THE UNIVERSITY OF NEW SOUTH WALES

THE PHOTOVOLTAICS SPECIAL RESEARCH CENTRE IS A SPECIAL RESEARCH CENTRE OF THE AUSTRALIAN RESEARCH COUNCIL

THE KEY CENTRE FOR PHOTOVOLTAIC ENGINEERING IS A KEY CENTRE OF THE AUSTRALIAN RESEARCH COUNCIL

Cover Photo: Wind, Solar Powered Car & Building (G8 Building at Birmingham, Photo Courtesy of David Shepherd, BP Solar)
ANNUAL REPORT 1998

UNSW

PHOTOVOLTAICS GROUP

(Incorporating The 1998 Annual Report of the PHOTOVOLTAICS SPECIAL RESEARCH CENTRE and Introducing the KEY CENTRE FOR PHOTOVOLTAIC ENGINEERING)

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New Associate Directors

During 1998, the Centre made another high-level appointment by appointing Dr. Armin Aberle as Associate Director with special responsibilities for thin film cells and characterization. Dr. Aberle was formerly Head of the Photovoltaic Department at the Institute for Solar Energy Research (ISFH) in Germany.

Dr. Christiana Honsberg and Dr. Jianhua Zhao are to be appointed Associate Directors in Buried-Contact and High-Efficiency Device areas, respectively, in 1999.

Silicon Cell World Records

Three new world records for silicon solar cell performance were established by the Centre during 1998. A cell on a multicrystalline substrate set a new world mark of 19.8% efficiency, well above the previous record of 18.6%. Early in the year, crystalline cell efficiency was increased to above 24% for the first time with a further improvement to 24.5% later in the year.

Licensee Announces New Plant

BP Solar, the first to commercialize the Centre’s buried contact technology, made two major announcements relevant to this technology. Early in the year, it announced an expansion of its Madrid facility to 10MW/annum capacity, with the whole facility converted to the Centre’s buried contact technology during 1998. Later in the year, the company announced its plans for a new Sydney facility using this technology, initially of 20MW/annum capacity, one of the world’s largest, but expandable to 50MW/year capacity.

World’s First Photovoltaic Degree

At the end of 1998, Professor Stuart Wenham resigned as Associate Director of the Centre to take on a new position as Director of the Key Centre for Photovoltaic Engineering. The Key Centre will offer a degree program commencing in the year 2000 leading to a Bachelor of Engineering in Photovoltaics and Solar Energy, the world’s first undergraduate engineering degree in this field. This reflects the rapid growth in both manufacturing capacity and job creation in the photovoltaics industry, with the industry growing at more than 30% per year.

Pacific Solar Begins Pilot Production

Pacific Solar, a “spin-off” company from the Centre, announced pilot-production of 30cm X 40cm thin-film polycrystalline silicon-on-glass modules, commencing in July 1998 and its plans to have commercial product available by 2002. Pacific Solar is a $70million joint venture between the University and Pacific Power, a leading Australian utility.
Centre Accredited ISO 9001 Quality Standard

In November 1998 the “Advanced Cell Division” of the Centre achieved accreditation to International Quality Standard ISO 9001 “Quality Systems-Model for quality assurance in design, development, production, installation and servicing”. The Centre was one of the first groups within an Australian University to receive such accreditation.

1999 Australia Prize

At the end of 1998, Professors Martin Green and Stuart Wenham, Centre Director and former Associate Director, were advised that they were to be awarded the 1999 Australia Prize for their outstanding achievements in energy science and technology, the first all-Australian team to receive this award since 1992. The prize is an international award for specific achievement in a selected area of science and technology promoting human welfare. It was presented by the Prime Minister, The Honourable John Howard, during a special ceremony at Parliament House in February 1999.

Other Major Awards

In February 1998, the Centre received the prestigious Chairman’s Award at the 1998 Australian Technology Awards shared jointly with its “spin-off” Pacific Solar Pty. Ltd. The award, for the “one most excellent project, regardless of its nominated category” recognized the outstanding success in bringing thin-film polycrystalline silicon-on-glass cells to the stage of commercial readiness.

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Centre’s Business and Technology Manager Mark Silver with the Australian Technology Award.

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The Photovoltaics Special Research Centre at the University of New South Wales (UNSW) was established in 1990 to develop photovoltaic technology into a sustainable power generation option for the future. Photovoltaic or “solar” cells convert sunlight directly into electricity using quantum-mechanical interactions between this light and electrons in the semiconductor material used to make the cell.

If this technology is to displace less environmentally desirable coal-fired and nuclear power plants, the cost of photovoltaics must be reduced, the energy conversion efficiency improved and new applications for the cells developed.

The UNSW Photovoltaics Special Research Centre is at the forefront of international efforts in addressing these three key areas. The 1998 year covered by this report was again a year during which the Centre demonstrated outstanding achievements across all three of its key research areas.

Continued International Growth
The rapid growth rate of the international photovoltaic industry noted during 1997 was largely sustained during 1998 with 30% growth reported. Residential rooftop programs in Japan, Europe and the USA drove this growth, with over 10 GW of photovoltaics targeted for such applications by 2010.

1998 Centre Highlights
The major results achieved by the Centre are highlighted on the previous page. It would seem that 1998, the penultimate year of the Centre’s operation, has been the most successful yet across the whole range of Centre activities. Not only did the Centre continue to lead the world in high efficiency solar cell research, its licensees had outstanding success in commercializing Centre technology. Centre staff received several prestigious local and international awards and the professionalism of its activities was documented by ISO9001 accreditation.

Key Centre
Recognizing the rapid growth of the photovoltaics industry and its need for trained staff, a Key Centre for Teaching and Research in Photovoltaic Engineering was awarded to the University, commencing in early 1999. This Key Centre will offer the world’s first undergraduate program in Photovoltaics and Solar Energy, beginning in the year 2000. Professor Stuart Wenham resigned from Associate Directorship of the Special Research Centre at the end of 1998 to take on the role of Director of the Key Centre. As detailed in Professor Wenham’s accompanying report and elsewhere in this volume, the Key Centre will initiate strong new programs, particularly in the undergraduate and postgraduate teaching areas and in industry-initiated research.

Prospects for Beyond 1999
The Special Research Centre is entering its final year of operation and is due to terminate at the end of 1999. Mechanisms are being sought to allow the continuation of the Centre’s basic research activities and maintenance of the fundamental processing capabilities developed during the Centre’s operation. Invariably, a considerable winding-down of Centre activities is anticipated during the second half of 1999 to accommodate the reduced resources likely to be available past this date.

I thank all staff and collaborators for their contributions during 1998 and wish them well for the coming year.

Professor Martin A. Green,
Director,
Photovoltaics Special Research Centre.
An exciting new era has dawned for the photovoltaic industry with rapid growth of between 30 - 40% per annum in recent years creating new needs and rapid evolution. Some of the outcomes include massive increases in production capacity, demands for new or adapted technology and a growing need for trained engineers. These are stimulating new activities for the UNSW Photovoltaics Group. In particular, in the research area, several new collaborative research projects are to be or have been established with industry while in the educational area, our group will be establishing the world’s first undergraduate engineering degree in Photovoltaics and Solar Energy, commencing in the year 2000.

The strong track record of the photovoltaics group in conjunction with the rapidly evolving needs of the photovoltaic industry has led to the establishment of a Key Centre for Teaching and Research in the photovoltaics area, funded by the Australian Research Council. This new Centre is funded for a period of six years, with one of the primary aims being to become self-sustaining by the end of the funding period. This is one of only eight Key Centres awarded Australia-wide across all disciplines, indicating the growing importance of photovoltaics and Australia’s international leadership in the area. Australian manufacturers are already the largest per-capita worldwide, with the market share expected to continue to increase in the future.

The new educational initiatives of the Key Centre require the development of a range of new and innovative teaching aids and materials, many of which will be multimedia interactive CD-based presentations. Increasing emphasis will be placed on offering web-based courses via the internet and a promotional CD is to be produced to portray the calibre and scope of our courses. In the new degree program, considerable importance will be placed on providing students with hands-on experience with photovoltaic devices, modules and systems. The program will also cover the more general solar energy area and will provide students with a grounding in other renewable energy technologies, such as the use of wind generators, biomass and solar thermal systems.

The new industry-initiated research programs for the Key Centre cover a range of areas that includes thin film technology, conventional bulk devices, new generations of bulk technology, and photovoltaic systems research that particularly focuses on grid interconnection. With licensees of UNSW technology now including companies from most major countries, it is anticipated that new collaborative research programs will be established on an ongoing basis to suit the particular needs of each individual company, such as with regard to chosen substrate type and infrastructural/equipment constraints.

For the first time, our Centre is planning to embark upon training courses in photovoltaic processing in the areas of high efficiency devices and our commercially successful buried contact solar cell. In the past, such material has been disseminated only through technology transfers to licensees, but with most major manufacturers now licensees of UNSW technology, the above courses may form an essential ingredient in the training of all new photovoltaics researchers and engineers internationally.

The Key Centre activities focus primarily in two areas: collaborative research with industry that is conducted on a full incremental cost recovery basis; and teaching where the primary new initiative is the world’s first bachelor of engineering in Photovoltaics and Solar Energy. The latter is also being strongly supported by the Sustainable Energy Development Authority (SEDA) and The University of New South Wales.

S. Wenham
Professor Stuart R. Wenham, Director, Key Centre for Photovoltaic Engineering.
The Centre's three major work areas are the Photovoltaics Research Laboratory, the Device Characterization Area and the Power Electronics Laboratory. Systems work is also undertaken at the Little Bay Research Facility.

Photovoltaics Research Laboratory
The Centre boasts the largest and most sophisticated bulk silicon solar cell research facility in Australia. Laboratory space of 430 m² is located on 4 floors of the School of Electrical Engineering building and is serviced with filtered and conditioned air, appropriate cooling water, processing gas, de-ionized water supply, chemical fume cupboards and exhausts. There is an additional 474 m² area immediately adjacent to the laboratories for the accommodation of staff, research students and laboratory support facilities. Off site, areas totalling 200 m² are used for the storage of chemicals and equipment spare parts.

