Magnetic Resonance Program

PROGRAM MANAGER

Dr Wayne Hutchison – UNSW@ADFA

MAGNETIC RESONANCE PROGRAM RESEARCHERS

Staff Dr Libu Alexander, Mr Todd Bell, Dr Greg Milford

COLLABORATING CENTRE RESEARCHERS

University of Melbourne, Australia
Dr Jeff McCallum, Prof Steven Prawer, Dr Paul Spizzirri
University of New South Wales, Australia
Dr Eric Gauja, Dr Hans Huebl, Dr Laurens Willems van Beveren,

OTHER COLLABORATORS

Walter Schottky Institute, Germany
Prof Dr Martin Brandt, Mr Felix Hoehne
Australian National University
Dr Matthew Sellars, Ms Rose Ahlefeldt

PROGRAM DESCRIPTION

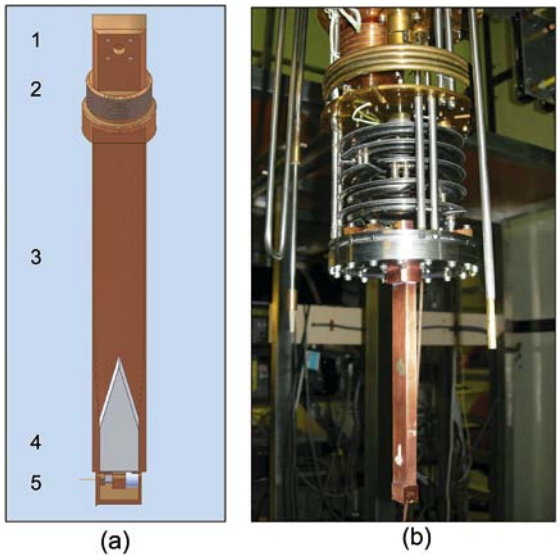
The general aim of this program is the use of magnetic resonance, directly, to measurements on spin systems which have application as spin based quantum computers (QC). The technique is also applied to investigations of the principal materials and fabrication processes. The emphasis is on electron spin resonance (ESR) studies of the phosphorus in silicon (Si:P) system. The experimental program has several main components as follows:

1. Pulsed ESR for Coherence Time Measurements

One of the attractions of a spin based quantum computer is the prospect of long coherence times. In particular the Si:P electron spin system is predicted theoretically to have extremely long coherence times. In this project, pulsed ESR is applied to ensembles of phosphorus spins to explore experimentally the maximum extent of spin coherence. The main variables to be considered in the pursuit of longer spin coherence times are the concentration of the phosphorus donors, that of the ^{29}Si isotope with non-zero nuclear spin, and the measurement temperature. A pulsed ESR system has been developed that can operate in conjunction with an electro-magnet down to 4 K, or with a dilution refrigerator and superconducting solenoid magnet down to millikelvin (mK) temperatures. Our mK system, pictured in Figure 1, has been tested down to ~50 mK. The main tool in coherence time studies is the electron spin echo (ESE). An ESE occurs following a two pulse sequence and measurement of the ESE magnitude as a function of pulse separation, τ, gives the ensemble decoherence rate T_M directly. The isolated single spin decoherence rate T_2 is extracted from the T_M data by either a multi-exponential fit or by multiple

FIGURE 1

The cold finger section of the millikelvin pulsed ESR system: (a) Schematic in cross section and (b) the actual unit attached to the dilution refrigerator.



