow extraction of carriers from the device through contacts which accept only a very narrow range of energies (selective energy contacts).

Experimental work in the Third Generation Strand is currently focused on selective energy contacts using resonant tunnelling structures based on similar Si quantum dot approach to that discussed in Section 4.5.2. Theoretical work is directed at investigating mechanisms for slowing carrier cooling by modifying phononic band structures in nanostructure superlattices.

Figure 4.5.16: Band diagram of the Hot Carrier cell. The device has two stringent requirements:
1. Slowing of thermalisation of photogenerated electrons (and holes) in the absorber material.
2. Extraction of these ‘hot carriers’ to external contacts over a narrow range of energies, such that excess carrier energy is not lost to the cold contacts.

4.5.3.1 Selective Energy Contacts

Fabrication of Selective Energy Contacts

Double barrier resonant tunnelling contacts have been investigated as selective energy contacts, with quantum dots (QDs) providing a discrete energy level between two insulating barriers. This will give conduction strongly peaked at the discrete energy level. The total energy filtering of a QD based structure is required of a selective energy contact rather than 1D energy filtering because the 1D energy filtering in, for instance, a quantum well resonant tunnelling device is only effective for carriers with momenta entirely perpendicular to the plane of the well [4.5.22]. Carriers with components of momenta away from this normal can be transmitted even if their total energy is outside the range of the energy filter. Hence work in this area is focused on resonant tunnelling structures using QDs or other discrete total energy confined centres as the resonant centres. These would give the required total energy filtering. Such a filter should exhibit negative differential resistance (NDR) in all directions.

Figure 4.5.17: I-V data at 300K for the sample structure described, showing NDR for two different mesa devices on one wafer.

Figure 4.5.18: Schematic of the sample structure for CAFM measurement.
Double barrier tunnelling structures consisting of SiO$_2$/SiQDs/SiO$_2$ layers have been fabricated by RF magnetron sputtering and $1150^\circ$C annealing using the Si QD technology described in section 4.5.2.

NDR characteristics have been previously measured for similar structures. A 4nm layer of Si QDs were fabricated between 5nm barriers of sputtered SiO$_2$. The whole structure was deposited on a degenerate n-Si wafer and capped with a heavily doped layer of sputtered n-Si. Mesas of $1/16$ cm$^2$ area were prepared lithographically and Al contacts evaporated to front and back by shadow masking. For the growth and anneal conditions used, each mesa of this size contains about $10^{10}$ Si QDs [4.5.23]. A significant proof of concept has been achieved, as shown in Fig. 4.5.17 with NDR observed at room temperature for a double barrier QD structure. The NDR resonance is not strong but nonetheless such a result at room temperature is very encouraging as proof of 1D energy selection.

New work, on resonant tunnelling behaviour of Si QDs in a silicon nitride matrix has now also been carried out. The double barrier tunnelling structures were fabricated by plasma enhanced chemical vapour deposition (PECVD), as shown in Fig. 4.5.18. The advantage of this technique is that QDs are formed during the deposition at the substrate temperature of about 400°C. [Note that the sizes and shapes of the QDs are not uniform for this in-situ technique.] This allows a thin front nitride layer to be used. Furthermore, the Si QD density produced in the film using this method is lower than obtained with the silicon dioxide matrix using RF sputtering. Both of these properties are desirable for better resolution in Conductive AFM measurements (CAFM).

**Electrical Characterisation of SECs**

Resonant tunnelling characteristics of Si QDs on oxide and nitride have been tested with conductive atomic force microscopy (CAFM) through collaboration with Dr Chris Pakes at Melbourne University. CAFM is a powerful tool for investigating the transport properties of nanostructures. This is achieved by modifying the local band profile - on a scale of a few nanometres - using an applied bias at the conductive probe tip. This technique can be used to map the current-voltage characteristics of a single layer of Si QDs, below an oxide/nitride layer of a few nanometres, at a very high areal resolution. Hence it can be applied to the mapping of resonant tunnelling sites on a sample [4.5.24].

![Figure 4.5.19 Current map for the QD structure as measured with CAFM at a constant voltage (10 V).](image)

The CAFM measurements were performed at room temperature in vacuum using a JEOL 4200 Scanning Probe Microscope. The current-voltage measurements were made using an amplifier with a gain of $10^9$VA$^{-1}$ and a low pass filter, giving a peak-to-peak noise level of about 10 pA. The bright regions indicate areas with a high current conduction, which is associated with the QDs in the sample. This was verified by additional CAFM measurements of the sample following by high temperature annealing in oxygen. The post annealed samples did not show any of these bright regions which we interpret as due to the oxidation of the QDs during the high temperature annealing. Thus it can be confirmed that the high conduction regions were originally due to Si QDs. Fig. 4.5.19 (b) shows the current profile across two spots in (a) indicated by the arrow. A large enhancement in the current across the dots is evident.
The results so far indicate that CAFM is useful for verifying the location and density of QDs non-destructively. Samples with thinner oxide layers (about 5 nm) are now being produced to increase the tunnelling current at QD locations to allow lower bias CAFM scans and hence to estimate the resonant energy levels more accurately. This is being done by back-thinning a thick (about 20nm) oxide layer by careful etching.

**Optical excitation of non-equilibrium carrier population for characterisation of SECs**

The technique of optically exciting a population of carriers and then measuring the I-V curve (optically assisted I-V) is being developed for improving the detection of resonant tunnelling features in selective energy contacts (SECs).

Conventionally, tunnelling IV measurements at an MIS structure involves a strong bias field for obtaining hot electrons at the SEC/Si interface which increases the tunnelling current density (TCD) such that it can be detected. A drawback of this approach is that the band bending of the tunnelling barrier is so strong that a subband within the barrier would have a zero overlap of the subband DOS on both sides of the barrier. A subband for resonant electron tunnelling would not stretch throughout the entire barrier, thereby rendering the electron tunnelling to be somewhat off-resonant. In the optimum case, the resulting dI/dV characteristic would show a blurred NDR feature. Increasing the subband width would eventually lead to a DOS overlap, but then the tunnelling electrons thermalise within the subband which again blurs the resonant feature of the dI/dV curve. As the hot electrons are generated by a strong bias field, their DOS as a function of energy can be estimated only, since the calculation of the exact relations in k-space is not feasible.

However with a high intensity monochromatic optical excitation, a population of hot carriers can be generated near to the barrier, providing a hot carrier DOS at the SEC without a large bias. This also requires that the optical generation rate within the absorber is high and/or that the tunnelling current is measured within a few picoseconds of the massive generation of hot carriers. Using a tuneable monochromatic light source the resonant energy level(s) of the SEC can be probed. To improve electron collection efficiency on the metal electrode, a small bias filed is necessary, although the band bending this imparts is minimal, resulting in a maximum overlap of the subband DOS on both sides of the barrier.