The laboratory is furnished with a range of processing and characterisation equipment including 37 diffusion furnaces, 5 vacuum deposition systems, 3 laser scribing machines, ellipsometer, microwave carrier lifetime system, rapid thermal annealer, four point sheet resistivity probe, quartz tube washer, silver, nickel and copper plating units, infrared and visible wavelength microscopes, 3 wafer mask aligners, spin on diffusion system, automated photoresist dual track coater, photoresist spinner, ion implantater, reactive ion etcher, electron beam and sputter deposition systems, and a laboratory system control and data acquisition monitoring system. Laboratory facilities are available for the growth of silicon films on both silicon and foreign substrates. Related services are also available through the Department of Electronics laboratories which are partly supported by the Centre. Additional facilities available in the latter laboratories include wafer prober and bonders and computer aided design for mask layout.

The PVSRC also owns equipment and has access to the new SNF, Semiconductor Nanofabrication Facility, this is a joint facility between Physics and Electrical Engineering and houses a microelectronics laboratory and a nanofabrication laboratory for e-beam lithography.

Additional equipment is available on the University campus, which is commonly used for cell work. Included in this category are electron microscopes, X-ray diffraction, surface analysis and photoluminescence equipment.

A computer network of 46 PCs, 1 Novell Server, 1 NT Server, 1 Intranet Server, 4 Macintosh, 1 Unix workstation and 1 Unix computer server support the device laboratory, simulation and Centre administrative activities. Another 20 PCs are dedicated for the computer control of laboratory equipment.

The device laboratories, Characterisation Area and adjacent facilities operate 24 hours per day, 365 days per year and are developed and maintained by the Laboratory Development and Operations Team. In 1998, the team, under the leadership of Mark Silver, comprised 6 full time and 2 part time employees, which include electrical, mechanical and industrial design engineers and technicians, a physicist, computer and network manager and administrative staff.

Over $0.5M has been earmarked for the upgrade of laboratory infrastructure such as exhaust and fume cupboards for 1999.

Device Characterization Area
Space in the basement of the Electrical Engineering Building was made available to the Centre by the University in 1995. The space contains a reception area, seminar room, library, offices for Centre staff interacting with the public and industry, including the Business & Technology Manager and Design Assistance Division Manager, computer workstations for the device modelling activities of the Centre, and the Device Characterization Area.
The Device Characterization Area houses characterization equipment including “Dark Star”, the Centre’s station for temperature controlled dark current-voltage measurements, the Centre’s Fourier Transform Infrared Spectroscopy system, Admittance Spectroscopy system, Ellipsometer, photoconductance decay equipment, infrared microscope and equipment for spectral response and related optical measurements.

**Power Electronics Laboratory**

This 40 m² laboratory is equipped with a range of power supplies for heavy current testing of DC-DC converters and inverters including a 60 V battery bank for remote area power supply testing. A range of test equipment is available including: high frequency oscilloscopes; true RMS meters up to 2 MHz response; current probes up to 1000 A and all the usual small metering equipment. The laboratory also has a number of microprocessor/microcontroller development systems which include TMS 320C25, and 80C196 systems which are particularly suited to power electronic applications. IBM-PC compatibles provide analysis software and printed circuit design and plotting systems. The laboratory also has access to programming facilities for a large range of programmable logic arrays.

**Little Bay Facility**

The Little Bay solar energy research facility (approximately 10 minutes drive from the main University campus) has been operating a grid connected PV system for over four years. The initial installation at the facility included a 3.8 kW array, battery systems and inverter connected to the local grid. Currently we have 3.8kW of BP and Solarex crystalline silicon arrays and a further 1kW of Canon amorphous silicon array (see Figure 3). These arrays are patchable to a large range of series-parallel configurations and are used for evaluating a variety of systems under actual operating conditions.

All the systems are being monitored by an extensive data acquisition system which logs environmental and electrical conditions of the systems under test.

A single axis tracking module test facility is also installed. Each module is connected to an electronic load which enables a complete current / voltage characteristic to be obtained. A data acquisition computer system controls the electronic loads and logs environmental conditions, module temperatures and electrical characteristics of the modules under test. The tracking system may be fixed in orientation or tracked to investigate module performance under both conditions.
High Efficiency Silicon Solar Cells

Senior Project Scientist:
Dr. Jianhua Zhao (project leader)

University Staff:
Prof. Martin Green, Prof. Stuart Wenham

Project Scientist: Dr. Aihua Wang

Visiting Fellow: P. Altermatt

Researcher: Fei Yun

1998 Objective - Improving PERL Cell Efficiencies

The major objective in 1998 for the high efficiency group was to further improve the efficiency of PERL (passivated emitter, rear locally-diffused) cells and modules, and also to demonstrate high performance on multicrystalline silicon substrates. The 1998 objective for the high efficiency group has been fulfilled with the demonstration of 3 new world record performances by mono-crystalline and multi-crystalline silicon cells. Another record matching performance was also demonstrated by a photovoltaic module with PERL cells.

Improved High Efficiency PERL Cells

Figure 5 shows the PERL cell structure, which had previously demonstrated a record AM1.5 efficiency of 24.0% for silicon cells in 1994. In 1998, the PERL cells have been redesigned to reduce the metallisation shading loss and metal resistance loss.

The history of the efficiency evolution for silicon solar cells is shown Figure 6. With the new cell designs, the efficiency records of silicon solar cells were broken twice by PERL cells fabricated at the Centre in 1998. The picture frame cells demonstrated 24.4% efficiency in February, 1998 and 24.5% in December, 1998.

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Figure 6: Efficiency evolution for silicon solar cells.

Table 1 lists the performance of these record-breaking PERL cells. One major improvement came from the improved short-circuit current densities of these cells. These resulted from the reduced metal shading loss of the new cell design. Improved equipment for the deposition of antireflection coating may have also contributed to this current improvement. The fill factor of the cells was also significantly improved without the need of the previous double-metal plating technique.

It was unfortunate that WLT2-3B had a markedly lower fill factor than the previous cell Wh06-3A. It is believed that a processing problem caused this lower fill factor. It was inferred that WLT2-3B would have demonstrated an efficiency of 24.8%, if it had not encountered this low fill factor problem.
19.8% Efficient ‘Honeycomb’ Multicrystalline Silicon Cell

After demonstrating an 18.2% efficiency by a planar multicrystalline cell in the previous year, research on multicrystalline cells concentrated on texturing techniques for the multicrystalline silicon substrates. A technique called ‘honeycomb’ texturing has significantly reduced cell surface reflection and improved the cell efficiency. Figure 7 shows the structure of these honeycomb cells. Except for the surface texturing, these honeycomb multicrystalline silicon cells have been processed similarly to the single crystalline PERL cells. Contrary to the traditional belief that low temperature processes were required for multicrystalline silicon, the high temperature PERL process (over 1000°C) did not destroy substrate properties.

A multicrystalline PERL cell of 1 cm² area has been measured at Sandia, demonstrating a record efficiency of 19.8%. Table 2 shows the performance of this honeycomb cell compared to a previous planar multicrystalline cell.

<table>
<thead>
<tr>
<th>Cell ID</th>
<th>Substrate</th>
<th>Cell Surface</th>
<th>$V_{oc}$ (mV)</th>
<th>$J_{sc}$ (mA/cm²)</th>
<th>FF (%)</th>
<th>$E_r$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WD4-2-4D</td>
<td>Eurosolare</td>
<td>Honeycomb</td>
<td>654</td>
<td>38.1</td>
<td>79.5</td>
<td>19.8</td>
</tr>
<tr>
<td>WD3-4B</td>
<td>Crystal Systems</td>
<td>Planar</td>
<td>643</td>
<td>34.5</td>
<td>82.0</td>
<td>18.2</td>
</tr>
</tbody>
</table>

Table 2. The performance of 1-cm² multicrystalline silicon cells tested at Sandia, under the standard 100 mW/cm² AM1.5 global spectrum at 25°C.

Most of the efficiency gain from the honeycomb cell over the previous planar cell came from the improvement in the cell current density. The honeycomb texture not only reduced the surface reflection, but also improved the light trapping performance of these cells. Figure 9 compares the surface reflection and external quantum efficiency of these two types of cell, and of a high efficiency crystalline PERL cell. It is clearly seen in Figure 9 that most of the reflection and quantum efficiency gain for the honeycomb cell over the planar multicrystalline cell is in the infra-red wavelength range, where the light trapping performance is a dominant factor.

Figure 7: Honeycomb textured multicrystalline silicon cell.

(a)                                           (b)

Figure 8: Details of the honeycomb textured cell surface.

Figure 9: The hemispherical surface reflection and the external quantum efficiency of the honeycomb textured cell (red curves), the planar multicrystalline cell (green curves), and the high efficiency single crystalline PERL cell (blue curves).
Novel Light Trapping Designs

New light trapping designs have been proposed to improve the PERL cell performance. Figure 10 shows the structure of these new designs. Figure 10(a) shows two sets of differently sized inverted pyramids. The different sizes allow offsetting of the pyramid locations, improving the trapping of the incident light. Figure 10(b) shows the perpendicular grooves on the same side of the wafer (“quiltwork” pattern). This allows the obliquely transmitted light (entering on one set of groove walls) to return to the front surface in the areas with grooves perpendicular to the entry grooves, assuming a good rear flat mirror surface and a properly designed cell thickness. This makes nearly all the light remaining trapped in the substrate after 2 passes. The initial experiments on these new light trapping structures did not give the expected clear advantage in cell performance. More experiments are needed to further investigate these new light trapping structures.

Improvement in Silicon Module Research

Large area PERL cells have demonstrated 23.7% AM1.5 efficiency. Two one-square-foot flat-plate modules made from 40 such cells have demonstrated record high efficiencies of 22.3% and 22.7% in 1996. These were the highest efficiency ever reported for a large area photovoltaic module made on any material. A third module with improved cell efficiency and improved encapsulation materials was fabricated in 1997. Unfortunately, this module had an unexpected soldering problem. One of the cells was completely disconnected in the module. This defect was repaired by drilling holes into the back of the module and rewiring the cells. This method caused an increased series resistance. Hence, the module gave a significantly lower fill factor than expected from the average fill factor of the constituent cells. Hence, 22.7% efficiency was measured at Sandia National Laboratories, which matched the previous record for module efficiency.

However, it was clear that the optics of the last module had been significantly improved giving markedly improved short-circuit current density. Hence, the module was estimated to have a potential 23.2% efficiency, if the module could have kept the fill factors marginally higher than the average cell fill factor, which was the case for the previous two modules.

