Quantum Measurement Program

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PROGRAM DESCRIPTION

The Quantum Measurement Program, located in the School of Physics at the University of Melbourne, uses both optical and electrical measurement techniques to study the fundamental elements of the Si:^{31}P solid-state, quantum computer architecture. These include measurements of Quantum Devices providing essential information about their design, fabrication and operation. The techniques used in this program provide opportunities to measure the quality of fabricated materials, and study donor-donor and donor-environment interactions. Our aims are to:

- Study electrical transport through a variety of implanted dopants, in order to uncover a distinct signature for implanted phosphorus donors;
- Study and optimise the ion implantation process used during device fabrication including: developing novel donor placement strategies, minimising lattice imperfections arising from the implantation process and ensuring dopants are activated even when in close proximity to the Si-SiO_2 interface [1];
- Study perturbations to donor electronic states arising from local strain and electric fields in addition to donor 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. Spectroscopic characterisation of the Si:^{31}P system for quantum computer applications

In 2009, we have continued to study the Si:^{31}P system using optical techniques in order to better understand donor state perturbations arising from: (i) processing damage (eg. ion implantation) [2,3], (ii) residual lattice strain and (iii) donor-donor interactions. In addition to optical characterisation of Si:^{31}P, this program has also been (i) developing new ways of placing donor atoms into silicon with nanometer precision using ion implantation techniques [4,5] in order to create new electronic materials with novel characteristics [6] and (ii) using spin resonance techniques to study donor states in proximity to silicon interfaces (eg. SiO_2, SiH) [7,8].

Electronic Raman spectroscopy measurements are performed at the Bio21 Molecular Science and Biotechnology Institute where we have established a unique spectroscopy laboratory which includes a Renishaw Invia Reflex near-infrared micro-Raman spectrometer. This instrument was specifically designed to perform high resolution measurements on silicon at wavelengths where e-Raman and photoluminescence emissions dominate. Figure 1 provides an example of such a measurement obtained using 1064nm laser (NIR) excitation. At this wavelength and temperature, this NIR laser is only weakly absorbed by silicon allowing the creation of electron-hole pairs which can recombine giving rise to photoluminescence (PL). The PL peaks observed in Figure 1 arise from phosphorus donor (bound) and free (unbound) exciton states (P_{TO}, P_{TA}, $FE_{LO,TO}$). In addition to PL transitions, Figure 1 also depicts the one photon forbidden e-Raman transition of phosphorus donors (P_{ERS}) and characteristic silicon lattice excitations (phonons) labelled as transverse optic (TO) and transverse acoustic (TA). The relative signal intensity of the PL and e-Raman transitions should be compared with that of the silicon TO phonon at ~520 cm^{-1} which is ~2 orders of magnitude more intense and off the scale of this plot. It should be recalled that only 1 photon in ~10^7 will be inelastically scattered into the silicon TO phonon.

An important series of measurements undertaken this year have been to look at the effect of lattice strain on the donor energy levels [9]. We have modelled changes to the ground and 1s(E) excited states of Si:^{31}P

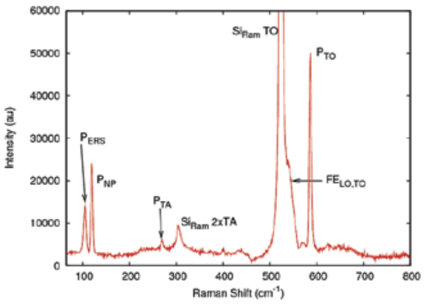

FIGURE 1

Low temperature (~4 K), NIR micro-Raman spectrum of bulk doped Si:P (0.3 Ω.cm) showing phononic transverse optic (TO) and acoustic (TA) silicon lattice excitations, the one photon forbidden e-Raman transition of phosphorus donors and photoluminescence arising from bound and free excitons (P_{TO}, P_{TA}, $FE_{LO,TO}$).