The optimum light source for such an optically assisted tunnelling IV measurement would be a tunable monochromatic one. However, for the proof of concept and initial measurements, a conventional light source (Xe lamp) is used with suitable wave length pass filters for tuning the minimum wave length ($\lambda$) to cut-off long wavelengths and so avoid undue heating and short wavelengths to avoid direct excitation over the tunnelling barrier.

![Figure 4.5.20: Optically assisted I-V measurement](image-url)
The rapid decay of a ‘hot’ carrier population will give a range of energies even for a monochromatic excitation. Hence a second order resonance is expected in I-V or dI/dV measurements. Furthermore, the general enhancement of the tunnelling current under illumination is due to defect states within the SiO₂ barrier layers being distributed rather smoothly in both spatial space and on the energy scale. This can be seen as a superposition of approx. 10¹³ cm⁻² trap assisted tunnelling paths (sputtered SiO₂ is of rather bad quality) on which the resonance of the Si QD array is superimposed. It is thus very encouraging to see a tunnelling resonance due to the QD array at room temperature.

Figure 4.5.21: (a) Dark and illuminated, or optically assisted, I-V measurements. Detail of (b) dark and (c) illuminated I-V traces.

The initial data shown in Fig. 4.5.21 were obtained last year but serve to illustrate the technique. The enhanced current at all biases for optically assisted measurements as compared to dark I-V, is tentative evidence for an enhanced hot carrier population near the contact. The increase cannot be explained purely by an increase in Fermi-distribution with temperature as the approximate temperature increase is only a few tens of degrees and hence it is likely to be due to a non-equilibrium hot carrier population. There is also tentative evidence for a resonance in the data in the dark at a bias of about 3.5V (Fig. 4.5.21(b)), which under illumination both increases in magnitude and decreases in required bias to about 2.2V (Fig. 4.5.21(c)). This is further tentative evidence for the collection of hot carriers as the energies appropriate to be collected by the contact are generated at lower bias voltages with optical assistance. However, it should be pointed out that this proof of concept is at present without the presence of additional filters to control the spectrum of light illuminating the sample. In subsequent measurements such filters - either providing a narrow range of energies or a sharp long wavelength pass cut-off - will allow more distinct quantitative data to be collected.

A new chamber has been designed to facilitate optically assisted IV. It consists of a five-fold cross chamber, containing a triple electric coaxial feed-through, an optical quartz window, a liquid N₂ cryostat, an evacuation flange and a pressure gauge. The sample will be placed on a Teflon sheet which is mounted on a steel brass. The latter is connected to the triple coaxial feed-through. The steel brass enables the two probe tips to be positioned freely by a magnet attached to each probe stand. Next to the sample position there is a thermocouple for monitoring the temperature of the sample. The Teflon sheet slides onto a copper tongue which ensures a good thermal conductivity from the cryostat to the sample. Two springs on the copper tongue ensure that the Teflon sheet is in optimum thermal contact with the copper. The vacuum pump attached to the chamber is capable of pumping down to a rough vacuum of 2 mbar, thereby eliminating most traces of water. This will minimize parasitic currents and will be necessary when using the cryostat.
In different modes, optically assisted IV should allow both investigation of the energy selectivity of an energy selective contact and the spectrum of a hot carrier population in a static regime. This represents a significant development in characterising elements of hot carrier solar cell.

**Thermal characterisation of SECs**

An alternative way to excite a hot carrier population is thermally. This amounts to a thermoelectric measurement. A small program of work is investigating the efficiency of a thermoelectric power generator with an energy selective contact. A schematic diagram of the device under investigation is shown in Fig. 4.5.22. The generator is made of a p-type and n-type thermoelectric material connected electrically in series and thermally in parallel. An array of 4 nm Si QDs, enveloped by 5 nm SiO₂ layers, is embedded between Si and the heat source.

Figure 4.5.22: Schematic diagram of a TE Power Generator.

The use of the quantum-dot structure is expected to provide energy selectivity through resonant tunnelling. Since carrier conductivities within the appropriate energy range are enhanced and other energies, whether higher or lower, are reflected back into the hot reservoir, this structure is expected to enhance the overall efficiency of the device, although the power out will be decreased. Measurements of the ZT and efficiency of such devices, compared with a reference sample having no energy selective contacts, will provide proof of concept. Although this structure can improve efficiency in principle, the increase may not be significant or even measurable due to the carrier losses in the silicon layer between the energy selective contacts and the heat sink. The efficiency of the device can be, however, increased if p/n-type material is replaced by nanostructures.

Figure 4.5.23: Voltage generation from devices shown in Fig. 4.5.22.

Initial proof of concept results for a device with no Si QD nanostructure, just p- and n-type Si contacts, are shown in Fig. 4.5.23 (a). When power is supplied to the resistors, the device is gradually heated thus producing a temperature difference across its two sides. As expected a voltage was generated which increased slowly with time reflecting the gradual increase in temperature difference. When the power to the heater was switched off, the voltage output gradually decreased to zero. This effect is reproducible for other similar
devices, as is evident from Fig. 4.5.23 (b). It can be noted that the voltage generation in this case is about four times larger than that in (a) because the power supplied was much larger and thus is expected to produce a larger temperature difference. It is also clear that the second voltage peak in (b) is smaller than the first. This is probably due to a gradual heating of the overall apparatus, reducing the effective temperature difference. Currently we are in the process of characterising devices with selective energy contacts. Hence this provides the potential for a thermal method of characterising selective energy contacts.

4.5.3.2 Modelling of carrier cooling in phononic band structures

Investigation in this area is currently focussed on obstructing the phonon decay mechanisms for carrier cooling. The current work (discussed in [4.5.25-27]) stems from the realisation that hot carriers lose their energy by scattering with optical phonons which in turn build up a hot- non-equilibrium population. Thus the critical feature in the overall carrier cooling is the rate of decay of the hot optical phonons. It has been identified by other workers that the principal and perhaps only mechanism for this is the decay of an optical phonon into two longitudinal acoustic (LA) phonons of energy half that of the optical phonon and of equal and opposite momenta. This is the Klemens’ decay mechanism.

In some bulk semiconductors, with a large difference in their anion and cation masses, there can be a large gap between the highest acoustic phonon energy and the lowest optical phonon energy. In a few cases – such as InN – this gap can be larger than the highest acoustic energy and hence prevent operation of the optical decay mechanism described above.