experiments with a decreasing second pulse width and projection of the resulting T_M verses pulse width data to zero. At any temperature $T_2 \leq T_1$, the spin lattice relaxation rate. At very low temperatures the Si:P T_1 becomes very long and an impediment to signal averaging in the ESE experiment. In our systems a pulse of light is used immediately following each echo to facilitate faster relaxation and signal averaging. Extensive testing has shown that this procedure does not appear to affect the shape of the ESE signal decay curves. We previously reported $T_2 = 5.6$ ms for natural silicon (~4.7% ^{29}Si) bulk doped with 10^{15} cm^{-3} phosphorus donors, and for $T_2 \approx 10$ ms for isotopically pure ^{28}Si (~ 0.1 % ^{29}Si) epilayers with a phosphorus concentration of 10^{16} cm^{-3}. Both of these results, determined by the projection method, were carried out at a measurement temperature of 0.9 K at which T_2 reached its limiting value. In the natural silicon case this limit is governed by ^{29}Si nuclear spin flips. In the epilayer case the limit might be thought due to phosphorus concentration. However new results on bulk ^{28}Si (99.92% pure) doped at 5 x 10^{15} P cm^{-3} would suggest otherwise. Some ESE results for the bulk ^{28}Si sample, at 4.2 and 0.9 K, are shown in Figures 2 and 3. Projections of these T_M's to zero second pulse widths are in Figure 4, from which the T_2's are estimated at 260(50) ms and 330(100) ms, respectively. Clearly these latter decoherence times are more than an order of magnitude longer than that of the epilayer even though the phosphorus concentration is only a factor of two reduced. It is emerging that the important factors for spin coherence in Si:P are ^{29}Si concentration and the quality of the lattice (that is free from defects and impurities). Finally, we note that additional experiments have been carried out on the bulk ^{28}Si sample at 0.2 K which indicate slightly longer T_M's, although the light resetting regime will require adjustment to give consistent results.

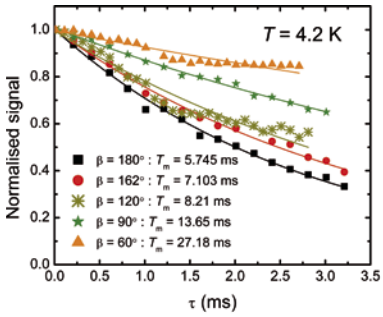


FIGURE 2

Si:P ESE decay data for various refocusing pulse turn angles (b) at 4.2 K.

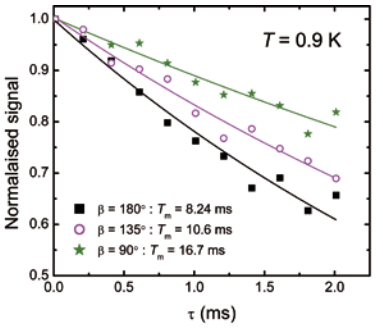


FIGURE 3

Si:P ESE decay data for various refocusing pulse turn angles (b) at 0.9 K

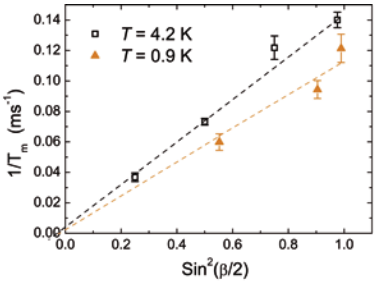


FIGURE 4

1/ TM v sin^2(β/2) plots from the ESE data at 4.2 and 0.9 K.

2. Electrically detected EDMR

Electrically detected magnetic resonance (EDMR), is where a change of the dc conductivity due to spin resonance is observed. Previously, working with UNSW, UM and WSI, we used EDMR to detect as few as 50 spins in a submicron size silicon device into which the phosphorus donors had been implanted. EDMR is also particular useful in the study of surface defects on semiconductors and their influence on donors placed near to the surface. In the case of shallow donors (eg phosphorus) in silicon (Si:P), it has been proposed that the spin dependent recombination/scattering of the photoelectrons proceeds via a process also involving (deeper energy) surface electron traps like the so called P_b silicon interface dangling bonds.

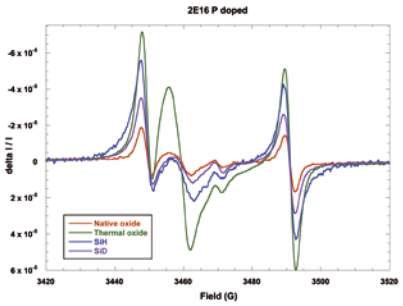


FIGURE 5

EDMR signals collected at ~5 K for Si:P devices with 2 x 10^{16} P cm^{-3}, for various surface types as labelled.

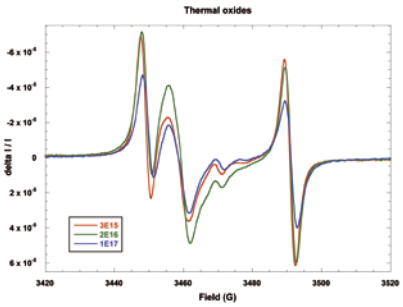


FIGURE 6

EDMR signals collected at ~5 K for Si:P devices with 3 x 10^{15}, 2 x 10^{16} and 1 x 10^{17} P cm^{-3} respectively, all with thermal oxide surfaces.

