Quantum Measurement Program

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PROGRAM DESCRIPTION

The Quantum Measurement Program, based at the University of Melbourne, uses both optical and electrical measurement techniques to study fundamental elements of the Si:P solid state, quantum computing architecture. These include measurements of Quantum Devices providing essential information about their design, fabrication and operation. The techniques used provide the opportunity to directly measure the quality of fabricated materials, study donor-donor interactions and estimate the extent of wavefunction overlap. Our aims are to:

- Study electrical transport through a variety of implanted dopants, in order to uncover a distinct signature for implanted phosphorus dopants;
- Study and optimise the ion implantation process used for device fabrication including: novel donor placement strategies, minimising lattice imperfections arising from implantation and effective dopant activation;
- Observe perturbations to donor electronic states including local strain and wavefunction overlap in order to estimate the exchange coupling constant (J);
- Utilise hybrid electrical optical techniques as an additional tool to manipulate and study single phosphorus dopants in silicon.

1. Electrical characterisation toward a Si:P quantum computer

In 2008, we have been working to expand the experimental capabilities in quantum measurements at the University of Melbourne. We have tendered for and ordered a new cryogen-free measurement system, which will arrive and be commissioned in 2009. The system selected is designed and built by Leiden Cryogenics (Giorgio Frossati) in conjunction with Cryogenics Ltd. Pulse tube refrigeration combined with a traditional dilution unit enables the fridge to reach a base temperature of <15mK, with a cooling power of 450μW at 120mK. A superconducting 3D vector magnet allows the application of a magnetic field up to 9T in one direction, and 1T in each remaining orthogonal direction. The gas handling system is fully automatic, including temperature control from base temperature up to room temperature. Furthermore, a cold-insertable probe provides the opportunity for rapid sample changeover – samples can be loaded at room temperature and inserted into the cold system. Samples can be therefore be cooled from room temperature to base temperature in a matter of hours. Optical access to the sample is available using optical windows in the base of the cryostat, or via optical fibre. This system will be a fundamental tool for the electrical-optical characterization of Si:P related samples in a low temperature, high magnetic field environment.

We have continued to investigate and apply the silicon radio-frequency single electron transistor (rf-SET). Last year, CQCT published the demonstration of the first silicon rf-SET. This year, those results have been extended with a characterisation of the silicon rf-SET at 4K [1]. This opens up the possibility of fast, sensitive charge detection at liquid helium temperatures, in contrast to aluminium rf-SETs which must be operated $\sim$100mK. Additionally, due to the higher operating temperature of the silicon rf-SET, temperature dependence studies of charge sensing are also possible. This silicon rf-SET had a charge sensitivity of 11μe/$\sqrt{\text{Hz}}$ at 100mK and 21μe/$\sqrt{\text{Hz}}$ at 4.2K. The silicon rf-SET is now an integral component of the Si:P quantum computing design (see Quantum Measurement & Control Chip and Integrated Quantum Computer Devices Programs for more details).

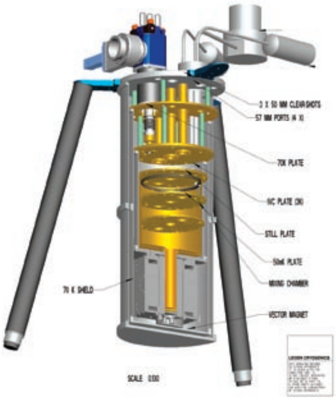

FIGURE 1

Schematic of a Leiden Cryogenics cryogen-free dilution refrigerator. Features include heavy (80kg) copper plates at each thermal stage which provide a stable, low vibrational environment, a large (340 mm) mixing chamber plate and a 3D superconducting vector magnet.

The silicon rf-SET has now successfully been used to perform charge detection on a nearby MOS-gated silicon dot. Measurements were performed during an extended visit to the University of Cambridge, under a collaboration with Dr Andrew Ferguson supported by a University of Melbourne Joint Research Project Grant. The samples were fabricated by Dr Ferguson at the University of Cambridge, as part of continuing investigations into charge sensing applications of the silicon rf-SET. The experiments aim to investigate few electron quantum dots in silicon, studying the effects of quantum confinement in silicon structures [2].

A joint project between CQCT and Sandia National Laboratories (as part of the Collaborative Research and Development Agreement (CRADA)) to investigate resonant tunnelling through individual structures is underway. Phosphorus, silicon and antimony samples will be produced in order to identify signatures of different atomic species. The device design was finalized during a visit to Albuquerque in August, and samples are now in production in the Microelectronics Development Laboratory (MDL) at Sandia. Initial characterization of the samples will be done at Sandia to facilitate rapid feedback between testing and fabrication. Detailed characterisation and analysis will then be performed using the new cryogen-free measurement system in Melbourne. The process of collaborating in device design and fabrication has already led to significant knowledge transfer between Sandia and CQCT, and in particular to an increased appreciation of the fabrication process in the MDL.

2. Spectroscopic characterisation of the Si:P system for quantum computer applications

During 2008, we have continued to study the Si:P system with a view to understanding:
(i) lattice defects arising from ion implantation,
(ii) the influence of interface states on donor ionisation and (iii) donor-donor interactions.

With the commissioning of a new, near-infrared (NIR) micro-Raman spectrometer this year, new opportunities to perform high resolution Raman [3 ,4] and photoluminescence (PL) [5] measurements on silicon [6] and Si:P have arisen. Traditionally, PL is used to monitor dopant activation, compensation and strain in silicon and other materials but the technique may also be employed to study phosphorus doped ensembles in nano-layers produced using ion implantation techniques.