Investigation of Improved Coatings

A plasma system has been set up for Si₃N₄ deposition. A preliminary experiment has demonstrated the same cell performance as with the standard ZnS/MgF₂ antireflection coatings. The plasma damage to the surface can be passivated by a later aluminium anneal. Further experiments are to be conducted to reduce this surface damage. Use of a remote plasma system is also expected to completely eliminate this surface damage problem.
Invited Centre Paper

The Centre was invited to present the “Peter Glaser Lecture” at the 49th International Astronautical Congress, Sept 28- Oct 2, 1998, Melbourne, Australia. Dr Jianhua Zhao presented this paper entitled: “High Efficiency Silicon Space Solar Cell Research at the University of New South Wales”. The paper attracted wide attention at the conference.

The paper was presented in the Solar Power Satellite (SPS) session of the congress, and NASA has recently restudied this concept. It believed that the SPS concept is much more practicable than 30 years ago, when first proposed. Some delegates to the conference were discussing a 16% global power supply using SPS by 2050. NASDA has started investigating the possibility of making some small SPS systems for remote areas in developing countries.

Based on the increasing demand for high efficiency space solar cells, the high efficiency group at the Centre has also redirected some of its research activities towards space solar cells. This program has been granted funding by the Australian Research Council. One of the goals of this program is to demonstrate 22% AM0 efficiency on silicon. The EOL (end of life) efficiency is also expected to be over 15% after $1 \times 10^{15} \text{ e}/\text{cm}^2 1 \text{ MeV}$ electron radiation damage.

Theory and Modelling

University Staff: Prof. Martin Green, Prof. Stuart Wenham, Dr. Armin Aberle, Dr. Gernot Heiser

Research Fellows: Dr. Pietro Altermatt, Dr. Richard Corkish, Dr. Alistair Sproul

Graduate Students: Donald Clugson (PhD), Om Kumar Harsh (Masters), Daniel Krcho (PhD)

Research Assistants: Volker Henninger, Tobias Kiesewetter, Tom Oates

Visiting Students: Frank Geelhaar (PhD), Marco Lammer, Axel Neisser (Diplomarbeit), Holger Neuhaus, Jürgen Schumacher

EBIC Modelling

We used the numerical simulator Dessis to simulate electron-beam-induced current experiments. We improved the accuracy of the numerical model, and compared the model with an analytical expression for the solar cell current resulting from an electron beam scanned across a grain boundary. The numerical model is being used to investigate realistic physical situations for which analytical models do not exist or are insufficiently sophisticated to correctly describe the real case. For instance, our numerical modelling has quantified the error introduced by neglect of the junction region in a frequently-used method for extracting grain and grain-boundary parameters from experimental EBIC data. Figure 11 shows the simulation mesh used to model a solar cell segment containing a grain boundary and illuminated by an electron beam.

Figure 11: Electron density in a silicon solar cell segment irradiated by an electron beam near a grain boundary.
Quantum Wells
We are studying the theory of quantum wells in solar cells. The introduction of quantum wells, extremely thin layers of a different semiconductor whose band gap is smaller than the host cell’s, into the active regions of solar cells, holds out the promise of potential efficiency increases. Quantum wells are already extensively used in other opto-electronic devices, such as lasers and infrared detectors, but their potential benefits in solar cells remain controversial. Theoretical work in the Centre has shown that, under the most beneficial assumptions, quantum well cells could slightly exceed the ultimate efficiency of other two-contact, two-bandgap cell structures. This year UNSW took delivery of a new semiconductor device modelling program which can simulate the behaviour of quantum wells and heterojunctions including so-called “hot” carriers. This program will be used in 1999 to carry out more realistic simulations of these devices than has been possible previously.

Recombination in the Depletion Region
We have been investigating recombination properties of depletion regions, especially for thin film applications. Currently we are setting up an experiment to analyse the distribution and capture cross-section of defects by means of admittance spectroscopy. This experiment is being used to investigate recombination centres in thin films, multicrystalline solar cells and highly doped test devices.

Doping Effects
We are working on a consistent set of silicon material parameters for the numerical simulation of crystalline silicon devices. In recent years we improved the set for low and medium doped crystalline silicon. This year, we have been investigating high doping and high-injection effects.

Auger Recombination
In the context of finding a consistent parameter set for the simulation of highly injected silicon devices, the ambipolar Auger recombination coefficient is being investigated. It is influenced by the presence of excitons. We are setting up a measurement facility to measure the recombination rate at injection densities up to $2 \times 10^{18}$ cm$^{-3}$, where no excitons exist. In order to find a value for the ambipolar Auger coefficient that is consistent with device parameters used in numerical modelling, we simulated the well-known Auger experiment of Sinton & Swanson, in collaboration with Dr. Ronald Sinton, Colorado, USA. In these simulations, we are applying the band gap narrowing model of Schenk as well. We demonstrated that free-carrier induced band gap narrowing is an important physical process in highly injected solar cells that needs to be included in the determination of the ambipolar Auger coefficient.

At high doping levels, the transport properties (as for example the free carrier mobility) need not be refined because they have been already investigated by other members of the Centre and by other groups around the world in previous years. However, the density-of-states (DOS) has not yet been quantified to satisfactory precision. In device simulation, the DOS of non-doped silicon is used at all doping densities, although an impurity band is formed at doping levels above $1 \times 10^{19}$ cm$^{-3}$, lowering the Fermi energy considerably. To extract the DOS from published photoluminescence measurements, we used a model for carrier-induced band gap narrowing recently developed by Dr. Andreas Schenk from ETH Zurich, who spent three weeks as a visiting researcher at the Centre. The model was implemented into the numerical simulator, Dessis. With the DOS data obtained, we resolved discrepancies between various measurements of the activation energy of dopants and, hence, we are able to compute the electron density of phosphorus doped silicon as a function of temperature with unprecedented accuracy. We also calculated incomplete ionisation and demonstrated that the Hall measurement technique, applied for determining the free-carrier density, is significantly affected by incomplete ionisation. With the DOS values, we also calculated the absorption edge of highly doped cells. Currently, we are performing tunnelling measurements of the DOS in phosphorus and boron doped silicon to complete the data.
Simulation of $J_o$
In contrast to analytical models, numerical simulations need no saturation current $J_o$ as input parameter. However, $J_o$ is a commonly determined experimental parameter. We are simulating various experimental techniques to measure $J_o$. It was found that there is a significant difference in $J_o$ among various measurement techniques. The simulation of $J_o$ is especially sensitive to the applied band gap narrowing models.

Optical characterisation
We are working in the area of optical characterisation of solar cell materials - particularly Fourier Transform Infrared Spectroscopy (FTIR). We are applying new and refining existing techniques, e.g. attenuated total reflectance (ATR), photothermal ionisation spectroscopy (PTIS), interferogram techniques, Kramers-Kronig analysis and infrared microscopy, to characterise impurities, free carrier behaviour, thin and layered sample properties.

Thin Film Solar Cells
University Staff:
Dr. Armin Aberle (project leader since 11/98), Prof. Martin Green, Prof. Stuart Wenham

Research Fellows:
Dr. Pietro Altermatt, Dr. Patrick Campbell, Dr. Mark Gross, Dr. Mark Keevers (project leader multilayer cells), Dr. Tom Puzzer, Dr. Alistair Sproul (project leader until 11/98), Dr. David Thorp (until 11/98)

Research Fellows:
Matthew Boreland, Oliver Nast, Daniel Krcho (all PhD)

Research Assistant: Holger Neuhaus

The primary aim of the thin-film group is to investigate polycrystalline thin-film silicon solar cells on glass, an approach that is widely recognised as being a pathway towards substantially lowering the cost of solar cells. These activities are complementary to those of our “spin-off”, Pacific Solar, and do not necessarily involve the same approaches as being commercialised by this company. In 1998, our main areas of work have been the crystallisation of amorphous silicon (a-Si) films on glass at low temperature (< 600°C) using metal-induced crystallisation and laser crystallisation, as well as the characterisation of the resulting polycrystalline silicon films. To date we have been primarily interested in a-Si films deposited via sputtering, due to the ease of scalability and the potential for low cost. In addition, we are performing detailed experimental investigations of performance constraints in the multilayer thin-film silicon solar cell, a novel device structure conceived at UNSW and presently being commercialised by Pacific Solar.

Metal-induced Crystallisation of Amorphous Silicon
The metal-induced crystallisation approach exploits the fact that a-Si crystallises in contact with certain metals at temperatures well below the usual crystallisation temperature. In the case of Al, crystallisation temperatures as low as 150°C have been reported. In 1998, our research on Al-induced crystallisation (AIC) of a-Si on glass has led to a major technical advance.
Using sputtered a-Si on Al, continuous, large-grained poly-Si films of uniform thickness (~0.5 µm) have been realised on glass at annealing temperatures of only 500°C.

Figure 13 shows scanning electron microscope (SEM) pictures of a typical sample before and after the 30 minute annealing step at 500°C. Note that the Si and Al layers change places during the AIC process. The striking feature of this plot is the exceptional structural quality of the polycrystalline Si film. The poly-Si films fabricated this way were found to be heavily p-doped (~0.04 Ωcm), presumably due to the presence of Al. From these results it can be concluded that the AIC method is extraordinary in terms of the nature of the growth process, required temperature, quality of crystal grown, ability to tolerate interfacial oxide, simplicity, and potential for low cost.

While it appears difficult at present to use AIC for the growth of a sufficiently thick film for solar cell applications (several microns) or even for p-n junction formation, the poly-Si films created by AIC are well suited to serve as a seeding layer for the subsequent deposition of 'thick' poly-Si films. The reason is that the Al film on the poly-Si films can easily be etched away. Figure 14 shows a SEM picture of an AIC-treated sample after etching off the Al film. It can be seen that, in addition to the poly-Si film of uniform thickness (0.5 µm), there are separate crystals protruding from the surface with a diameter of several hundred nanometres. Using energy-dispersive x-ray spectroscopy (EDS), these crystals were identified as silicon. Due to their large surface area, a suitable chemical etch will eliminate these crystals with little sacrifice in the thickness of the underlying poly-Si seeding layer.