Once the probability of this Klemens’ mechanism decay is reduced by a large gap in the dispersion, optical phonon decay is forced to proceed via the less efficient Ridley mechanism of emission of a TO and low energy LA phonon. This is only possible whilst still maintaining E & k conservation, if there is a wide DOS for optical phonons (as shown for InN in Fig. 4.5.24).

![Figure 4.5.24: Phonon dispersion for InN from [4.5.28] in which E_{LO}>2E_{LA} such that LO → 2LA (only) is forbidden. Also showing schematically the Ridley mechanism.](image)

![Figure 4.5.25: Dispersion curve of acoustic phonons of a QD superlattice 1x1 nm with soft interface modes.](image)
This DOS is much greater for a hexagonal material than for a cubic one. Thus cubic InN should prevent the Ridley mechanism as well as the Klemens one. However cubic InN is very difficult to fabricate, precisely because the atoms are very different in size. Nonetheless there is evidence that other cubic materials with a large gap in the phononic dispersion – such as AlSb and InP – do have long optical phonon lifetimes [4.5.26].

The current work is investigating achieving similar effects in less exotic materials based on silicon, by exploiting the reflection that occurs at the mini-Brillouin zone boundaries of superlattices. As discussed in [4.5.25-26] and in the 2005 annual report, this opens up mini-gaps in the phonon dispersion for acoustic phonon energies which satisfy the Bragg condition. These dispersions can be modelled using nearest neighbour or Rytov calculations, for well (QW) and QD (QD) superlattices respectively, but only QD nanostructures exhibit complete gaps in the phonon DOS. In principle the QD size and spacing can be carefully engineered to give dispersion gaps that coincide with the required phonon energies for Klemens decay. If this was the case then the Klemens mechanism would be prevented, phonon populations would build up, and carrier cooling would be slowed. However, to achieve such effects in practice, the structure would need to be very finely tuned.

More recent work has looked at the effect of interfaces between the QDs and the matrix on the phonon dispersion [4.5.26-27]. Fig. 4.5.25 shows a nearest neighbour force constant calculation of the acoustic phonon dispersion with a very soft interface modelled as being two atomic spacings in thickness. The super-periodicity of the interface causes the mini-gaps to group into doublets with a larger gap in the centre. [This can be thought of physically as the soft interface preventing the transmission of phonon energy.] This would improve the ease of fine tuning the QD superlattice such as to block the optical phonon decay. Modelling of ‘soft’ interfaces as compared to ‘hard’ interfaces shows that both produce splitting of the dispersion into doublets with larger gaps between doublets, but that the ‘soft’ interface produces larger gaps and more physically meaningful dispersions.

Furthermore, because of the larger gaps, it may be possible to engineer a nanostructure with soft interfaces, which blocks decay by the Ridley mechanism as well as the Klemens mechanism.

Material parameters for these structures are currently being applied to real material systems with a view to designing and potentially fabricating slowed carrier cooling structures.

4.5.4 Other Third Generation projects

Up-conversion

Researchers: Avi Shalav, Daniel Ball, Claudia Strümpel, Gavin Conibeer

A low level of activity has continued on Up-conversion. This has focussed on an attempt to ‘sensitize’ the region of the spectrum below the band gap of Si but above the absorption level of the erbium (Er) absorption level at 14800-1520nm. Sensitization of this region would then aim to pump this Er level and hence boost the number of IR photons that can be upconverted. Thulium (Tm) or Dysprosium (Dy) co-doped with Er in NaYF have been investigated for this purpose.
The results are that Dy acts to poison any up-conversion in Er, presumably because it has too many levels which allow parasitic non-radiative recombination, see Fig. 4.5.26. The results for Tm are less definite. The co-doped Er:Tm sample still shows a lower up-conversion efficiency in photoluminescence (see Fig. 4.5.26) for the main Er peaks at 980 nm and 550 nm but does indicate a slightly higher efficiency at 810 nm and 660 nm compared to Er on its own. This may indicate a slightly higher efficiency of up-conversion to high Er levels. This is not directly useful for up-conversion for a Si cell but may help elucidate the mechanisms further.

**Surface Plasmons**

**Researchers:**
Supriya Pillai, Kylie Catchpole, Martin Green, Thorsten Trupke

Surface plasmons are the collective oscillation of the conduction band electrons in metals. Incident light can excite surface plasmons in metal nanoparticles that are characterised by enhanced electrical fields and strong scattering. The scattering from the surface plasmons can be used to couple light with the waveguide modes of the semiconductor thereby increasing absorption. The reverse process holds true for light emission.

We deposit silver metal nanoparticles on thin film SOI structures by thermal evaporation followed by annealing. A series of experimental results investigating the effects of surface plasmons on thin-film SOI devices as well as wafer based cells have shown promising results. Following the results published in last year’s annual report for thin film SOI structures, the effect of varying size/shape of the particles were investigated on similar devices. This effect follows the scattering theory where the scattering cross-section of the metal nanoparticles increases with size of the particles, hence increasing the scattering efficiency. A clear red shift in the enhancement peaks was seen on increasing the particle size/shape due to the shifting of the bare island resonance which also appears broader with increase in size. It was found that smaller particles gave an overall photocurrent enhancement in the visible region, but larger particles resulted in greater enhancement at longer wavelengths as shown in Fig. 4.5.27. This was consistent for thin film and the wafer based cells alike.0 The enhanced photocurrent at longer wavelengths according to the reciprocity theorem would lead to enhanced emission as well. The results from the electroluminescence emission from the 95 nm thick Si on SOI structures but with different sized particles gave us up to 12 fold enhancement for the largest size particles (corresponding to 27 nm mass thickness of silver), a significant increase from our 7 fold enhancement reported earlier and shown in Fig. 4.5.28.
Surface plasmons have good potential of increasing light trapping in thin film silicon devices without introducing recombination problems of conventional light trapping schemes like texturing. The results are particularly encouraging for Si photonics considering the fact that Si is an indirect bandgap material and hence a poor absorber and emitter of light. There is also scope for further reduction in the thickness of the thin-film silicon solar cells with good light trapping provided by the surface plasmon layer. One of the major advantages of this approach is that the Ag islands can be deposited by a low temperature process at the final stage of device processing and hence no processing incompatibilities are involved.
4.5.5 Concluding remarks for the Third Generation section

In 2006 the most significant developments have been in the Si nanostructure tandem cell project, through the continued support of the Stanford GCEP project. This has seen a further transfer of Si QD technology to an in-situ nitride deposition; successful transfer to Si QDs in SiC and also to Sn QDs in SiO$_2$. There has also been significant development in the TEM, XRD and electrical characterisation of these structures and further development in ab-initio modelling, with the scales of modelling and of fabrication almost overlapping. This work has been greatly facilitated by the full operation of the multi-target sputtering machine and by the installation of the computer cluster. The work is now poised to move to the next stage of device fabrication in these structures, indeed initial experiments have been started in this area.

