Integrated Quantum Computer Devices Program

PROGRAM MANAGER

Prof Andrew Dzurak – UNSW

IQCD RESEARCHERS

Staff Dr Eric Gauja, Dr Fay Hudson, Dr Linda Macks, Mr Frank Wright
Students Mr Kok Wai Chan (PhD), Mr Nai Shyan Lai (PhD), Mr Wee Han Lim (PhD), Mr Kuan Yen Tan (PhD), Mr Graeme Lowe (Masters), Mr Eugene Siew (EE Thesis), Mr Henry Yang (EE Thesis), Ms Qingwen Wang (Summer Scholar)

COLLABORATING CENTRE RESEARCHERS

University of New South Wales, Australia
Dr Chris Escott, Dr Andrea Morello, Mr Jarryd Pla, Dr Laurens Willems van Beveren, Dr Floris Zwanenburg
University of Melbourne, Australia
Prof David Jamieson, Dr Changyi Yang, Dr Jeff McCallum, Mr Brett Johnson, Prof Lloyd Hollenberg

OTHER COLLABORATORS

Sandia National Laboratories, USA
Dr Malcolm Carroll, Dr Michael Lilly
University of Oxford, UK
Dr John Morton, Prof Andrew Briggs
Helsinki University of Technology, Finland Dr Mikko Möttönen
University of Wisconsin-Madison, USA
Prof Mark Eriksson, Prof Sue Coppersmith
Purdue University, USA
Prof Gerhard Klimeck
Walther-Meissner Institute, Germany
Dr Hans Huebl
University of Cambridge, UK
Prof Charles Smith

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 been a critical step in the development of a fully MOS spin qubit architecture in recent years. This technology has been successfully applied to the production of a range of devices which delivered significant research milestones in 2009, including fully tuneable Si quantum dot devices which have been operated in the single electron limit, transport devices in which tunnelling through single-P-donor states has been studied and spin qubit devices in which single shot spin readout has been demonstrated. The latter marks a major milestone in the development of a Si quantum computer.

Si MOS Spin Qubits

The MOS-based spin qubit architecture developed in 2008 [Morello et al., *Physical Review B* **80**, 081307 (2009)] was the main focus of the IQCD Program's fabrication efforts in 2009, with a range of devices produced (Figure 1) and measured in close collaboration with the QMCC Program. Key outcomes from these measurements include the first demonstration of single shot spin readout in a silicon nanostructure – full details are given in the QMCC Program report.

Spin Dependent Tunnelling through Single P Atoms

Throughout 2009, PhD students Kuan Yen Tan and Kok Wai Chan continued to study spin dependent tunneling through donor states in specially designed nano-scale field-effect-transistors (Figure 2).

Transport measurements performed on these devices (including detailed bias spectroscopy measurements performed in magnetic fields up to 7 T – Figure 3) allowed the D^0 and D^- charge states of individual donors to be identified, their charging energies to be determined and the Zeeman shift of donor spin states to be explored. [Tan et al., *Nano Letters,* **10**, *11 (2010)]*.

Further measurements in collaboration with Dr Mikko Möttönen focused on the behaviour of the density of states (DOS) of the electron reservoirs forming the leads in these devices (Figures 4-5). This study provides an insight into DOS effects in quantum devices which is critical in order to distinguish discrete quantum behavior from artefacts arising from DOS fluctuations in the leads. [Möttönen et al., submitted to *Physical Review B* – see also arXiv:0910.0731v1]

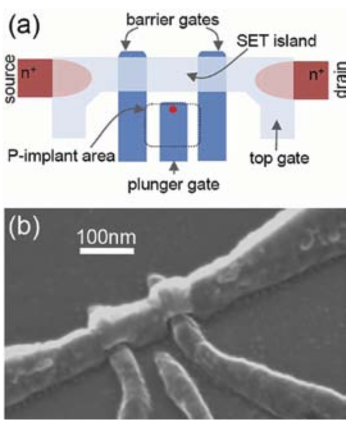

FIGURE 1

(a) Schematic top-view and
(b) SEM image of one of the range of spin qubit devices produced and measured during 2009.