**Figure 13: SEM picture of (a) the a-Si/Al/glass structure before annealing and (b) the Al(+Si)/poly-Si/glass structure resulting from a 30 min anneal at 500°C.**

While other methods that are principally suited to the fabrication of silicon seeding layers on glass generally lead to crystal sizes of only about 1 µm, the polycrystalline silicon films produced in the Centre by AIC exhibit crystallites with very large lateral dimension (typically above 20 µm!). This large grain size and the fact that continuous poly-Si films can be grown on glass over large areas shows that AIC-produced films are highly promising seeding layers for the fabrication of high-quality polycrystalline silicon films on glass.

**Laser Crystallisation of Amorphous Silicon Using Copper Vapour Lasers**

The copper vapour laser (CVL) provides a pathway to relax some of the sample restrictions encountered by excimer lasers, and allows reapplication of the techniques developed for excimer lasers. Using a CVL focused spot, combined with low temperature substrate heating (<300°C) to control the solidification velocity, grain sizes up to 0.44 µm have been achieved, with an area weighted average up to 0.24 µm. These grain sizes, which are comparable to reports using excimer lasers on much thinner films, were achieved on 1 µm thick PECVD a-Si on quartz substrates, making the CVL approach potentially interesting for photovoltaic devices.

**High Resolution EBIC Imaging of Polycrystalline Silicon Solar Cells**

Another area of work during 1998 has been the development of an imaging technique capable of characterising recombination activity in thin-film polycrystalline silicon solar cells. Conventional electron beam induced current (EBIC) imaging is routinely used to characterise recombination at grain boundaries and other defects in large-grained polycrystalline silicon solar cells. However, to date very little work has been done in applying this technique to materials with grain sizes of the order of 1 µm.
The approach we have taken is to use low-energy electron beams (typically 2 - 5 keV) instead of the more typical 20 - 30 keV. Lower electron energy means that the excitation volume within the silicon is smaller, and can have a diameter of less than 1 μm. This allows higher lateral resolution, and for solar cells with a high response, excellent low-noise imaging is possible. The capability of this technique is demonstrated by Figure 15, which shows a high-resolution EBIC image of intersecting grain boundaries in a conventional large-grained polycrystalline silicon solar cell.

As part of this work we also found that by combining the information obtained from a conventional SEM image with an EBIC image we were able to identify regions within the EBIC image that were influenced by topographic effects rather than carrier recombination. A clear example of this is shown in Figure 16. Figure 16(a) shows a conventional single-crystalline silicon solar cell with a textured surface viewed at normal incidence using a SEM. In this image the valleys are dark and the peaks are bright, indicating low and high backscattering of electrons, respectively. In the corresponding high-resolution EBIC image (Figure 16(b)) of the same area the contrast is reversed. This EBIC contrast is not due to recombination differences but is simply a result of the sample topography. At the peaks, more of the electrons from the beam are backscattered. As a result they do not generate as many electron-hole pairs in the silicon as would be expected for a flat surface. Hence, the EBIC signal at this point is low. The reverse argument holds for the ‘valleys’.

We have made extensive use of this technique to characterise a wide variety of small-grained polycrystalline thin-film silicon solar cells from our laboratory, from overseas research laboratories, as well as from commercial manufacturers. As an example, Figure 17 shows the SEM image and the high-resolution EBIC image of a cell provided by Dr. Ralf Bergmann from the University of Stuttgart, Germany. The investigated cells generally exhibited good EBIC response, however, we were able to identify small clustered regions where the EBIC signal was low. Our investigations clearly showed that these low EBIC signals were not correlated with the sample topography.
Characterisation of Thin-Film Silicon by FTIR Spectroscopy

Fourier transform infrared (FTIR) spectroscopy is a very useful technique for the characterisation of thin films of silicon and associated materials deposited on various substrates. In the infrared, many impurities such as hydrogen and oxygen exhibit quite strong absorption. Additionally, in IR spectroscopy this absorption occurs at specific frequencies, depending on the chemical nature of the impurity, allowing the identification of the bonding arrangement of the impurity in the material.

Typically, films are deposited on silicon wafers, glass, or metal substrates. Room temperature transmission measurement is used to determine the oxygen and hydrogen content and bonding configuration in amorphous and polycrystalline silicon and silicon nitride films deposited on silicon wafers. Periodic baseline patterns due to multiple reflections in the film are used for film thickness and/or refractive index determination. The baseline is modelled and the film spectrum retrieved. An example of such a measurement for an a-Si film deposited on a crystalline silicon wafer is shown in Figure 18. The H concentration can be determined from the magnitude of the Si-H absorption peak at 2000 cm⁻¹, as well as the film thickness and refractive index from the period and magnitude of the maxima and minima present in the baseline spectrum. The sharp absorption peaks in the vicinity of 1000 cm⁻¹ are due to the c-Si substrate.

Light trapping and reflection control in thin-film silicon solar cells

Light trapping and reflection control is crucial for highly efficient thin-film polycrystalline silicon solar cells. We are developing techniques to emboss surface textures at the silicon/glass and glass/air interfaces, and have begun pressing glass specimens with textured silicon masters. We are also studying photoconductance methods to spectrally characterise light trapping, and are evaluating the effectiveness of novel pigmented dielectric reflectors.

Fabrication and Characterisation of Multilayer Thin-Film Silicon Solar Cells

The multilayer thin-film cell, shown in Figure 19, theoretically enables high efficiency on low-cost, very-poor-quality polycrystalline silicon. The cell structure is theoretically tolerant of both impurity and grain boundary effects, with efficiencies over 15% predicted for devices less than 10 µm thick on 10 ns lifetime silicon. The work described here is the first detailed experimental study of the multi-layer cell, outside the commercialisation efforts of Pacific Solar. Since this study has more of a focus on fundamentals, the multilayer cells are fabricated from chemical vapour deposition (CVD) epitaxial layers grown on inert silicon wafer substrates (rather than the glass substrate/superstrate of Fig. 19).
In 1998, the focus of our work has been the design and fabrication of high-efficiency, truly parallel-connected multilayer cells, that is, cells with all layers of the same doping type connected in parallel. With the fabrication techniques used, this has proved to be a significant challenge, much greater than was the previous fabrication of 17.6% efficient pseudo-multilayer cells containing many ‘floating’ (unconnected) layers. The present cell design consists of 1 cm² mesa-shape devices separated by 25 µm deep isolation trenches, with interdigitated n- and p-type buried contact grids of about the same depth defined by photolithography and wet chemical etching (or, alternatively, by laser scribing). The cells consist of n-p-n-p-n epilayers (doped 10¹⁷ cm⁻³, respectively; total thickness 17 µm) on a 15 µm thick p⁺ buffer layer (doped > 10¹⁸ cm⁻³) grown on a 0.01-Ωcm single-crystal p⁺ CZ silicon wafer.

Aside from some practical processing obstacles that had to be overcome, the major processing achievement in 1998 has been the development of a photolithography sequence compatible with the device’s 25 µm vertical features.

Optimisation of the cell design and processing sequence has required detailed characterisation of the fabricated cells. This has included current-voltage (I-V) measurements (light, dark, Jsc-Voc), suns-Voc, quantum efficiency, focused ion beam (FIB) and EBIC, as well as device modelling using PC-1D. Figure 20 is an example of the detective work used to optimise the processing sequence. It shows a cross sectional EBIC image of the top corner of a p-type finger of a multilayer cell. The clean cross section was obtained by milling a well-defined trench into the cell using the FIB.

The figure clearly shows three (of the five) p-n junctions, the extent of the p⁺ groove diffusion, and the electrolessly plated metal layers.

Successful parallel connection of the p-type layers is evident. Additional FIB images (not shown) revealed that the insulating oxide barrier does prevent the metallisation from shunting the topmost p-n junction.

Using the above-mentioned approach, multilayer cells with efficiencies exceeding 10% have been fabricated in 1998. Future work aims at the fabrication of a sufficient quantity of highly efficient multilayer cells for systematic studies of the impact of material quality on device performance, with material quality controllably degraded using proton irradiation. These experiments also enable the assessment of the suitability of silicon multilayer solar cells for space applications.

Buried Contact Solar Cells

University Staff:
Prof. Martin Green, Dr. Christiana Honsberg (project leader), Prof. Stuart Wenham

Researchers:
Dr. Jeff Cotter, Dr. Ximing Dai, Dr. Hamid Rezah Mehrvarz

Graduate Students:
Linda Koschier (PhD), Keith McIntosh (PhD), Bryce Richards (PhD), Stephen Pritchard (PhD), Alexander Slade (PhD), Bernhard Vogl (Masters)

Undergraduate Students:
Gurbir Deol, Gaurav Naik, Tee Hain Teo, Leong Theng Wei

The primary objective of the buried contact silicon solar cell research is the development of new solar cell processes and structures that enhance the economic viability of silicon solar cells. Established buried contact solar cell technologies continue to enjoy considerable success, both in the laboratory and in the commercial market. This year, a new licensee, Eurosolare, joined the family of buried contact licensee. Eurosolare, whose parent company is the major oil company Agip (ENI S.pA.), is a major European solar cell manufacturer, and plans to use the buried contact technology to realise efficiency improvements in multicrystalline wafers. The buried contact modules produced by the other European licensee, BP Solar, are still the highest efficiency commercial silicon module produced and these modules are coming under interest for building integrated applications. Figure 21 shows a building integrated application using buried contact solar modules produced by BP Solar.
Double Sided Buried Contact Solar Cells

The double-sided buried contact solar cell shown in Figure 22 offers a commercially realistic method to enhance the performance of the rear surface in commercial solar cells by using the floating junction passivation technique in combination with laser-scribed rear groove contacts. Floating junction passivation and its close relative, inversion layer passivation, have shown exceptional levels of rear surface passivation, and world record open-circuit voltages have been achieved using floating junction passivation. An additional key advantage of both inversion layer and floating junction passivation is that they can be easily used in a bifacial solar cell, and the key aim in 1998 was to demonstrate the suitability of floating junction passivation in a bifacial silicon solar cell.