The area of Hot Carrier cells has also seen a fair amount of activity, with support from Toyota. This has mainly been on the further development of characterisation and fabrication techniques for selective energy contacts. Work on carrier cooling theory has also refined the modelling of modified phonon dispersions with new decay mechanisms investigated. Work is now progressing on specifying real material parameters in order to investigate fabricating real test structures. Work in other Third Generation areas has mainly been on Up-conversion with a development of the understanding of up-conversion from co-doped rare-earth elements. There has also been a watching brief kept on some other potential Third Generation areas.

4.5.6 References

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4.6 Silicon Photonics

4.6.1 Photoluminescence based characterisation of silicon

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4.6.1.1 Background

The further development and improvement of photoluminescence (PL) and electroluminescence (EL) based characterisation techniques has been the focus of the photonics group in 2006. In the previous two years our group has established quasi steady state photoluminescence (QSS-PL) lifetime measurements and so called Suns-photoluminescence (Suns-PL) measurements as practical characterisation tools which, compared to the more widely used quasi steady state photoconductance (QSS-PC) technique have some fundamental advantages: 1) QSS-PL is not significantly affected by the so called depletion region modulation (DRM) [4.6.1] effect. 2) QSS-PL is also unaffected by minority carrier trapping [4.6.2]. Both the DRM effect and trapping are detrimental effects that lead to significant artifacts in QSS-PC. 3) QSS-PL is orders of magnitude more sensitive to small excess carrier concentrations, which allows fast measurements of the minority carrier lifetime over an unprecedented injection level range and also allows implied current voltage curves to be determined accurately over a wide range of implied voltages. Both the QSS-PL and the Suns-PL techniques are set up in a user friendly system in the characterisation lab at the ARC Centre of Excellence and are being used by research groups at the Centre for routine process monitoring and also by various collaborators on a daily basis.
Progress in 2006 was focussed mainly on the development of advanced luminescence imaging techniques, in which the luminescent emission from silicon wafers or from silicon solar cells is captured with a CCD camera. These techniques provide high-resolution images (typically 100 µm per pixel) of electronic properties such as the minority carrier lifetime or the diffusion length with very short data acquisition times of typically one second or less. In EL imaging [4.6.3] the luminescence is excited by application of a forward bias to a finished solar cell in the dark. In contrast the excitation is optical and thus contactless in PL imaging [4.6.4], which allows monitoring the electronic quality of silicon wafers at any processing stage. A prototype combined PL/EL imaging system which was established at UNSW in late 2005 has been significantly improved during 2006 by upgrading various hardware components. The speed of the system has been improved by a factor 50 and now allows large (up to 15x15 cm$^2$) unprocessed raw multicrystalline silicon wafers to be measured with a data acquisition time of only one second with sufficient signal to noise ratio. Fig. 4.6.1 shows an example of two PL images, one taken on a fully processed industrial silicon solar cell, the other one taken on the unprocessed sister wafer cut from the same block. The comparison of the two images (printed on a different relative colour scale) shows the same lateral features of good and bad quality regions. This is one example how solar cell or wafer manufacturers may be able to use luminescence imaging for quality control purposes.

The existing PL/EL imaging prototype system at UNSW is being used extensively for routine process monitoring purposes by all research groups at the Centre developing bulk silicon devices (i.e. first generation cells). In many cases the application of PL imaging has allowed exceptionally efficient process monitoring and the development of new device concepts to be optimised with an unprecedented speed. Examples include the optimisation of SiN as a passivation layer on n-type silicon, the development of high efficiency silicon solar cells, the development of laser doping or localised doping via conducting pastes.

Figure 4.6.1: PL images of a fully processed screen printed solar cell (15x15cm$^2$) on the left and of a raw sister wafer cut from the same block (right). Similar features of high and low material quality are observed in the two images. The improved system at UNSW can capture such images within one second, potentially allowing manufacturers to use PL imaging as a quality control tool for raw material.
4.6.1.2 Diffusion length from spectral luminescence imaging:

Collaborators:
Peter Würfel

In both the QSS-PL lifetime measurements and in luminescence imaging techniques the measured signal normally consists of the integral luminescence intensity emitted by the sample, i.e. no information is obtained about the spectral content of the emitted radiation. During two research visits at UNSW Prof. Peter Würfel introduced the idea that the relative spectral distribution of the emitted luminescence contains information about the minority carrier profile throughout the wafer and thereby about important physical quantities such as the diffusion length and the minority carrier lifetime. In collaboration with Centre staff an analytical and experimental method was developed that uses the ratio between two luminescence images, measured with two different spectral filters, in order to obtain two dimensional images of the absolute diffusion length.

The basic idea is that the fairly broad spectral distribution of photons that are spontaneously emitted by crystalline silicon contains short wavelength photons (e.g. ~900nm) with a penetration depth (~30µm) that is much smaller than the thickness of a silicon wafer and longer wavelength photons (up to >1200) with penetration depths of several centimetres, i.e. much longer than the thickness. Short wavelength photons that are spontaneously emitted at a position within a wafer that is further away form the emitting surface than their penetration length cannot escape the sample because they are reabsorbed before they can escape the sample. As a result the short wavelength luminescence only probes the carrier density near the emitting surface. In contrast the entire volume of the sample contributes to the long wavelength emission. A detailed theoretical analysis shows that the ratio of luminescence intensities measured with two different short pass filters has a one-to-one relationship with the diffusion length (Fig. 4.6.2). The ratio of two luminescence images taken with different filters can thus be used to obtain the spatially resolved diffusion length of silicon solar cells. The experimental verification of this new technique is currently in progress.

Compared to the more established spectral LBIC technique the luminescence technique has the main advantage of being orders of magnitude faster. In preliminary experiments the total data acquisition time for the luminescence measurements was less than one minute for a one mega pixel diffusion length image. With binning that data acquisition time could be reduced quite substantially (e.g. with 4x4 binning, the total measurement time could be reduced to a few seconds). LBIC measurements with similar spatial resolution take several hours.
Using one single EL image as a measure for the diffusion length distribution was proposed by Fuyuki et al. [4.6.3]. That simplistic approach neglects reabsorption of photons within the silicon wafer, is only valid in principle for diffusion lengths that are smaller than the thickness and does not account for lateral variations in the voltage that can be the result of series resistance variations or local shunts. Also, the results from a single EL image only give relative values, which must be scaled against an independent calibration measurement. In contrast, in the luminescence technique reabsorption is quantitatively accounted for, it produces absolute values for the diffusion length, it works for small and large diffusion length (less accurately though for large diffusion lengths) and, most importantly, local voltage variations cancel out in the calculation of the ratio of two images.