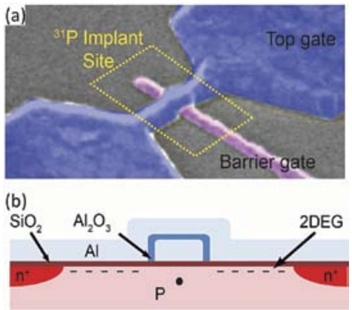

FIGURE 2

(a) Coloured SEM image and (b) cross-sectional schematic of a nanoFET designed to study tunneling through donor states.

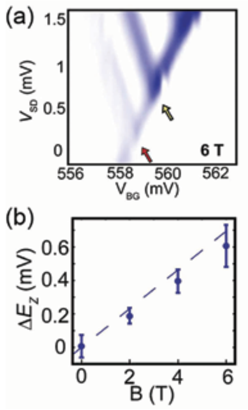

FIGURE 3

(a) Bias spectroscopy of a resonant tunnelling peak at 6 T for the device shown in Figure 2. Red (yellow) arrows indicate spin-down (-up) states entering the bias window.
(b) Energy splitting (ΔE_Z) of the spin-up and spin-down states from 0-6 T. The dashed line indicates $2\mu_B B/e$ for reference, where μ_B is the Bohr magneton.

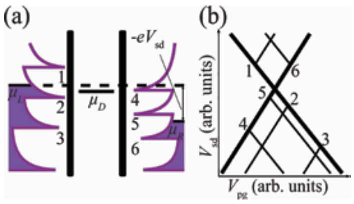

FIGURE 4

(a) Schematic representation of single electron tunneling through a discrete quantum level, showing reservoir DOS. (b) Schematic stability diagram showing conductance through the discrete quantum state, with extra structure due to reservoir DOS peaks.

Si MOS Quantum Dots

Transport studies of Si quantum dot devices continued throughout 2009, with PhD student Wee Han Lim and Dr Floris Zwanenburg demonstrating the ability to tune a double dot system through a wide range of inter-dot coupling strengths [Lim et al., Applied Physics Letters **94**, 173502 (2009)].

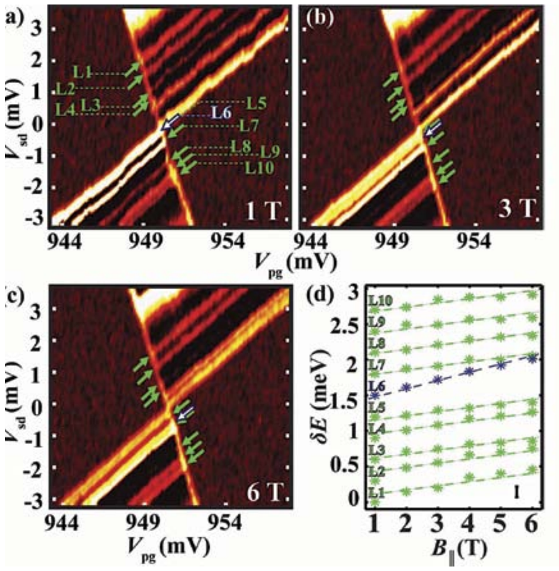

FIGURE 5

(a-c) Bias spectroscopy (stability diagrams) of a tunneling device in applied magnetic fields. The spin excited state in this device is marked with a blue and white arrow. DOS features are marked with green arrows.
(d) The conductance shift in magnetic field for the spin excited state has a slope of $2\mu_B$, while DOS features have a slope of μ_B.

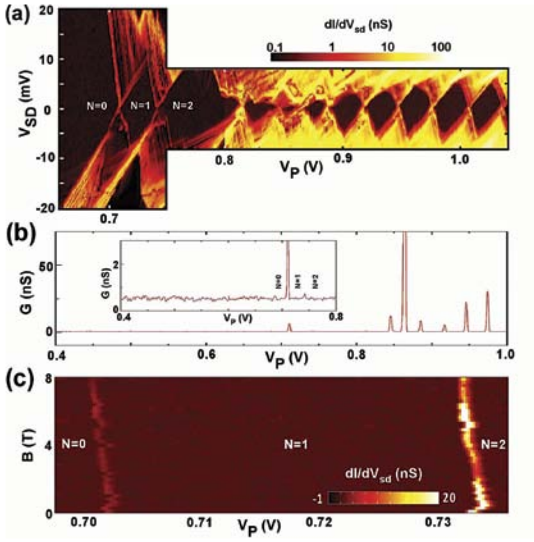

FIGURE 7

(a) Bias spectroscopy of the quantum dot device in the few electron regime.
(b) Coulomb peak heights of the last few electrons.
(c) Magneto-spectroscopy of the ground states of the first two electrons to occupy the dot.