A central issue in the use of floating junction passivation that has hindered development is the presence of a parasitic shunting mechanism, which introduces an injection level dependence in the effective rear surface recombination. However, both modelling and experimental measurements demonstrate that the effect of this parasitic shunt can be eliminated in a commercial solar cell, particularly by using bifacial illumination. Modelling in Figure 23 demonstrates that under even moderate bifacial illumination, the presence of a moderate shunt resistance becomes insignificant. For example, at rear illumination levels above 0.3 suns, a shunt resistance of only 200 $\Omega \text{cm}^2$ allows over 95% of the maximum rear power to be collected from the solar cell. While these modelling results demonstrate a desirable insensitivity to the shunt resistance, experimental SEM/EBIC observations suggest that the shunt resistance can be eliminated. The combination SEM/EBIC micrograph in Figure 24 suggests that the collecting region around the rear groove is not shunted. Furthermore, solar cells fabricated on high resistivity wafers (5 $\Omega \cdot \text{cm}$) had voltages in excess of 650 mV from both the front and rear, bifaciality factors of 94% (which is higher than any previously reported for solar cells using no photolithography) and high transparency from both front and rear through the use of a buried contact grid on both sides. These results demonstrate that a high efficiency, bifacial solar cell using laser-defined grooves and floating junction passivation can be produced.
Simplified Buried Contact Solar Cells

The simplified buried contact solar cell uses a number of innovations in the processing sequences to reduce the cost of fabrication while retaining the efficiency advantages of the buried contact technology and is designed especially for Czochralski and multicrystalline wafers. While a multitude of simplified buried contact processing sequences can be envisioned depending on the particular silicon parameters, work in 1998 focused on a simplified buried contact process for low to moderate quality silicon wafers such as multicrystalline wafers. For such wafers, the performance benefit of a selective-emitter process begins to vanish because the open-circuit voltage becomes dominated by the dark saturation current of the base region, especially for bulk lifetimes less than about 50 µs. This effect is illustrated in Figure 25, which compares the efficiency of the two emitter structures and shows that the single-step emitter is capable of the same efficiency as the selective emitter structure.

Experimental results from silicon mc-Si wafers demonstrate the feasibility of achieving high efficiencies using a homogenous emitter. Experimental measurements on homogenous emitters, with emitter and groove diffusions at 50 to 100 Ω/□ and metallised grooves, gives combined emitter and groove saturation currents below 2.5 x 10⁻¹³ A/cm². These saturation currents are consistent with open circuit voltages in excess of 650 mV, thus allowing a mc-Si or CZ solar cell to remain limited by the electrical parameters of the base of the solar cell. Titanium dioxide plays a key role in allowing the homogeneous emitter to be used in the simplified buried contact process, replacing silicon dioxide as the primary front surface coating. The surface passivation of titanium dioxide is therefore of primary importance. Figure 26 shows the emitter saturation current density measured on diffused multicrystalline wafers with various titanium dioxide coatings. By careful choice of the emitter resistivity or by the use of an intermediate silicon dioxide layer, the emitter saturation current density can be controlled enough to allow open-circuit voltages in excess of 650 mV.
University Staff: Associate Prof. Hugh Outhred, Dr John Kaye
Project Staff: Dr Muriel Watt, Mark Ellis, Dean Travers (PhD), Iain MacGill (PhD)

Staff contributed to a range of activities during 1998 associated with electricity industry restructuring with the objective of ensuring that the restructured industries will be both economically efficient and sustainable. Particular attention continues to be given to the role of distributed resources. Highlights include:

- A visit by Professor Tim Mount, Director of the Cornell Institute for Social and Economic Research as Honorary Visiting Professor for the period January - June 1998. The purpose of this visit was to investigate electricity industry restructuring and sustainability in the Australian context.
- The provision of advice to the South Australian Government on the facilitation of distributed resources in the context of electricity industry restructuring.
- The submission of PhD theses by Iain MacGill and Dean Travers, which addressed issues associated with the interaction of distributed renewable energy generators with electric power systems.
- Finalisation of a study on photovoltaics in buildings commenced in 1997.
- The appointment of Hugh Outhred to the National Electricity Tribunal and continuation of his appointment to the NSW Licence Compliance Advisory Board (LCAB). The LCAB’s 1998 annual report discusses the environmental outcomes for the NSW electricity industry for the first time. Future annual reports will discuss progress by retailers in meeting their environmental targets and distributors in meeting their least-cost planning obligations.

System Hardware and Performance Monitoring
University Staff: Ted Spooner
Project Staff: Greg Harbridge

The systems hardware and monitoring strand covers a wide range of activities related to the interfacing of PV to other systems. Of particular interest are Remote Area Power Supply (RAPS) and grid connected systems as these are going to be major uses for PV in the future.

Grid Connected System Monitoring
Grid connected Photovoltaic systems are being monitored at our Little Bay Energy Research Facility. The performance of arrays and inverter systems under actual operating conditions continue being analysed in a long term study for energyAustralia.

Module testing
Comparison of performance of modules under actual operating conditions is being carried out at Little Bay. Modules under test are mounted on a single axis tracking system. Each module is connected to an electronic load which enables a complete current / voltage characteristic to be obtained. A data acquisition computer system controls the electronic loads and logs environmental conditions, module temperatures and electrical characteristics of the modules under test. The data gathered is being analysed to investigate the long term performance and temperature coefficients of modules under test.
Standards Development

The development of standards is an important area which influences the acceptability and uptake of technology. We are currently involved in the development of Australian Standards for remote area power supply systems. An Australian Standard for “Stand-alone Power systems parts 1 and 3 are being published now, with part 2 still under revision. “Australian guidelines for grid connection of energy systems via inverters” has been developed in conjunction with the Electricity Supply Association of Australia and will next year undergo a major review.

The standards area will expand in the future in conjunction with Standards Australia to cover individual system components safety and performance requirements, and grid connected systems.

Olympic Athletes Village

The Centre has played an important role of consultation and testing for Pacific Power and energyAustralia on grid connection issues related to the Olympic Athletes Village. The village will contain 665 houses, each with 1kW peak of PV, connected to the grid via small inverter systems. A major section of the village is now complete and is connected to the grid and exporting power.

PV Simulator

Design and implementation of six, 1kW (100V 10A) solar simulators is now complete. The solar simulators have been modelled to have I-V characteristics of PV modules. The simulator power supplies are configurable in series and / or parallel to allow operation from 100V, 60A to 600V, 10A. Computer control facilities allow the output to represent ‘real’ solar day output profiles. The simulators allow control of the output current and the maximum power point voltage in real time. This will enable evaluation of maximum power point tracking performance of inverter and regulator systems.

International Contacts

Important links have been established in the area of PV standards for grid connected systems with: IEEE Standards, IEC Standards, NREL (US), UnderWriters (US), KEMA (Netherlands), EcoFlys (Netherlands), Sandia National Labs (US), Fraunhofer-Institut fuer Solare Energiesysteme (Germany), and New Energy Development Organization - NEDO (Japan).

Ted Spooner is a member of the IEC TC82 committee systems working group.

International Visitors

Dr Peter Zacharias Institute for Solar Energie Technologie visited from 2nd March to 16th April. Peter assisted with the Olympic village project and collaborated in harmonic simulation of grid connected inverter systems, and participated in discussions with Pacific Solar. He also presented two seminars: “Modular PV- and Hybrid Energy Supply Systems” and “Miniaturisation and Integration of PV Inverter Technology”.

Stefan Janssen and Laurens Peeters were visiting Non-Award Practicum students who have participated in the construction of a PV simulator.

External courses

Energy Beyond 2000 Applied PV 2 day course taught through IPACE, Unisearch Ltd., to US students (July 1998).

Inverter and regulator testing 2 day course taught through IPACE, Unisearch Ltd., to Indonesian Engineers (Nov 1998).
Education and External Activities

University Staff:
Robert Largent, David Roche, Dr Christiana Honsberg, Paul Rowley

Australian Short Courses

Short courses in energy efficiency and renewable energy for building companies, school and community workshops and local government forums have all contributed to a successful portfolio of education and training programs at the Centre. These programs are supported by strong research foundations; currently, projects involving energy management and policy development, along with technological aspects of renewable energy generation are in progress at the Centre.

Education and training activities have also involved cooperative project development with a number of State and Commonwealth bodies, such as the Sustainable Energy Development Authority and the Australian CRC for Renewable Energy (ACRE). Additionally, the Centre’s education and training facility has won a number of consultancy contracts. These include development of SEDA’s Energy Smart Homes Training program and short course provision for industry groups.

Internet and CD based Course Materials

The Centre is at the leading edge of program delivery technology - its work in developing Internet and World Wide Web-based education programs and learning networks has gained international recognition, including the involvement of the BBC On-line in its development.

An internet based “Applied PV” course was run in 1998, in conjunction with ACRE for 35 students worldwide. Course material was supplied via CD-Rom and tutoring via internet. Six students subsequently undertook an in-house supplementary course, allowing hands-on laboratory and computing work. The course will be offered again in 1999.

Work continues on CD-ROM teaching materials, initially based on the Centre’s Applied Photovoltaics undergraduate course. The aim is to be able to use the CDs at different levels, catering for high school, undergraduate and postgraduate PV courses.

International Short Courses

The PVSRC conducted a three week intensive course in Applied Photovoltaics for high level engineers and policy makers of Indonesia’s BPPT. BPPT is currently finishing off the installation of 38,000 domestic home lighting systems in remote areas of Indonesia. Each system consists of a 50 watt Solarex PV module, a lead acid battery and three fluorescent lights. Provisions are also made to power a radio and a small television. BPPT reports that plans are being made to expand the project to 1,000,000 PV lighting systems for remote areas.
High School Education

Rooftop PV arrays for schools have significant educational value. As well as being responsible for the technology (such as the 1kW array on Fort St High School in NSW), the PVSRC is working on an ACRE Solar Schools project with Murdoch University and the Australian National University, with the aim of developing an educational program for teachers and students. Educational groups have also taken advantage of Centre expertise with special lectures involving electricity demonstrations to high school students. These lectures have proved to be very popular with the Siemens Science Experience and the gifted children groups and help teach basic electricity concepts to budding engineers and scientists.

Photovoltaics for Non-Engineers

This year a new course was offered at UNSW specifically designed for teaching photovoltaics to non-engineering based students. The course was taught through the general education system and only non-engineering students were eligible to enrol. Photovoltaics concepts were taught through the study of the 1996 World Solar Challenge with subjects as follows: Aerodynamics, solar arrays, motors, motor controllers, batteries, suspension, brakes and wheels. The students designed, built and raced model solar cars constructed of recycled materials utilising the concepts learned during the course. The race itself was a striking event with several hundred university students attending.
Industrial Design
The PVSRC assists Industrial Design students from UNSW and the University of Sydney in final year projects. The design criteria used by Industrial Design is tailored to sound engineering principles. The PV module’s physical size, the battery dimensions and mass, the energy storage requirements and energy control are all evaluated and, over a period of months, the student’s effort form the project into a PV product.