4.6.1.3 Series resistance imaging

Experiments in 2006 have shown that local variations of the series resistance have a large impact on the local luminescence intensity [4.6.5]. This is easily explained qualitatively in the case of EL imaging: The application of an external voltage to a cell with locally variable series resistance will result in a local variation of the voltage drop over the series resistance and thereby in a local variation of the diode voltage. The luminescence intensity (which to a first approximation increases exponentially with the diode voltage) thus reflects the variation in the voltage drop over the series resistance and areas of high series resistance will appear dark. Using the same argument it can be shown that in PL images with current extraction areas of enhanced series resistance appear bright. Recent work focussed on a more quantitative analysis of luminescence images in terms of series resistance variations [4.6.6].

![Image](image_url)

Figure 4.6.3: Series resistance in $\Omega \text{cm}^2$ of a monocrystalline silicon solar cell determined from two luminescence images. The large area of enhanced series resistance in the middle of the cell results in about 2% (absolute) lower efficiency of that cell compared to normal cells. The inset shows a greyscale image of the high series resistance region and shows where the front grid makes good (dark) and bad (bright) contact to the silicon, respectively.

The analysis of this problem shows that two luminescence images taken under different excitation conditions are required in order to be able to separate out variations in the series resistance from variations in the minority carrier lifetime. Fig.4.6.3 shows the series resistance of a monocrystalline silicon solar cell that is determined from two PL images, a first one taken under open circuit conditions and a second one taken near the maximum power point [4.6.6]. The image shows a large area of enhanced series resistance in the middle of the cell and four square shaped areas of enhanced series resistance underneath the busbars. The comparison with a Corescan measurement on that cell confirms the locally enhanced series resistance in the centre. Calculation of the total
series resistance from that image gave good quantitative agreement with data obtained from the IV characteristics. With a total data acquisition time of only a few seconds that was required for these measurements luminescence imaging thus represents an excellent technique for quantitative measurements of the local series resistance. Compared to Corescan (currently the most widely used technique for spatially resolved measurements of the series resistance) the luminescence imaging technique is currently estimated to be somewhat less quantitative, especially on multicrystalline silicon solar cells. On the other hand with total data acquisition times of only a few seconds it is orders of magnitude faster, could potentially be used in-line in industrial manufacturing, it is non-destructive (in contrast to Corescan) and it measures series resistance effects occurring on both sides of the cell.

Broken metal grid lines are a specific cause of enhanced series resistance in screen printed solar cells. Dark lines that run parallel to specific grid fingers were observed in EL images taken on many screen printed solar cells from various manufacturers (see for example Fig.4.6.4). The same lines appeared bright in PL images taken with current extraction (see arrows in Fig.4.6.3). The comparison with optical inspection through a microscope showed an unambiguous correlation between those dark lines and broken metal fingers. Often such broken fingers were observed in the same position on different cells from the same batch, indicating that the problem is process induced, e.g. by a congested screen. Luminescence imaging represents an easy to interpret and fast method to identify such problems in-line in an industrial environment.

Figure 4.6.4: EL image of a screen printed cell. Comparison with optical microscope inspection showed a clear correlation between the dark grid lines and broken metal grid fingers. The areas behind broken fingers that appear dark in EL measurements appear bright in PL images with current extraction (see arrows in Fig.4.6.3).
4.6.1.4 Shunt imaging

Collaborators:
Fraunhofer ISE
Max-Planck Institute, Halle
Deutsche Cell GmbH

The most widely used and most accurate technique for shunt localisation and shunt analysis is lock-in thermography (LIT) [4.6.7]. In 2006 the detection of shunts by luminescence imaging has been demonstrated at UNSW [4.6.8] and elsewhere [4.6.9, 4.6.10]. However it was pointed out relatively early that luminescence based techniques, while much faster, cannot be expected to be as quantitative and accurate for shunt analysis as LIT techniques [4.6.11]. Experimental evidence for that prediction was presented recently [4.6.10], where a strong and extended shunted region was undistinguishable from low lifetime regions. However, our experimental results suggest that specific types of shunts, specifically strong and very localised shunts, can be localised fairly accurately in both PL and EL image [4.6.8]. Figure 4.6.5 shows a PL image of an industrial multicrystalline screen printed silicon solar cell. Upon variation of the contrast the position of various shunts can be identified reasonably accurately in that image. The position of the shunts as determined from the luminescence image could very accurately be confirmed by a LIT measurement. The possibility to use luminescence imaging techniques for shunt localisation thus clearly depends on the exact nature (strength, position and size) of the shunt. To shed more light on this issue some current work that is carried out in collaboration with Fraunhofer ISE focuses on a theoretical analysis of the influence of shunts on luminescence images via two dimensional network modelling.

Additional experimental methods to distinguish shunts e.g. from low lifetime regions are currently under investigation.

Figure 4.6.5: PL images of a shunted screen printed solar cell before (left) and after (right) laser isolation of the shunted regions. Both images were measured with a data acquisition time of one second each.
4.6.1.5 Laser shunt isolation

Collaborators:
Fraunhofer ISE
Max-Planck Institute, Halle
Deutsche Cell GmbH

In cases where shunts can unambiguously be localised (as in Fig. 4.6.5), the extremely short data acquisition times required for luminescence imaging offer interesting in-line applications to reduce the influence of shunts on the average yield in industrial manufacturing as proposed earlier [4.6.8]. Some of these techniques have recently been realised experimentally in our group [4.6.12]. Laser isolation trenches through the emitter and trough metal grid fingers were scribed around the shunted areas within the shunted solar cell shown in Fig. 4.6.5. This procedure electrically isolates the shunts, which are currently thought to be caused by SiC inclusions, from the rest of the cell. The right hand side of Fig. 4.6.5 shows a PL image of the same cell after the laser shunt isolation. PL images taken with current extraction confirmed that the laser processing has electrically isolated the areas within the laser written squares and circles. Calibrated IV measurements under standard one Sun illumination conditions showed that the laser processing resulted in a quite impressive improvement of that cell from 9.6% to 13.3%. This technique largely benefits from the fact that the efficiency limiting shunts are very small. The loss in short circuit current, which is in proportion to the ratio of the isolated area to the total cell area can therefore be relatively small (~2-3% in Fig. 4.6.5) and is largely overcompensated for by a moderate increase of the cell voltage and by a dramatic improvement of the fill factor.

LIT measurements performed on the cell after the laser isolation indicates that especially the laser isolation of metal grid fingers is problematic as it introduces additional shunts. Current work therefore focuses on the further optimisation of the laser isolation process, on alternative processes to isolate contact fingers and on an efficiency improvement of more moderately shunted cells.