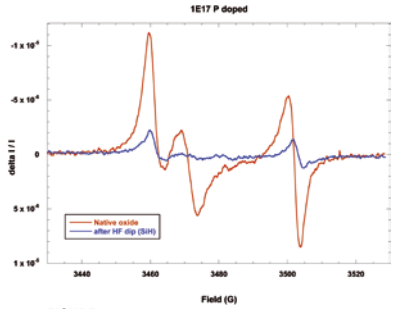


FIGURE 7

EDMR signals collected at ~5 K for Si:P device with 1 x 10^{17} P cm^{-3}, with native oxide surface and immediately following a HF etch which replaced the oxide with a hydrogen terminated surface.

In this past year, in conjunction with UM a robust multi-micron EDMR device in silicon has been developed, with a view to detailed comparisons of the effects of different surface preparations, as well as variations in donor profiles. Preliminary results using bulk doped substrates with native and thermal oxides, as well as H- and D-terminated surfaces have been measured, using facilities at WSI. EDMR spectra were collected for the three P concentrations and the various surface types, for example Figure 5 shows data for various surfaces at 10^{16} P cm^{-3}. As for Figure 5, the maximum P and P_b signals occurred with the thermal oxide surface at all concentrations. This is perhaps unexpected given that the thermal oxide should have a much lower Pb trap areal density than the native oxide. The results for the thermal oxide cases are reproduced for direct comparison in Figure 6. Surprisingly there is little variation in the signals as a function of in P concentration, over nearly 3 orders of magnitude, and indeed are slightly smaller at the higher concentration (10^{17} cm^{-3}). The trend is clear with the P and P_b signal magnitudes moving in concert. The devices with thermal oxide surfaces have the largest signals, while native oxides have the smallest (of the pre-prepared set). These trends are virtually independent of the P concentration. The H- and D-terminated surfaces provide signals intermediate between the other two. These preparations, however, do not appear to represent true trap free interfaces when compared to the results in Figure 7, where much smaller signals were obtained from a freshly prepared (i.e. just prior to measurement) SiH surface. These results clearly demonstrate that a photo current recombination model for EDMR in Si:P requiring the presence of deep charge traps is valid. There is an optimal relative concentration of traps to donors to get large EDMR resonances. Too many traps (eg native oxide) deplete donors. With too few traps (fresh SiH) the recombination path is blocked. Anecdotally, from our measurements the thermal oxides in combination with bulk P densities between 10^{15} to 10^{16} cm^{-3} seems optimal for maximum strength EDMR signals.

3. Swept field ESR Measurements

Conventional (swept field) ESR studies of large area Si:P implants (ensembles) produced at the University of Melbourne are also ongoing. The study of implanted P^+ and molecular P_2^+ via ESR is of interest to examine dopant activation levels and exchange coupling of the pairs in the later case. Such studies also complement photoluminescence and Raman spectroscopy measurements, as well as identifying suitable samples for coherence time studies. Focus continues on examination of various preparation methods with a view to maximise donor activation, as viewed by ESR, and to minimise unwanted charge traps, which are mostly associated with the implantation process itself. Poor donor activation has been observed (using ESR) when using low energy implantation into substrates with surface oxides and is a non-trivial issue to resolve. Previous work revealed that for the lower energy implants, even say 15 keV, ESR signals from donors can be very weak compared with deeper implants and that theoretically predicted. There was a strong indication that donor electrons are being poached by traps when the donors are placed near to the surface (i.e. the donors are effectively compensated by interfacial traps). There are many approaches to improve the yield of low energy implants and ESR can be applied as a diagnostic. The central issue is the reduction of interface charge trap densities. High quality thermal oxides are found to be useful but the key factor is whether these can be produced repeatably. Other methods of preparing clean, hydrogen terminated, oxide free surfaces (which yield better donor activation levels at even lower implant energies) are also being explored. Trap densities, as observed by ESR, largely manifest as the magnitude of the signal from interface dangling bounds known as P_b centres.

During 2009 ESR measurements were also conducted on Nd^{3+}:$EuCl_3.6H_2O$, a system under study at the ANU as a possible quantum computing host whereby spin states are detected and manipulated via optically (Raman hetrodyne) detected NMR. The purpose of the ESR was to establish the ground state of the Nd^{3+} ions in this lattice.