UNSW Courses and Careers Day and Faculty of Engineering Open Day.
This year UNSW Courses and Careers Day was held on 5th September, allegedly the month of lowest annual rainfall in Sydney and, similarly to last year, it rained. Fortunately, rain did not dampen the enthusiasm of those prospective students lining up to learn about photovoltaics, land the interactive solar powered model helicopter and receive their “free orange juice” squeezed by Centre volunteers on solar powered juicers. Over 10,000 prospective students visited UNSW with many flocking to the Engineering faculty with its interactive displays. The displays, designed by Gordon Bates, were supplemented with career advice from senior academics and a lecture by the Centre’s External Relations Manager, Rob Largent, entitled “Clean, Green & Cost Effective: Electrical Engineering designing New Solar Energy Systems”.

Figure 36: Industrial Design Student Marcel Julliard’s PV Lantern and Portable Power Supply.

Figure 37: Industrial Design Student Marcel Julliard’s PV Lantern Ready for Charge.

Figure 38: Prospective students and friends queue at the Centre display, Courses and Careers Day 98.

Figure 39: Perfect touchdown for the interactive solar powered model helicopter.
EXTERNAL ACTIVITIES

External Relations

Managers: Robert Largent, David Roche
Project Staff: Linda Koschier, Donald Clugston, Matt Borland

A high level of public and media interest in the Centre was maintained throughout 1998. This interest was met through the usual channels of phone and e-mail correspondence, printed information sheets, laboratory tours, exhibition displays, open days, media liaison and the Centre’s world-wide web site.

The Centre’s information sheets were updated and expanded to cover additional topics. These information sheets form a core aspect of the Centre’s external relations, since they provide a wealth of information on photovoltaics and the Centre’s work in a readily available and easily understood format. These information sheets are accessible on the Centre’s world-wide web site “http://www.pv.unsw.edu.au/info/”.

Numerous national and regional radio interviews were conducted throughout the year on topics ranging from energy efficiency to solar cars.

The Centre’s work or staff appeared in a number of publications including the Sydney Morning Herald, the Melbourne Age, Geo Magazine, Australian Energy News and Uniken.

Sunswift Perth to Sydney Race

PV SRC helped sponsor the UNSW student solar car team, Sunswift, in their 10 day effort to break the world record for the fastest crossing from Perth to Sydney by a solar powered car. The record, currently held by a team supported by Dick Smith, continues to stand as unseasonable rains and floods impeded the team’s efforts.

The race data indicates that had the weather held up the Sunswift car would have certainly broken the record or been a very close contender.

Although the Sunswift team did not set the world record in this attempt, the secondary motive for the race was achieved: to run-in the team’s newly built car and to prepare it and the team for the gruelling Darwin to Adelaide World Solar Challenge in October, 1999.
Stand Alone Power Supply Systems

The Centre’s expertise in applied photovoltaics has been effectively put to use by the National Parks and Wildlife Service (NPWS).

The success of the NPWS Montague Island PV/diesel hybrid system installed in 1997 has prompted NPWS to install a 6 kW PV/diesel hybrid system at Green Cape on the far south coast of NSW. This system is due for commissioning in early 1999.

Ongoing data analysis from the Montague Island hybrid system has shown that the diesel required to power the island has been reduced by over 80%. NPWS has reported that the PV/diesel hybrid system will pay for itself in only eight years based solely upon the per litre cost of diesel. If NPWS also takes into account the costs associated with the transport of the diesel to the island the system will pay for itself much sooner.

Montague Island is an ecologically sensitive area with Australia’s only year round seal colony and penguin rookeries. NPWS desired both to reduce the ecological risk of a diesel spill and reduce the financial burden of supplying fossil fuel for electricity generation.

As with Montague Island, in the Green Cape project the PVSRC was chosen for its non-partisan expertise in renewable energy systems. The DAD evaluated the community’s power requirements, set tender specifications, conducted a technical site visit for tenderers, and clarified the technical content of the tenders during tender evaluation thus allowing NPWS to make informed a decision.

This site is similar to Montague Island with a light house and two cottages. The PV/diesel hybrid system will supply power for up to 20 people.

Figure 45: Montague Island: 4 kWp PV Array used to power island community.
**Lighting**

Industrial consulting and research (through Unisearch Ltd) has resulted in a DAD designed 2.54 MHz inverter used to power Philips induction lamps and a high efficiency Maximum Power Point Tracker designed specifically for BP Solar’s BP 585F (Buried Contact) PV module. This fully dimmable lighting system has a bulb life of fifteen years.

A pre-commercial lighting system using this technology has been installed at Gate 9 of the UNSW Kensington campus.

![Figure 46: High Efficiency, Fully Dimmable Lighting System.](image)

**PV in Buildings**

A growing level of technical support is being sought by architectural firms for projects both within and outside of Australia. Collaborative effort involving Solarch and the DAD is helping to meet this demand.

**Photovoltaics and Sculpture**

Artist Allan Giddy’s sculpture ICE HEART was a great success during its showing on Tamarama Beach during the Sydney Organising Committee for the Olympic Games’ Sculpture by the Sea exhibition. The artwork used four buried contact solar modules on loan from BP Solar to power a refrigeration system which kept an anatomically modelled piece of ice shaped as a human heart on display.

The DAD aided in the design of the refrigeration and energy systems for the artwork.

![Figure 47: Sculpture Allan Giddy Inserting Ice Heart.](image)

**Reflection Analysis**

The DAD offers reflection analysis for proposed PV arrays. In some cases, it is necessary to determine in advance the intensity of reflection, the times of day and the directions that will be affected by reflections from PV arrays. These reflections can be of concern in both city and rural areas and in both cases small adjustments to the orientation or tilt of the array may be able to minimise the effects of these reflections.

![Figure 48: The Sculpture ICE HEART at Tamarama Beach.](image)
Background
Recognizing the rapid growth of the photovoltaics industry and its need for trained staff, a Key Centre for Teaching and Research in Photovoltaic Engineering was awarded to the University, commencing in early 1999. This Key Centre will offer the world’s first undergraduate program in Photovoltaics and Solar Energy, beginning in the year 2000. Professor Stuart Wenham resigned from Associate Directorship of the Special Research Centre at the end of 1998 to take on the role of Director of the Key Centre. As detailed in Professor Wenham’s report at the front of this volume and further below, the Key Centre will initiate strong new programs, particularly in the undergraduate and postgraduate teaching areas and in industry-initiated research.

The following sections outline the initial industry-linked research projects being undertaken by the Key Centre and gives a detailed outline of the new undergraduate program leading to the degree of Bachelor of Engineering in Photovoltaics and Solar Energy.

Commercial Research
Project with BP Solar
BP Solar, one of several licensees of the BCSC technology, presently manufactures the highest performing commercial cells using the standard BCSC process with cell efficiencies in the vicinity of 17%. The aim of this new collaborative project negotiated with BP Solar is to develop and implement a new solar cell rear structure that appears to solve the primary limitation of all current commercial solar cells - poorly passivated rear surfaces. To aid in the commercial implementation of the UNSW patented designs, funding has been successfully sought by BP Solar from the European Union’s JOULE program. The expected outcome will be the achievement of significantly higher efficiencies approaching 20% for the BCSC technology using solar grade materials, while simultaneously lowering costs.

A novel approach for contact formation is to make use of selective solid phase epitaxial (SSPE) growth. The aluminium (Al) mediated SPE growth process is extraordinary in terms of the nature of the growth process, required temperature, quality of crystal grown, ability to tolerate interfacial oxide, simplicity and potential for low cost. A crystalline silicon surface coated by a layer of Al and then a layer of sputtered amorphous silicon (a-Si), when heated to 500°C (below the Al-Si eutectic temperature), leads to the SPE growth of Al doped silicon onto the adjacent silicon surface. The a-Si penetrates into the Al (in which it has high mobility and solubility) to reduce its free energy, following which epitaxial growth takes place at the crystalline surface as the free energy of the Si atoms is further reduced. A concentration gradient of Si within the Al results, leading to continual diffusion of Si from the a-Si interface to the crystalline silicon surface where it epitaxially grows, doped with Al at its solid solubility. Consequently, the juxtaposed Si and Al layers change place with the a-Si being converted to crystalline silicon.

For implementation into the BCSC process, the front surface is fabricated in the usual way. Continuous (Figure 50(b)) or intermittent (Figure 50(a)) grooves can be formed in a grid pattern on the rear surface by a number of techniques. Damage created by this process may require etching as is normally the case with front grooves for the BCSC. The SSPE growth process is then implemented and should facilitate SPE growth of p+ silicon onto the exposed substrate p-type region following the automatic reduction or removal of the native oxide. Regions with thick oxide should remain unaffected as demonstrated by preliminary work in Figure 51 where a 3,000Å thick oxide layer provided protection for the crystalline Si surface from the overlying layers of Al and Si. The exposed Al following the SPE growth appears well suited to standard electroless metal plating used for conventional BCSC devices. UNSW owns the corresponding intellectual property and has already negotiated rights with BP Solar.
Although this approach has not as yet been applied to PV devices, work to date funded by the ARC Special Investigators Award has demonstrated:

- good crystallographic quality of the epitaxially grown material as verified by Rutherford back scattering (RBS) analysis;
- achievement of low contact resistance onto p-type silicon to suit reduced area contact solar cells;
- that the epitaxially grown material is doped with Al at $2 \times 10^{18}$ atoms/cm$^2$ and that the surface Al purity is 95-100% following growth;
- the ability of the Al to reduce native surface oxides at only 500°C;
- simple and reliable formation of junctions by SPE growth directly onto n-type wafers with and without phosphorus diffused surfaces with the achievement of high shunt resistances;
- the achievement of 560 mV at the equivalent of one-sun photogenerated current density using an SPE grown junction.

This latter result corresponds to a metal contact with 100% area coverage which is consistent with achieving open circuit voltages above 640 mV when used in the described manner as a reduced area contact. Extensive modelling predicts likely cell efficiencies in the vicinity of 20%.

Figure 50: Rear contacts by grooving & SSPE growth.