Our preliminary experimental results so far indicate that the combination of fast luminescence imaging and local isolation of shunted regions could be an industrially viable process that can result in higher average yield and efficiency in industrial manufacturing with the benefit that precision laser systems that already exist in modern silicon solar cell production lines for edge isolation could be used without any significant modification.

4.6.1.6 Theoretical work

Reabsorption of photons within the silicon wafer is an effect that can cause experimental artefacts in injection level dependent minority carrier lifetime measurements. A theoretical analysis of this problem [4.6.13] showed that at room temperature the influence of photon reabsorption is generally small but must be accounted for in very accurate measurements, in particular in cases where the minority carrier lifetime varies in the range 1µs to 50µs.
4.6.1.7 Collaborative work

In a joint project a QSS-PL lifetime system identical to the system at UNSW was provided by Centre researchers to the Fraunhofer ISE, with the purpose of investigating temperature dependent QSS-PL measurements. Preliminary results were already presented [4.6.14]. The effect of reabsorption on temperature dependent QSS-PL measurements was neglected in that study. Current work focuses on the theoretical analysis of the influence of reabsorption on such temperature dependent measurements.

In another collaborative project Centre researchers assisted staff from the Australian National University with QSS-PL measurements aiming for a more precise analysis of the lifetime crossover point upon dissociation of iron boron pairs in p-type silicon [4.6.15]. In ongoing work the suitability of luminescence imaging for spatially resolved measurements of the iron concentration is being investigated.

4.6.1.8 Publications

In 2006 the photoluminescence characterisation project has resulted in seven Journal publications, all of them in either Journal of Applied Physics or in Applied Physics Letters. The PL work has also resulted in two invited oral presentations in 2006 at major international silicon workshops in Denver, USA and in Sendai, Japan. In addition four conference papers at the 4th world conference WCPEC-4, Hawaii, USA and one conference paper at the 21st European conference in Dresden were presented. One paper by Florence Chen was awarded the prestigious best Poster award in the Silicon Photovoltaics section of the WCPEC-4. Four provisional patents have been filed, of which two have gone to the PCT stage. Potential routes towards the commercialisation of the PL imaging technology have been actively pursued by key researchers of the group, assisted by staff from New South Innovations, the University's commercial arm.

4.6.1.9 Summary

QSS-PL techniques are now established as standard characterisation tools at UNSW, where they are used on a daily basis. In particular QSS-PL lifetime measurements have proven to be very useful research tools. However, at this stage, the benefit of these measurements over more established techniques such as QSS-PC are mostly limited to research type applications. In contrast the luminescence imaging techniques developed in late 2005 and in 2006 are of major interest to both research groups and industrial manufacturers. With extremely short data acquisition times for high resolution images and the versatility of obtaining spatially resolved information about shunts, series resistance and lifetime variations and given the ease with which luminescence images can be interpreted to identify processing problems luminescence imaging has a tremendous potential. The very positive response that we received from collaborators and industrial partners so far and the research activity that has been started in other research groups around the world leaves little doubt that luminescence imaging techniques will be used as standard techniques in research laboratories and quite likely in production lines in the not too distant future.
4.6.2 References


4.6.15 Macdonald D., Roth T., Deenapanray P.N.K., Trupke T., Bardos R.A. Doping dependence of the carrier lifetime crossover point upon dissociation of iron-boron pairs in crystalline silicon. Appl. Phys. Lett. 2006; 89(14); 142107.
Technology Commercialisation and Industry Collaborative Research

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The Centre has a large number of collaborators including many cell manufacturers working with the Centre to improve or develop new solar cell technology for commercialisation. This interest is in part being stimulated by the booming photovoltaic industry indicated in the figure below.

Figure 4.7.1: Growth of annual PV production capacity.

The Centre’s technologies of most interest in terms of industry collaborative research and commercial licences fit broadly into six areas, with the main collaborators coming from China, Germany, the United States, Australia, Italy and Taiwan. These companies include Suntech-Power, BP Solar, Nangjng PV-Tech, CSG Solar, E-ton Solar, Enitechnologie and JA Solar. The six technology areas having the greatest impact and of most interest to industry for commercialisation are:
4.7.1 Laser Grooved Solar Cells

Despite this technology being commercialised more than a decade ago, it remains a key technology for collaborative research with industry and continues to do well commercially with close to $1 billion of product now deployed in the field. In the 2006 European Inventor of the Year Awards, this technology contributed to Green and Wenham receiving a Top 3 Ranking (out of more than 200,000 inventions world-wide in the period 1990-2000) for inventors outside Europe. A further distinction for this technology is its listing amongst Australia’s Top 100 Inventions of the 20th Century as determined by the Australian Academy of Technological Sciences and Engineering. The original design for this solar cell has the buried metal contacts on the top surface although in more recent years the interdigitated rear contact design applied to n-type wafers shown below has become particularly popular and a focus of UNSW research. Efficiencies of 20% have been demonstrated on small area devices with efficiencies of 21% eventually believed achievable on large area CZ material.

![Buried contact cell with interdigitated rear contacts.](image)

4.7.2 Laser Doping with Self Aligned Metallisation

The benefits of a selective emitter have been well known and quantified for many years. The benefits of heavy doping beneath the metal contacts contribute significantly to the high performance levels achieved by technologies such as the Laser Grooved Buried Contact Solar Cells, the semiconductor finger solar cell, the point contact solar cells and the world-record holding Passivated Emitter and Rear Locally diffused (PERL) solar cell. The heavy doping not only facilitates reduced contact resistance between the metal and the silicon, but probably more importantly it shields the high recombination velocity metal/silicon interface from the active regions of the cell. In addition, by restricting the heavily doped material to the immediate regions beneath the metal contact, little light absorption takes place in such regions thereby avoiding problems with carrier collection from heavily doped regions where the minority carrier diffusion lengths are very short.

Despite the commercial success of the Laser Grooved Solar Cell described in (1) above, a potentially more effective and simpler way of achieving a selective emitter is by using laser doping to produce the heavily doped regions beneath the metal contacts as shown in the schematic. Following top surface emitter phosphorus diffusion to about 100 ohms per square and silicon nitride deposition, an n-type dopant source is applied or can even be incorporated into the silicon nitride layer. A 532 nm NdYAG laser is used to melt the silicon to a depth in the vicinity of a micron while simultaneously releasing the n-
type dopants into the molten region. The molten silicon subsequently regrows epitaxially, heavily doped with phosphorus. Just as importantly, the overlying silicon nitride layer is removed from the silicon surface in isolated regions, facilitating direct plating to the exposed n\(^{++}\) surface. Electroless plating of Ni and Cu provides a particularly effective self aligned metalisation scheme to provide metal lines wherever the laser doping was effected. The laser doped regions are typically 15 microns wide, leading to metal lines of only 35 microns width after plating.