With a modified gate structure (Figure 6), independent control over the electrons in each dot was achieved, allowing the single electron regime to be explored in detail. Bias spectroscopy measurements (Figure 7 a-b) tracked depopulation of the dot from ten electrons down to the last electron leaving the dot.

Magnetospectroscopy of the first two charge transitions (Figure 7 c) revealed that the first two electrons to occupy the dot are both spin-down. Published in 2009 [Lim et al., *Applied Physics Letters* **95**, 242102 (2009)], these exciting results were highlighted on the cover of Applied Physics Letters (Figure 8).

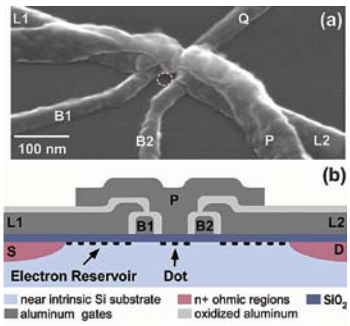

FIGURE 6

(a) SEM image and (b) schematic cross-section of a Si MOS quantum dot. Barrier gates (B1 and B2) control tunnel coupling between the dot and the electron reservoirs forming the leads. Lead gates (L1 and L2) control the electron density in the leads. A plunger gate (P) independently controls the electron occupancy in the dot.

Si:P Spin Qubit Control Using Cavity ESR

Working with Dr John Morton's team at the University of Oxford, PhD student Kok Wai Chan and EE thesis student Eugene Siew have designed and fabricated Si:P MOS qubit structures (Figure 9) that are compatible with both X-band (10 GHz) and W-band (100 GHz) ESR cavities at Oxford. We aim to achieve coherent control of electron spin using pulsed ESR. Measurements, which will take place in Oxford during 2010, will also aim to measure the hyperfine splitting of the P-donor electron spin.

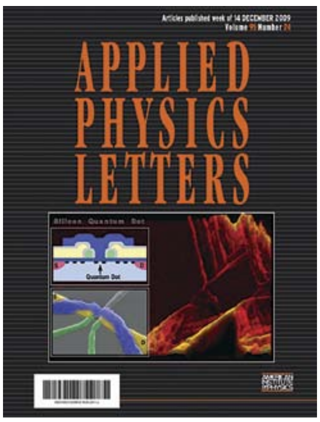

FIGURE 8

Lim et al 'Observation of the single-electron regime in a highly tunable silicon quantum dot' featured on the cover of *Applied Physics Letters*.

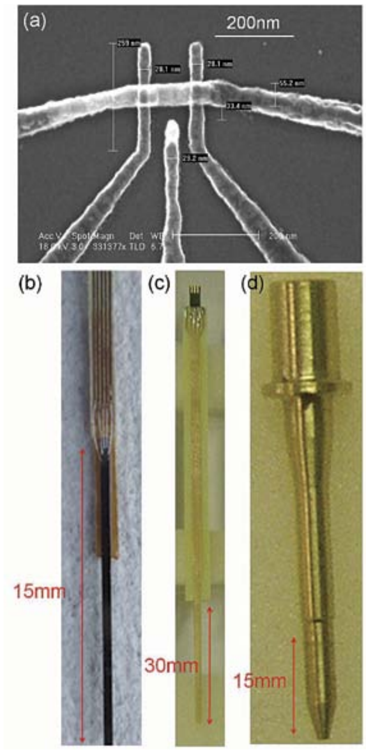

FIGURE 9

Si:P Qubit Devices for Cavity ESR. a) SEM of Si:P MOS qubit device. b) 15 mm substrate mounted on PCB. c) PCB carrier for device to be inserted into resonator. d) ESR resonator.