(a) Textured front surface not shown

(b) Amorphous Silicon

Figure 51: The structure of (a) when heated to 500 degrees leads to the formation of (b) leaving the oxidized silicon surface unaffected by the process.
**Project with Eurosolare, Italy**

A collaborative research plan has been agreed upon with Eurosolare addressing major adaptation of the BCSC fabrication to suit existing screen-printing equipment/infrastructure. New intellectual property to suit these requirements has been recently generated at UNSW. A licensing agreement is being negotiated with incentives for Australian manufacture. A further challenge for the collaborative research is to develop processes compatible with constraints imposed by Eurosolare’s polycrystalline silicon substrates. A three year program has been agreed upon, including exchange of researchers (including a UNSW PhD student) between UNSW and Eurosolare. A technology transfer to Eurosolare is planned during 1999.

**Project with Pacific Solar**

Pacific Solar has already purchased the rights to UNSW thin-film technology. Collaborative research will focus on improving the silicon material quality by capitalizing on state-of-the-art characterization equipment available at Pacific Solar in conjunction with the high level of expertise available through the Key Centre. A detailed research plan has been agreed upon with the involvement of 3 PhD students anticipated.

**Grid-connected PV Projects**

These projects focus on grid-connected issues for PV such as system design, grid dynamics, impedance matching, harmonics, long life inverter design, transmission line voltage distribution, etc. as well as more general system hardware issues. Emphasis will also be placed on broader institutional/policy and environmental issues and the restructuring of the electricity industry. The scope of the corresponding program will be expanded where appropriate into related areas of research to generate additional knowledge for the teaching program. To date, one project has been negotiated with, and will be funded by, Pacific Solar relating specifically to grid-connected inverters.

**Space Cells Project with Unisearch**

Cells for space applications vary significantly from terrestrial cells with greater importance placed on performance and tolerance to radiation damage from the harsh space environment. UNSW high efficiency solar cells may be prime candidates for space where a premium can be paid for their unique attributes.

Device reliability, performance at “end-of-life”, suitability for the environment, radiation hardness and thermal design are some of the issues to be addressed by this research strand. Funding to establish and operate a pilot production facility has already been granted by UNSW with future work expected to be self-supporting. The future of this work (in the context of the Key Centre) will depend on the industry’s interest in high performance silicon solar cells for space use.

**Teaching**

**Overview of course 3642 in Photovoltaics and Solar Energy**

The undergraduate engineering degree program in Photovoltaics and Solar Energy is to be established in the year 2000 in response to rapid growth in the industry in both manufacturing capacity and job creation. Course materials cover all aspects of photovoltaic engineering including: research, development, education and training; photovoltaic technology, manufacturing, quality control and product reliability; photovoltaic applications, system design, performance optimisation, system integration, balance of system components including interface and control electronics, grid interface issues, system analysis, fault diagnosis and reliability; device theory and design; marketing, analysis, life cycle costing, modelling and policy; and a broad education in solar energy, renewable energy technologies and sustainable energy. All areas are covered briefly in the first two years while in the 3rd and 4th years, scope exists for specialising in preferred areas. Throughout the course, considerable emphasis is placed on gaining hands-on experience of working with photovoltaic devices, modules and systems, such as through the solar car project and solar powered houses, such as in the Olympic village.

A unique feature of the degree is that students are given the opportunity to also specialise in a complementary area, such as one of the other engineering disciplines. In 2nd year, students are able to enrol in one 18 Credit Point strand chosen from the areas of computing, electronics, telecommunications, chemistry, mathematics, environmental/civil engineering, electric energy and mechanical engineering. The chosen strand will provide the necessary core material to facilitate subsequent selection of more advanced electives from the corresponding area in the 3rd and 4th years of the Photovoltaics and Solar...
Energy degree. This may make it feasible through an extra 5th year of study to achieve a double degree such as in Photovoltaics and Solar Energy combined with say Electrical Engineering. It may also be possible for students with an alternative engineering degree to also gain a degree in Photovoltaics and Solar Energy through a 5th year of study.

**Course Outline**

The following is the course outline to be printed in the Faculty Handbook pending final approval from The University of New South Wales.

**YEAR 1**

<table>
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<tr>
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<th><strong>CP</strong></th>
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<td>ELEC1011 Electrical Engineering 1</td>
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<td>MATH1241 Higher Mathematics 1B</td>
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MATH1141 and MATH1241 may be taken at the ordinary level.

**YEARS 2 & 3 STRAND OPTIONS**

Students have the opportunity to select one of eight possible strands to complement their education in Solar Energy and Photovoltaic Engineering. Each strand comprises 18 Credit Points with the opportunity to subsequently select additional Electives in the corresponding area in the final two years. The eight strands available are listed below with the subject(s) comprising the last 6 Credit Points to be taken in year 3.

**YEAR 2**

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<tr>
<td>SO LA2020 Photovoltaic Technology and Manufacturing</td>
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### YEARS 2 & 3 STRAND OPTIONS

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### Strand 7: Civil Engineering

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### Professional Electives for Years 3 & 4

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<td>SO LA4011</td>
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<td>Renewable Energy Policy and International Programs</td>
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Electives can also be chosen from the subjects listed as electives for Electrical Engineering, Mechanical Engineering, Civil Engineering, Environmental Engineering, Computer Science and Engineering and Chemical Engineering for which appropriate pre-requisite requirements have been satisfied and which conform to the credit point requirements.
Business Developments

The Advanced Cell Division provides the Photovoltaics Special Research Centre customers with photovoltaics technology products and design services. Current projects for the Advanced Cell Division involve space cells and high performance PERL cells which are led by world record holding researchers Dr Jianhua Zhao and Dr Aihua Wang.

ISO9001 accreditation demonstrates to prospective technology customers that not only are our products and services first class but the customer support, organisational processes and management structures behind our business outputs are also in place and under constant review. As a research and teaching organisation we can better appreciate the requirements of the majority of photovoltaics manufacturers that are working with quality system accreditation and also of our customers, especially those in the space industry.

Accreditation followed in November 1998, a remarkably short time frame for any ISO quality accreditation program. Critical success factors were initial support from our spin off company Pacific Solar Pty Ltd who shared its recent ISO9001 experience to kick-start our enthusiasm; the extremely high levels of commitment and effort by already busy teams from research, laboratory development, administration and management; the reduction in the ISO 9001 paperwork burden and simplification of record keeping with the design and implementation of a system that integrated an already high level of word processing skills by team members into a PVSRC custom intranet computer based system.

Figure 52: Portion of the Advanced Cell Division quality team. Left to right Lawrence Soria (Lab Development), Brendon Vandenberg (Quality Coordinator), Tim Seary (Lab Development), Aihua Wang (Researcher), Martin Brauhart (Lab Development), Anna Votsis (Lab Development), Jianhua Zhao (Researcher), Oliver Nast (Researcher), Jules Yang (Lab Development), Mark Silver (Business and Technology Manager/Quality Management Representative).

The ISO 9001 quality systems project instigated by Prof Martin Green, officially commenced in June 98 under the leadership of the Centre’s Business and Technology Manager, Mark Silver, in the role of Quality Management Representative and PVSRC engineer, Brendon Vandenberg as Quality Coordinator.

Figure 53: Screen snapshot of the PVSRC ISO 9001 Intranet, designed to reduce the paper burden of documents and store records.

Another business highlight of the year was the signing of a buried contact solar cell license agreement between Unisearch, the commercial arm of UNSW, and Eurosolare S.p.A. in August 98. Eurosolare S.p.A. is a major European solar cell manufacturer based in Rome and a subsidiary of the giant Agip (ENI S.p.A) petrochemical conglomerate. In addition to the standard buried contact process Eurosolare S.p.A are licensed to evaluate a new “simplified buried contact” technology that is designed to utilise much of an existing manufacturers capital equipment and hence provide a low cost stepping stone into the high performance buried contact technology.

Once again our licensee BP Solar continued its success with UNSW buried contact cells. Production has grown for another year and our royalty income stream, whilst intentionally modest to promote the technology, increased 37% over last years result. Other BP Solar successes include the provision of buried contact...
solar cells for the grid connected roof top panels in the new athletes village at the Sydney 2000 Olympic site (Figure 28) and the announcement in October 1998 of a new 20-50MWpa buried contact production facility to be built at Belrose in Sydney.

In addition to the above activities, the Centre continued to provide technical services to the photovoltaics and electrical utility industry, with new product testing at its Little Bay Solar Research Facility, the development of new standards and guidelines for renewable interconnection to the supply grid, and various studies, courses and seminars in the general area of renewable energy systems.

Contracts and Agreements

Pacific Solar Pty. Ltd.

Pacific Solar commenced operation in February, 1995 as a $64 million collaborative venture between Pacific Power and Unisearch Ltd. The company’s mission is to commercialize the multilayer thin film technology developed by the Centre. The company is leasing the Centre’s Bay Street facility (Figure 54) from the University and is engaging the Centre’s services for contractual research. Additionally, a number of Centre staff have been seconded from the Centre for the duration of the company’s developmental phase to assist in meeting the company’s objectives. During 1998, Pacific Solar commenced pilot production of thin-film polycrystalline silicon-on-glass modules using Centre technology.

energyAustralia

energyAustralia provided Foundation Sponsorship for the Little Bay Solar Energy Research Facility. Their sponsorship includes funding of photovoltaic-based power systems installed at the site. Funding of $85,000 was provided towards construction of the building in 1994 and another $240,000 over 3 years towards the photovoltaic system.

energyAustralia has also been involved in other collaborative projects with the Centre including the Australian High School Project and the Australian Technology Park photovoltaic installation.

Additional activities included performance assessment of selected crystalline and thin film silicon module technologies and electronic interface hardware.

Sandia National Laboratories

The long term association of the Centre with Sandia continued into 1998, completing over 11 years of very fruitful collaboration. During 1998, Sandia supported the development of advanced silicon cells by testing some of the best cells and modules under internationally recognised standard reference conditions.

Australian Cooperative Research Centre for Renewable Energy (ACRE)

The University of NSW was a foundation member of ACRE, when it was established in 1997 and is undertaking collaborative research at the PV Centre and at SOLARCH, the University’s solar architecture group.