Figure 4.7.3: Laser doped, electrolessly plated solar cell.

Contact resistances below 0.001 ohm cm\(^2\) have been demonstrated, leading to fill factors in excess of 80% and efficiencies approaching 18% on commercial-grade CZ p-type silicon. Of particular importance has been the defect generation accompanying the laser doping process, particularly in conjunction with dielectric-coated, textured silicon surfaces. Planar surfaces present minimal challenge in terms of achieving near defect free regions in the vicinity of the laser melted regions. Textured surfaces however, particularly in conjunction with dielectric coatings of significantly different thermal expansion coefficient, have provided a significant challenge to match the low defect densities achievable with planar devices. Important processing parameters in the optimization of the laser doping process for textured surfaces have included laser pulse envelope shape, pulse duration, pulse frequency, laser light frequency, laser power, beam focus as well as the type of dielectric and dopant source being used.

The most sensitive electrical parameter of the devices in response to these laser induced defects appears to be the junction recombination and hence the local ideality factor. This is demonstrated below for three devices with significantly different levels of damage resulting from varying the duration of the laser melting process when using silicon nitride coated textured silicon surfaces. As can be seen, the local ideality factor varies significantly. Most importantly, at voltages corresponding to the maximum power point, the optimized processes achieve ideality factors close to unity indicating minimal Schottky diode shunting and junction recombination. This translates to devices with fill-factors in the range of 80-81% verifying the effectiveness of these conditions in minimizing problems with laser damage. Interestingly, the best results are achieved with the shortest duration for laser melting indicated by LD1-9-a, with the results getting progressively worse for longer times. The results given by LD1-4-a correspond to the silicon being held molten by the laser for 10 times the duration of cells depicted by LD1-9-a. All of these devices had standard textured surfaces and silicon nitride AR coatings and were electrolessly plated using Ni sintered at 400 degrees followed by Cu.
Pilot production of this new technology whereby the laser doped self aligned contacts are used to replace the front surface screen-printed contacts is currently being established in conjunction with a commercial manufacturer. This change is expected to increase cell efficiencies from typically 16.5% to 18.5% with minimal if any cost increase. Two other popular implementations of the laser doping technology with industry collaborators is the bifacial structure using laser doped self-aligned contacts of opposite polarity on both surfaces and the interdigitated rear surface laser doped contacts for rear junction n-type devices. Initial work on the latter indicates that efficiencies on n-type CZ should be capable of efficiencies comfortably above 20% in large scale commercial production.

### 4.7.3 Semiconductor Finger Solar Cells

The broad aim of this work has been to develop the next generation of screen-printed solar cell for implementation on the Suntech-Power production line. In particular, the fundamental limitations of the conventional screen-printed solar cell that have limited its performance for the last 30 years have been identified, and innovative approaches to redesigning the emitter and front metal contact have been devised, developed and analysed in this work. In addition to overcoming the current and voltage limitations imposed by the design shown below, a further aim of this work has been to retain compatibility with existing equipment and infrastructure currently used for the manufacture of screen-printed solar cells.
Figure 4.7.5: Standard screen-printed solar cell.

Screen-printed solar cell technology dominates commercial photovoltaic manufacturing, with well over 50% share of international markets. Despite the dominance of this technology, this solar cell design shown above has significance performance limitations that limit the cell efficiencies to well below those achievable in research laboratories around the world. In particular, the front surface screen-printed metallisation necessitates a heavily diffused emitter to achieve low contact resistance and also to achieve adequate lateral conductivity in the emitter since the metal lines need to be widely spaced compared to laboratory cells to avoid excessive shading losses. Such cells therefore typically have emitters with sheet resistivities in the range of 40-50 ohms per square, which inevitably give significantly degraded response to short wavelength light. To raise this sheet resistivity to above 100 ohms per square as required for near unity internal quantum efficiencies for short wavelength light, serious resistive losses are introduced, both in the emitter and the contact resistance at the metal to n-type silicon interface.

Furthermore, the conventional design for screen-printed solar cells has quite poor surface passivation in both the metallised and non-metallised regions. Even if good ohmic contacts could be made to more lightly doped emitters, the large metal/silicon interface area would significantly limit the voltages achievable due to the high levels of recombination in these regions and the corresponding contribution to the device dark saturation current. These voltage limitations are not of major significance at the moment due to the limitations imposed by the substrates. However, in the future as wafer thicknesses are reduced to improve the device economics, the cells will have the potential for improved open circuit voltages, but only provided the surfaces, including under the metal, are well passivated.

The new emitter design developed in this work is shown below. The top surface is diffused to 100 ohms per square, while the heavily diffused grooves act as semiconductor fingers to carry the current to the screen printed silver fingers that run perpendicular to the grooves as shown. Also not shown in the figure is the surface passivating dielectric that not only passivates the lightly diffused surface so as to give near unity internal quantum efficiencies for short wavelength light, but it also isolates the metal from these same regions to minimise the device dark saturation current. Importantly, the silicon is only exposed within the grooves, with the screen-printed metal having been shown to make excellent ohmic contact to the heavily phosphorus diffused silicon in these regions. Both thick oxides and silicon nitride layers, when used with appropriate pastes, appear to provide adequate protection to the lightly diffused surface regions, preventing the screen-printed metal from contacting the silicon.
Figure 4.7.6: Cross-section of the innovative emitter design using semiconductor fingers, developed to address the fundamental limitations of screen-printed metal contacts with their inability to produce fine lines and make ohmic contact to lightly diffused emitters.

Figure 4.7.7: Screen-printed fingers running perpendicular to the heavily diffused grooves where electrical contact is made. A dielectric/AR coating passivates the top surface and isolates the metal from the lightly diffused top surface.

Fill factors above 79% have been demonstrated with this structure on large area devices of approximately 150cm$^2$, verifying the effectiveness of this contacting scheme for minimising resistive losses. These cells also have near perfect response to short wavelength light as shown below, leading to Jsc values of 36-37mA/cm$^2$. Even though commercial p-type substrates are not capable of voltages above about 640mV, Voc's approaching this value have been achieved in pilot production with this technology, with corresponding efficiencies in the vicinity of 18%.

Figure 4.7.8: Spectral response of semiconductor finger cell.

