Integrated Quantum Computer Devices Program

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PROGRAM DESCRIPTION

The IQCD Program, based within the School of Electrical Engineering at UNSW, provides the Centre with engineering design, modelling and nanofabrication of fully-configured Si:P qubits and associated pathway devices. The Program makes extensive use of the Semiconductor Nanofabrication Facility (SNF) at UNSW, and works closely with the Ion Beam and Materials Characterisation Programs based at UM. The team is also actively involved in device measurement in close cooperation with the Quantum Measurement Program at UNSW.

The Program's development of a MOS-compatible Al multi-layer gating technology has supported the production of a range of new devices in recent years, including fully tuneable Si quantum dot devices. When connected to a resonant tank circuit, the operation of such quantum dots as highly sensitive rf single electron transistors (SETs) has been demonstrated. The same multi-layer gating technology was used in 2008 to produce: i) transport devices in which tunnelling through single-P-donor states has been studied; and ii) spin qubit pathway devices in which Si rf-SETs were used for donor state readout.

With existing capabilities in the production of on-chip detectors for the electrical registration of single ion implants, the Program is now producing fully-configured spin qubit devices.

Si MOS Spin Qubit Architecture

During 2008, the IQCD Program's focus shifted to a MOS-based spin qubit device architecture as depicted in Figure 1(a) [Morello et al., submitted to *Physical Review Letters*, see arXiV:0904.1271]. This fully scaleable architecture combines accurate P donor implantation via our existing single-ion counting technology developed in collaboration with the Ion Beam Program [Jamieson et al., *Applied Physics Letters* **86**, 202101 (2005)] with newly demonstrated capabilities in local electron spin resonance [Willems van Beveren et al., *Applied Physics Letters* **93**, 07102 (2008)] for coherent spin manipulation, and Si rf-SETs [Angus et al., *Applied Physics Letters* **92**, 112103 (2008)] for highly sensitive readout.

Figure 1(b) shows the energy landscape of the device with Zeeman–split donor states. Spin-to-charge conversion is achieved by tuning the Fermi energy such that only excited (spin-up) states may tunnel onto the SET island, allowing the qubit state to be read by single-shot detection of charge transfer.

Important new measurement results on these devices are reported in the QMCC Program (pages 18–19).

Spin Dependent Tunnelling through Single P Atoms

PhD students Kuan Yen Tan and Kok Wai Chan have fabricated and measured a series of transport devices to study tunnelling through donor states [Tan et al. in preparation for *Nano Letters*]. Controlled ion implantation through a PMMA mask allowed small numbers of P donors (2, 3 or 4) to be accurately positioned within an intrinsic Si substrate. Using our multi-layer Al gating technology, overlapping top- and barrier-gates were fabricated above the implanted donors resulting in the device structure shown in Figures 2(a-c). The top-gate is used to induce an electron layer at the Si/SiO_2 interface, and the barrier gate is used to control the energy of the donor states.

Transport measurements (Figures 2(d,e)) clearly probe states below the conduction band, with stronger coupling apparent in devices implanted at lower energy, consistent with tunnelling through donor states located closer to the surface. The absence of these transport signatures in measurements of control samples with no P implants (Figure 2(d)) provides strong evidence that donor states are being probed in implanted devices.

Further measurements undertaken with Dr Möttönen tracked Zeeman splitting in an applied magnetic field (Figure 2(g)) allowing the identification of D^0 and D^- states of individual P donors.

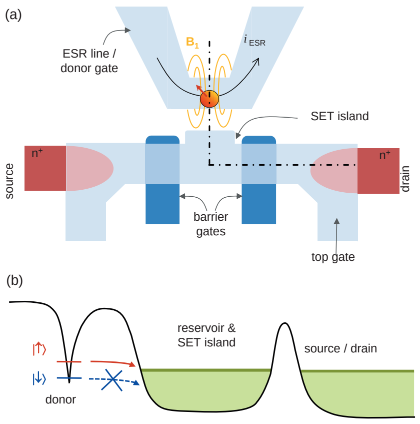

FIGURE 1

(a) Schematic top view of the MOS spin qubit device. (b) Energy landscape along the dash-dotted line shown in (a).