Projects are variously funded by ACRE, UNSW, industry and other research organisations. The PV Centre is currently receiving around $100,000 per year from ACRE for collaborative work on three projects in ACRE’s Education program: energy information, short courses and school & community education; and 2 projects in the Systems Integration program: standards for PV systems and evaluation of remote area power supply options.
Other Research Contracts and Grants
Individual researchers affiliated with the Centre attracted additional grants from other bodies such as the New South Wales Department of Energy, Environment Australia, the NSW Sustainable Energy Development Authority, and The Australian PV Power Systems Consortium.

Licensing Agreements
Companies now on public record as being licensed to use technology developed at the Centre (or assigned Centre intellectual property) include:

BP Solar Australia Pty. Ltd.
BP Solar Espana S.A.
Central Electronics Ltd., India
Eurosolare S.p.A, Italy
Pacific Solar Pty. Ltd.
Samsung Electronics Co. Ltd.
Solarex Corporation
Solarex Pty. Ltd.

Conferences
Staff or students affiliated with the Centre presented papers relevant to photovoltaics at the following local and international conferences during the year:

- 36th Annual Conference of the Australian and New Zealand Solar Energy Society (ANZSES), Christchurch, November, 1998;
- II Workshop on Optoelectronic Materials and their Application, including Solar Cells, Cuba, November 1998;
- Space Power Satellite Session on the 49th International Astronautical Congress, September, Melbourne, 1998;
Technology Transfer

The main objective of the technology transfer group is to facilitate the transfer of cell technology from the Centre’s research laboratory to companies which license the technology. The technology transfer group bridges the gap between the small-scale solar cell processes used in research work, and the large-scale production used in industry. This is done by establishing candidate sequences on the Centre’s pilot production line, thereby demonstrating the suitability of the technology to commercialisation and providing a training ground for the Centre’s licensees.

The technology transfer group works closely with Unisearch Ltd, the commercial arm of the University of New South Wales. When transferring technology to a licensee, its activities may be divided into two main sections:

Cell-Processing Training.
This includes the following:
• The preparation of a document outlining the scientific and engineering principles underlying the design, fabrication, operation and commercialisation of the new technology;
• The provision of a series of seminars on various aspects of the new technology;
• The provision of practical training for licensee personnel in all aspects of the production of the new photovoltaic devices. The training is carried out at the Centre’s pilot production facility. The trainees are provided with detailed documentation of the processing sequence. They observe and participate in the day-to-day operation of the pilot production facility. The level of training is such that the trainees are in a position to fabricate devices with minimal assistance from Centre staff;
• Technology transfer visits are organised at appropriate stages of the development of the licensee’s own pilot production facility. During these visits, one or more research engineers from the Centre visit the licensee’s facilities for a period of approximately one week. The main purpose of these visits is to get first hand experience of any problems which may arise, to suggest solutions to these problems, and to establish a strong communication link between key technical personnel;
• The Centre’s research engineers make themselves available to offer the licensees prompt and specific technical assistance by facsimile or telephone, if the need arises.

Advising on Equipment.
The Centre provides technical support and advice to licensees as they establish their own laboratories and pilot production facilities. The degree of the Centre’s involvement may include all or any part of the full spectrum of system integration:
• Cost analyses;
• Feasibility studies;
• Planning;
• Design of equipment (where appropriate);
• Acquisition of equipment and materials (technical specifications, quotations, freight);
• Installation and commissioning of equipment and plant;
• Implementation and optimisation of the production process.
PHOTOVOLTAIC SPECIAL RESEARCH CENTRE FINANCES

The Photovoltaics Special Research Centre was established in 1990 with broadly based funding received under the Australian Research Council’s (ARC) Special Research Centres Scheme and from Pacific Power. Under the approved program, the Special Research Centre funding is used to provide infrastructure for Centre operations, seeding funds to bring projects to the stage where they can attract external support and complementary funds to improve the viability and scope of externally supported projects. In addition to this broadly based funding, individual researchers within the Centre receive research grants and contracts for specific projects within the Centre’s general area of interest.

Total expenditure during 1998 was $3.1 million, with a breakdown of expenditure by source of income shown in Figure 56.

Only 28% of total expenditure was from income from the ARC Special Research Centres scheme, meeting the Centre’s target of 45% or less for this figure. Another substantial source of funds was Pacific Solar, with large funding totals also received for specific projects proposed by researchers affiliated with the Centre supported by the Australian Research Council’s grants and fellowship schemes. Significant amounts were received from the Australian Co-operative Research Centre in Renewable Energy and Greenhouse Gas Abatement (ACRE), and a variety of other sources. The Centre also received considerable support from the University in the form of infrastructural support grants and a major capital grant. The University also provided other substantial non-cash support to the Centre.

Figure 56: Breakdown of expenditure by source of external income (total expenditure is $3.1million).

Figure 57: Overall expenditure by category (total expenditure is $3.1million).

The chart above (Figure 57) shows the broad areas where funds were spent. Salaries accounted for close to 50% of expenditure. The Centre has a target for 1999 of reducing expenditure to 40% on salaries. Figure 57 also shows the progressively smaller percentages spent on equipment, materials and travel.

Figure 58 shows the corresponding breakdown for the expenditure of the specific funds received under the ARC Special Research Centres Scheme. These funds have a special role in maintaining and developing the Centre infrastructure.

Figure 58: Expenditure by category of ARC Special Research Centre funds (total of expenditure shown is $887,491).
A breakdown of total Centre expenditure by project area is shown in Figure 59. This expenditure, as in the early years of the Centre, was weighted heavily towards near-term bulk device research. This primarily reflected the success in obtaining external funding for specific research projects in this area, including a large capital grant during 1998.

With the maturing of the thin film device work, appreciable external funding is now being received for this area so that it now approaches the level of support for bulk device work. Although a smaller component of total expenditure, external funding for the expanding activities in the systems area is also becoming significant. The figures shown do not accurately reflect total Centre effort directed to the areas indicated, since University resources directed to these areas by way of salary, space and other infrastructural support are not included.

Figure 59: Breakdown of total Centre expenditure by project area (total expenditure is $3.1 million).

Finally, Figure 60 shows the breakdown of expenditure by project area of broadly based funding received by the Centre from the ARC Special Research Centres Scheme. The ARC funding has been used primarily to provide support for the operation, maintenance and development of Centre laboratories and facilities, with special attention paid to the nurturing of system research activities.

Apart from direct cash funds received and shown in Figure 56, support from the University is not included in any of the previous figures. The University provides salaries for 9 of the academic staff and 4 of the non-academic staff involved with the Centre. The University also provides accommodation and a range of services for the Centre, as well as infrastructural support by way of facilities, such as the library.

Figure 60: Breakdown of expenditure by project area of funding from the ARC Special Research Centres Scheme (total expenditure shown is $887,491).
THESIS

BOOKS, BOOK CHAPTERS


REFEREED JOURNALS


Green, M.A., “Recent Developments in Photovoltaics”, 2nd Workshop on Optoelectronic Materials and their Application, including Solar Cells, Havana, Cuba, 2-6 November, 1998.


PUBLICATIONS IN PRESS

Cotter, J.E., “Light Trapping in Silicon-Film Solar Cells with Pigmented Diffuse Reflectors”, Progress in Photovoltaics, accepted for publication.


APPENDIX A

Photovoltaics Special Research Centre Advisory Committee

1. FULL MEMBERSHIP

(a) University Representatives
1. Deputy-Vice-Chancellor (Professor C.J.D. Fell)
2. Dean, Faculty of Engineering (Professor M. Wainwright)

(b) Centre Representatives
3. Director (Professor M.A. Green)
4. Associate Director, Thin-Film Devices (Dr. A.G. Aberle) (from 11/98)
5. Associate Director, Systems (A/Professor H.R. Outhred)
6. Associate Director, Devices (Professor S.R. Wenham) (to 12/98)
7. Associate Director, Buried-Contact Cell (Dr. C.B. Honsberg) (1999)
8. Associate Director, High-Efficiency Cells (Dr. J. Zhao) (1999)
9. Associate Director, Multilayer Technology Commercialization (A/Professor P.A. Basore)

(c) Representatives of Major Sponsors
10. Pacific Power
11. N.S.W. Office of Energy
12. Unisearch Ltd.

2. ASSOCIATE MEMBERSHIP

(a) Manufacturing Representatives
14. B.P. Solar Australia Pty. Ltd.
15. Solarex Pty. Ltd.

(b) Other Representatives
16. Electricity Supply Association of Australia
17. Australian CRC for Renewable Energy (ACRE)
18. Director, Key Centre for Photovoltaic Engineering (from 1999)
Director:
Martin A. Green, BE, MEngSc (Qld.), PhD (McMaster), FAA, FTS, FIEEE, FIEAust.

Associate Directors:
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Paul A. Basore (Thin-Film Commercialization), BSc (Oklahoma State), M S, PhD (MIT), MIEEE
Christiana B. Honsberg (Buried-Contact Cells), BEE, M Sc, PhD (Delaware) (from 1999)
Hugh R. Outhred (Systems), BSc, BE, PhD (Syd.), AMIEEE, MIEEE, FIEAust.
Stuart R. Wenham (Devices), BE, BSc, PhD (UNSW), SMIEEE (to 12/98)
Jianhua Zhao (High-Efficiency Cells), ME, PhD (UNSW), MIEEE (from 1999)

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G. Heiser, BSc, MSc, PhD (ETH Zurich), SMIEEE, MACM
R.J. Kaye, BE, MEngSc (Melb.), PhD (Calif.), MIEEE
I.F. Morrison, BSc, BE, PhD (Syd.), CPEng, FIEAust, MIEEE, MIEEE.

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J. Cotter, BEE, MSc, PhD (Delaware)
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D. Krcho, RNDr (Bratislava)
H.R. Mehrvarz, PhD (UNSW)
O. Nast, Dipl Phys (TU, Berlin)
D.H. Neuhaus, Dipl Phys (Hannover)
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A.B. Sproul, BSc (Syd.), PhD (UNSW) (P/T)
D. Thorp, BA (Cambridge), PhD (UNSW) (to 11/98)

Visiting Academics:
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Dr. A. Schenk, Integrated Systems Laboratory, ETH-Zurich, Switzerland (March 1998)

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M. Lammer, Dipl. Ing. (Darmstadt) (since 8/98)
A. Neisser, BSc (Manchester), Technical University of Berlin (to 3/98)

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J. Haji Babaei, BE, MS (Iran)
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IS A SPECIAL RESEARCH CENTRE OF THE AUSTRALIAN RESEARCH COUNCIL

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