The grooves are typically spaced less than a millimetre apart so as to minimise resistive losses within the lightly diffused emitter, while the screen-printed metal lines can be spaced significantly further apart than in normal screen-printed cells due to the comparatively excellent lateral conductivity of the emitter achieved by the very heavy doping within the grooves. This concept of semiconductor fingers does not appear to have ever been used in commercial solar cells, and has considerable appeal as it facilitates good conductivity within the emitter, but without the normal trade-off found in screen printed cells. Normally, such regions of good emitter conduction are located at the top surface and therefore degrade the cell spectral response and current generating capability due to the corresponding extremely short minority carrier diffusion lengths in such regions.
Following successful pilot production of this technology during 2005/2006, Suntech-Power commenced production of cells of this design in late 2006. In early production, cell efficiencies lie predominantly in the 17-17.5% range although average efficiencies of 17.5-18% are believed achievable during 2007.

A simplification of the proposed emitter design is to apply a phosphorus doped passivating dielectric after lightly diffusing the top surface. The laser scribing conditions for groove formation are then modified so as to melt the silicon rather than ablate it, thereby allowing large amounts of phosphorus to penetrate into the molten silicon, producing heavily doped channels rather than grooves. This avoids the need for etching the grooves and subsequently diffusing the groove walls. An important benefit of this approach for multicrystalline silicon wafers is that the heavily doped regions are able to be formed without heating of the entire wafer. Some multicrystalline silicon wafers are known to degrade significantly if heated to temperatures above about 900 degrees Celsius. The performance of these devices with CZ silicon however does not currently match that of the devices produced using the emitter design based on the use of laser grooving.

Suntech-Power has been particularly generous, not only funding all the collaborative research conducted in China, but also funding the collaborative research at UNSW. The cash contribution alone for the latter has been $500k for 2006. In addition, Suntech funded all the living, travel and accommodation expenses for the staff and students who worked at Suntech on the collaborative research.

4.7.4 Inkjet Technology for Solar Cell Fabrication

Inkjet technology has been an area of rapid development over the last decade, particularly for printing. In recent years, its application has been spreading to other fields, but as yet has had only minimal impact in photovoltaics. The first company apparently to commercialise a photovoltaic technology incorporating inkjet technology is CSG Solar who during 2006 commenced production of a thin-film technology that uses inkjet printing of a corrosive material to etch patterns in a resist layer to facilitate metal contacting to the underlying silicon. In the present work, the use of inkjet technology has been expanded to encompass a range of solar cell fabrication processes including texturing, grooving, patterning of dielectric layers for metal contacting, localized diffusions, etcetera. The techniques developed to carry out these processes are uniquely different to those used before. A non-corrosive plasticizer is inkjet printed onto a low cost resist layer, altering the chemical properties of the resist layer in these localized regions to make them permeable to etchants such as hydrofluoric Acid (HF). This facilitates the patterning or etching of underlying dielectrics or semiconductor material to facilitate a range of semiconductor processes. Importantly, the change in resist permeability is a reversible process making it feasible to return the resist to its original state after carrying our processes on the underlying material. This also opens the option to partially reverse the permeability to reduce the hole or feature size produced in the underlying material.

A particular exciting application of this inkjet technology work is for very high efficiency silicon solar cells. The University of New South Wales has held the world record for silicon solar cell efficiencies for the last 15 years, initially with the Passivated Emitter solar cell (PESC) and more recently with the Passivated Emitter and Rear Locally diffused (PERL) solar cell. Despite the performance and achievements of these two technologies, neither have been used commercially, apart from for space cells, primarily due to the sophistication, cost and complexity of the processes involved.
The photolithographic based processing is probably the main contributor to this. In this work, inkjet printing techniques have been developed for patterning low cost resist layers as a simple, much cheaper alternative to photolithographic based processing. These new approaches appear capable of achieving similar device performance levels but with the greatest challenge being to match the dimensions of features in the resist patterning achievable with photolithography. Test devices to date based on inkjet technology have achieved feature dimensions such as holes of 30-40 microns diameter as shown in the matrix of holes below. However, these dimensions need to be reduced to about 10 microns diameter to fully match the performance levels demonstrated with photolithographic based processing. New and innovative inkjet printing techniques have been recently developed for further reducing the resist patterning dimensions. This work is being greatly assisted by the recent availability of the new 1 picolitre inkjet heads.

Figure 4.7.9: 30-40 micron diameter holes formed by inkjetting.

4.7.5 Thin-film Crystalline Silicon on Glass Solar Cells

2006 has been an important year for this exciting new thin-film crystalline silicon on glass PV technology. Large scale production commenced at CSG Solar with first product sales taking place in midyear. In late 2006, CSG Solar was the recipient of the prestigious World Technology Award for Energy for its work with this technology. This award is sponsored by the New York Stock Exchange and was won ahead of a star-studded field including other leading PV companies such as First Solar. The Centre continues to collaborate with CSG Solar primarily in the characterisation and modelling areas. These activities are expected to expand as the company’s sales volume increases during 2007 and subsequent years.

4.7.6 Photoluminescent Imaging for Device and Material Characterisation

With the current growth in the photovoltaic industry and the trends towards higher cell efficiencies, generally achieved on lower quality and thinner silicon wafers, there is an increasing demand in research laboratories and in industrial manufacturing for fast and easy to use characterisation tools. Recent research at UNSW has established photoluminescence (PL) techniques as extremely fast and useful tools for the characterisation of silicon wafers and of silicon solar cells.
In particular this work has shown that luminescence imaging techniques give two dimensional high resolution images of electrical parameters such as the minority carrier lifetime shown below for a multicrystalline silicon solar cell, with data acquisition times on the order of typically only one second per measurement, which is orders of magnitude faster than any competing experimental techniques. High resolution images of other electrical parameters such as the series resistance or the shunt resistance are also feasible.

Figure 4.7.10:  Luminescence image of a completed multicrystalline silicon solar cell.

A prototype bench-top system established at the Centre is in heavy demand by various UNSW research groups and for consultancy projects and has helped identify a variety of unexpected processing problems and developing new processing sequences much more quickly than previously possible. In many cases the two dimensional information contained in PL images has given very easy to interpret clues about the origin of specific problems. The ability to measure a large number of samples in a short time is very beneficial in this context.

Collaboration with various industrial partners has also identified various processing problems previously unknown to the manufacturers. In addition, recent research at UNSW has shown how the luminescence imaging technique could be used for in-line process control, for example to remove the influence of shunts. Other potential industrially relevant in-line applications for luminescence imaging that are under investigation include crack detection, spatially resolved series resistance monitoring, quality control of raw material and process control of individual key processing steps such as the emitter diffusion. The collaborative work with various industry partners and several journal and conference publications have resulted in significant interest worldwide in the technique, specifically in a commercial PL imaging system. Several patents in relation to luminescence imaging have been filed and the commercialisation of the technology is currently being pursued through New South Innovations.