Single-electron pumping in silicon quantum dots with tunable electrostatic confinement

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Introduction
A crucial step towards a more reliable SI unit system is to redefine the Ampere through a high accuracy single charge pump where current = number of electron × electron charge × frequency [1]. The Si quantum dot (QD) with tunable confinement barriers is an excellent candidate for this application since its electrostatic-confinement can be controlled through specially engineered electrodes [2]. This thesis demonstrated in software simulation that the two confinement gates can effectively improve the charge pumping accuracy by suppressing electron nonadiabatic excitation. A silicon metal-oxide-semiconductor single electron transistor (SET) [3], which can be used for either electron counting [6] or electron pumping [5], has been successfully fabricated and characterized at low temperature (4.2K).

1. Device Architecture
- Multi-gate stack structure allows separate electrostatic control over the dot and source/drain region, which makes it possible to pump single electrons through the dot by only applying an AC signal to one of the barrier gates (Ratchet Mode).
- Two confinement gates (C1,C2) were placed on two sides of the quantum dot (QD). They can be biased below the threshold voltage during pumping to enhance the QD’s electrostatic confinement [2].

2. Nonadiabatic Excitation
- The conduction band energy profile simulated by TCAD indicates that the confinement gates can tune the dot size.

3. Initialization Fidelity
- The number of electrons in the dynamic QD can be estimated by fitting experimental data into the decay cascade model [4].
- Fitting results showed that proper tuning of the confinement gate can effectively lower the initialization error rate (σP) by orders of magnitude.

4. Nanofabrication
- Single top gate SET has been fabricated using the state of the art equipment at ANFF-NSW.
- The SET can be used either for charge pumping [5] or electron counting [3].

5. Measurement
- SET’s DC I-V properties have been characterised at 4.2K by using an AC lock-in technique.
- The dot between the two barrier gates did not appear since its charging energy is comparable to the thermal energy.
- Two separate QDs can be defined under two barrier gates.
- The device can have single QD by bringing one of the barrier gates above the threshold voltage. QD underneath the left barrier can reach the few electron regime by properly tuning the gate voltage.

6. Conclusion
- We presented a technique to study the nonadiabatic excitation through software simulation. This can be used as a design aid in future quantum device development.
- We reported that the confinement gate structure could effectively improve the initialization accuracy in dynamic QD. This modelling was used to support experimental demonstration of a Si charge pump, and has been published in the journal Nano Letters [2].
- A single electron transistor that can be used both for charge pumping and electron counting has been successfully fabricated and tested.

7. References