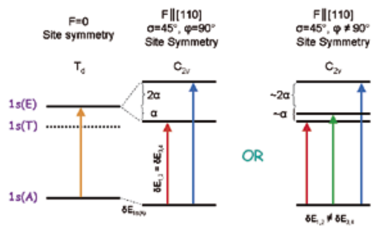

FIGURE 2

The splitting and shifting of phosphorus donor levels in silicon with strain applied parallel to one of the silicon crystal axes (F ||[110]). The arrows indicate the allowed transitions from the ground state ($1s(A_1)$) to the split 1s(E) levels as observed using e-Raman spectroscopy for the stated site symmetry designations [10].

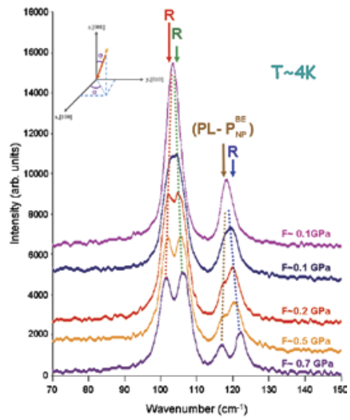

FIGURE 3

Strain induced splitting and shifting of the phosphorus donor levels in ensembles as observed using the electronic micro-Raman scattering technique. The sample is bulk doped (0.05 Ω.cm) and spectra have been offset for clarity. Labels "R" correspond to e-Raman transitions while "PL" corresponds to photoluminescence transitions.

after the application of uniaxial strain using the deformation potential constants for phosphorus ensembles. Since the transition from the ground state to the 1s(E) level is (parity) forbidden [10], changes to this state cannot otherwise be easily studied. The e-Raman technique however, is able to observe these changes directly so we have applied this technique to the study of donor state splitting and shifting as a function of the applied strain.

Figure 2 shows the energy level diagram for unstrained (**F**=0) Si:^{31}P however, under uniaxial compressive strain, the degeneracy of the 1s(E) state can be lifted giving rise to spectral multiplicities. For a compressive force **F** aligned parallel to the [110] crystal axis (ie. $\theta=45$ and $\phi=90°$), we expect the single donor transition to split into two as depicted in the figure [11]. If the direction of **F** is changed such that $\phi\neq90°$, further axial degeneracy is lifted as shown.

Figure 3 shows low temperature (~4 K) electronic micro-Raman measurements from bulk doped Si:^{31}P with a phosphorus concentration of 2x10^{17} donors cm^{-3} obtained under compressive strain. As the magnitude of the applied strain (**F**) is changed, there is a clear increase in the splitting of the 1s(E) donor states which start off initially broadened. These states are normally doubly degenerate in unstrained silicon. The coloured arrows associated with each peak are the same as those used in the energy level diagram of figure 2 to indicate the origins of each transition. One of the peaks observed in figure 3 arises from phosphorus bound exciton (no-phonon) photoluminescence at around 120 cm^{-1}. While bound exciton states are known to be very sensitive to strain fields, it is clear from these measurements that the donor transitions clearly also undergo large strain dependent changes. The appearance of 3 spectral lines associated with donor transitions is a consequence of the application of off-axis strain (**F**). Using the measured energies of these transitions, it is possible to extract **F**, θ and ϕ.

2. Electrical characterisation toward a Si:P quantum computer

Toward the end of 2008, a cryogen-free measurement system was ordered. The system consists of a Leiden fridge with a base temperature of <15 mK and a superconducting 3D vector magnet from Cryogenics LTD. In 2009, the manufacturer began fabricating both the fridge and magnet assemblies. The complexity of this system has resulted in a shipping delay however it is now nearing completion and expected to arrive early in 2010. The laboratory that will house this facility and its related equipment is now fully furnished with the necessary utilities such as compressed air, cooling water and power. This laboratory is situated adjacent to the CQCT Cleanroom Complex which houses other instruments associated with Centre programs. A services room has also been configured next to the new low temperature laboratory to house the helium compressor so that acoustic and mechanical vibrations are minimised in this facility.

Instrumentation for sensitive electrical characterisation has already arrived and is currently being used in the electrical characterization laboratory. Various research programs are also being developed to utilise this equipment. The optical accessories will be developed following the arrival of the fridge.

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 2010 will see the combination of electrical and optical measurements on nanofabricated structures which will be facilitated by the delivery of the new <50 mK cryostat.

4. REFERENCES

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