Measurements of PL (Simon Fraser University) arising from ion implanted Si:P ensembles are shown in Figure 3 and has two dominant spectral features. The first is the P_{NP} (no phonon) transition arising from non-interacting donors while the second is the P_{NP} cluster band (broad transition) which arises from excitons bound to clusters of interacting donors. The centre of the cluster band shifts with increasing P concentration (coloured region) which we varied by changing the ion fluence and energy. This band shift has been successfully modelled down to donor pair spacings of ~5 nm [7].

In addition to PL, electronic Raman scattering (ERS) measurements were also performed using the new instrument. This technique is sensitive to donor wavefunction overlap and may be used to estimate J (exchange coupling constant) [9]. Measurements of a bulk doped Si:P sample are shown in Figure 4 [10]. A number of overlapping transitions are evident which evolve both with temperature and excitation polarisation. The transition at ~120 cm^{-1} is PL and originates from P no phonon bound excitons while that at ~105 cm^{-1} arises from donor ground state absorption (ERS). Peak splitting is evident at each temperature and for each transition indicating that the sample is under strain.

This Program has also been working in collaboration with the Magnetic Resonance (MR) Program to study [10] ion implanted ensembles. The EPR technique is sensitive to defects at the Si-SiO_2 interface and can also be used to quantify dopant activation as a function of the implantation depth. Results of these studies can be founding the MR Program report. These studies were supplemented [11] by far-infrared, magneto-spectroscopy (absorption) measurements of ion implanted ensembles. Using a neutron transmutation doped (NTD) control sample, phosphorus transition intensities were compared to assess the level of donor activation. For implanted ensembles, no donor transitions were observed. This may be due to: imperfect P substitution on the host lattice, residual lattice damage following the high temperature anneal or donor ionisation caused by localised charge traps (i.e. lattice imperfections).

3. Conclusions and Future Developments

This year, the Quantum Measurement Program has successfully employed a range of electrical and optical techniques to the study of: devices, ensembles, fabrication strategies and materials associated with solid state quantum computing architectures. Future directions in 2009/10 will see the combination of electrical and optical measurements on nanofabricated structures which will be facilitated by the acquisition of a new <50mK cryostat with combined optical and electrical access. Samples will be able to be measured in magnetic fields of up to 9T. The goal will be to increase the sensitivity of optical techniques to smaller numbers (and ultimately single) donors. Electrical characterisation will be used to perform both ensemble characterisation of implanted dopants and also to investigate quantum effects using the single electron transistor.

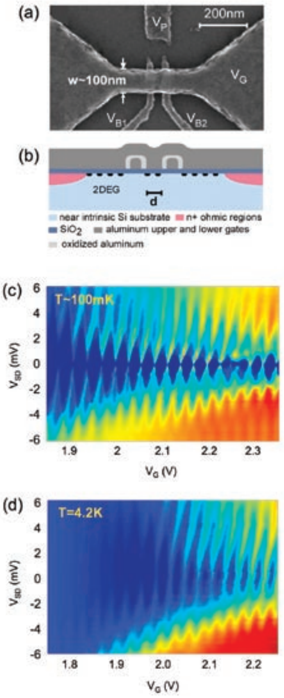

FIGURE 2

The silicon rf-SET. (a) An SEM image of a typical silicon SET. (b) Cross-sectional schematic illustrating the island formed in the two-dimensional electron gas in the silicon substrate. (c) and (d) A comparison of the bias spectroscopy of the silicon rf-SET at 100mK and 4.2K.

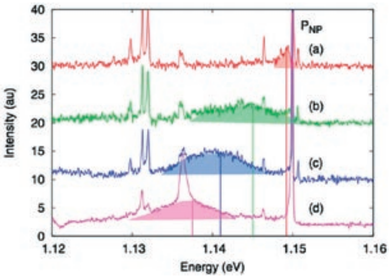

FIGURE 3

Low temperature Si:P photoluminescence from ion implanted ensembles. Samples were prepared as: (a) 70keV P^+; fluence: 1×10^{12} cm^{-2}, (b) 70keV P^+; fluence: 5×10^{12} cm^{-2}, (c) 70keV P^+; fluence: 1×10^{13} cm^{-2} and (d) 35keV P+; fluence: 1×10^{13} cm^{-2}. Coloured lines indicate the approximate position of the centre of the PNP cluster band.

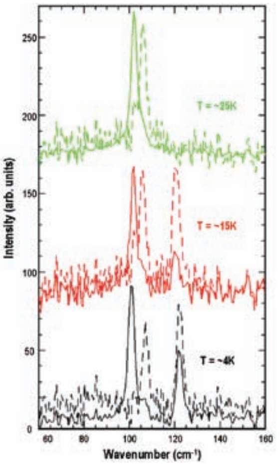

FIGURE 4

Electronic Raman measurements of 0.1Ω.cm Si:P (8×10^{16} P cm^{-3}) obtained using NIR excitation showing a strain split, P no-phonon bound exciton line at ~120 cm^{-1} as well as the donor ground state absorption at 105 cm^{-1}. The same sample was measured at various temperatures (T< 50K) and linear excitation polarisations (Dashed line: laser polarisation is aligned with the detector. Solid line: laser polarisation is perpendicular to the detector).

4. References

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