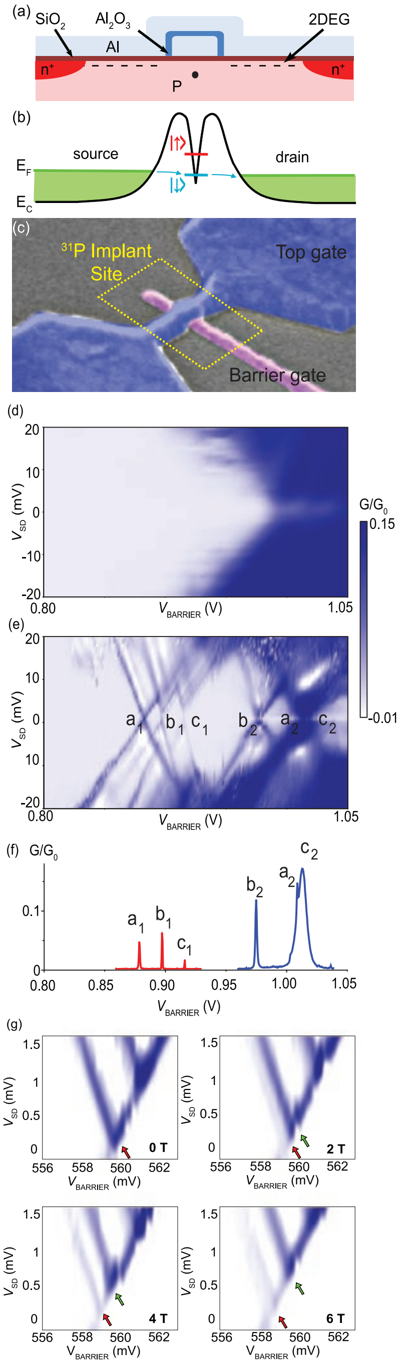

FIGURE 2

(a) Cross-sectional schematic of a transport device designed to study tunnelling through donor states. (b) Energy landscape through the bound donor state. (c) SEM image of completed transport device. (d) Bias spectroscopy of a control device with no implanted donors. (e) Equivalent measurement on a device with three donors implanted at 14 keV. (f) Conductance line trace at zero source-drain bias. Resonant tunnelling peaks associated with three donors are identified. (g) Zeeman splitting (highlighted with arrows) consistent with P donor states is observed in an applied magnetic field.

Si MOS Quantum Dots

Overlapping Al top- and barrier-gates are also used to produce Si quantum dot structures. The top gate is used to induce an electron layer and the barrier gates are used to locally deplete this, creating a quantum dot which is separated from source and drain leads by fully tuneable tunnel barriers [Angus et al., *Nano Letters* **7**, 2051 (2007)].

A single quantum dot connected to a resonant tank circuit may be operated as a highly sensitive rf-SET. Demonstration measurements of a Si rf-SET by PhD student Susan Angus achieved a charge sensitivity of order 10 $\mu e/\sqrt{Hz}$ at 2 MHz [Angus et al., *Applied Physics Letters* **92**, 112103 (2008)]. This excellent sensitivity enables measurement of charge transfer equivalent to 1% of an electron, with a measurement time of $\sim 1\ \mu s$.

Throughout 2008, the group's Si quantum dot research was extended to fully tuneable double quantum dot structures (Figure 3). PhD student Wee Han Lim performed transport measurements to individually characterise each dot, achieving device operation in the few electron regime. When operated as a double dot system, the ability to tune the device through a wide range of inter-dot coupling strengths was demonstrated. [Lim et al., accepted for *Applied Physics Letters*].

The extension of these studies to Si triple quantum dot devices provides a test-bed for scale-up via the coherent transfer by adiabatic passage (CTAP) protocol [Greentree et al., *Physical Review B* **70**, 235317 (2004)].

Implanted Si:P Cluster Devices

To characterise the Si:P material system and develop the fabrication technology required to build Si:P qubits, the IQCD Program has completed, over many years, a comprehensive study of devices featuring clusters of implanted P atoms. Gate-controlled large dots (containing tens of thousands of P atoms) have been fully characterised throughout a wide range of occupancy regimes using SETs to monitor charge transfer events [Mitic et al., *Nanotechnology* **19**, 265201 (2008)]. In smaller dots (hundreds of P atoms), the incorporation of source and drain leads allowed transport signals to be correlated with SET outputs [Hudson et al., *Nanotechnology* **19**, 195402 (2008)].

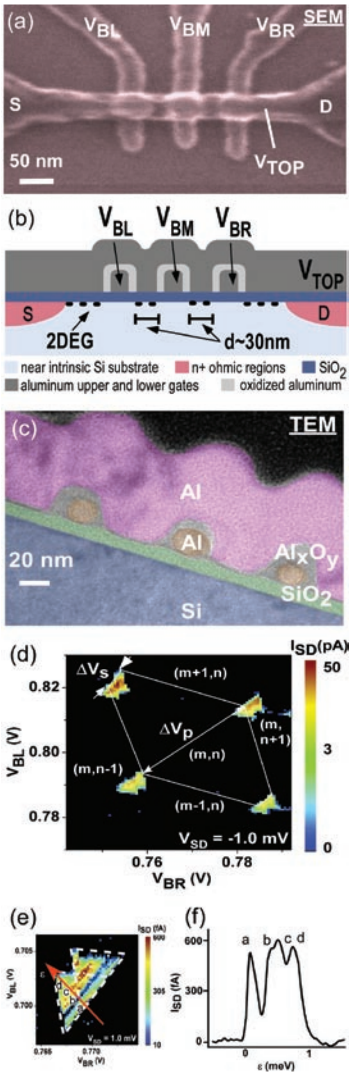

FIGURE 3

(a) SEM image of Si double quantum dot structure. (b) Schematic and (c) colour-enhanced TEM image of device cross-section. (d) Bias spectroscopy of coupled double-dot system. (e) At finite source-drain voltage, the triple points develop into triangle pairs. (f) Line trace along the red line shown in (e).


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Featured article
Gate-controlled charge transfer in Si:P double quantum dots
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IOP Publishing

FIGURE 4

Hudson et al., "Gate-controlled charge transfer in Si:P double quantum dots" featured on the cover of *Nanotechnology*.