Magnetic Resonance Program

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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:

FIGURE 1

Pulses of light are used to circumvent long spin lattice relaxation for the millikelvin pulsed ESR system: (a) Laser light entry points at room temperature, and (b) optical fibre links to the ESR resonator.

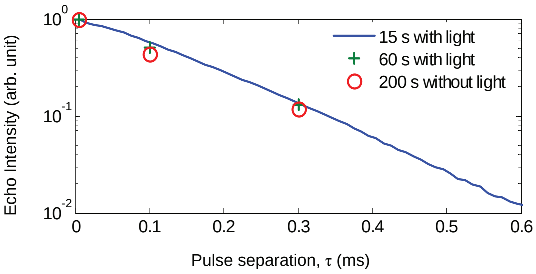
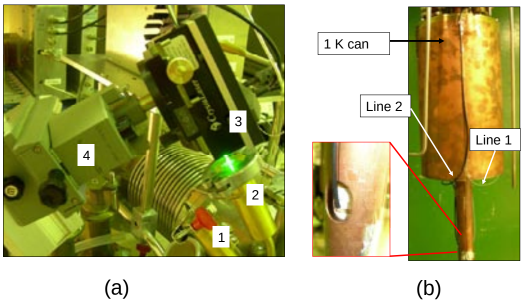


FIGURE 2

A test of the light set up in the millikelvin pulsed ESR system. A favourable comparison of ESE amplitudes between shorter sequence repeat intervals with a light pulse and much longer (200s) without light. Measurements were made with a 28Si epilayer doped with 10^{16} cm^{-3} phosphorus donors at 4.2 K.

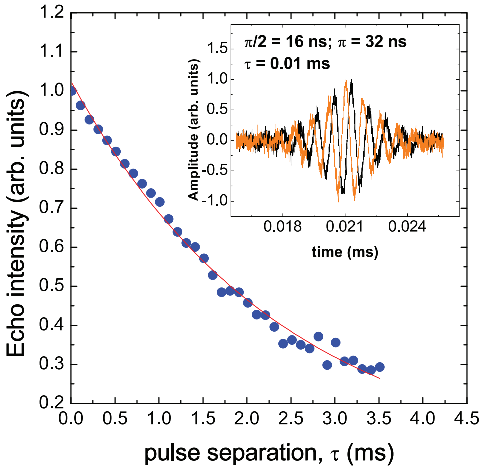


(a)

(b)

FIGURE 3

Example ESE data for bulk ^{28}Si doped with 5×10^{15} cm^{-3} phosphorus donors at 4.2 K. A fit to the data indicates a ensemble decoherence time $T_M \approx 10$ ms for the pulse sequence indicated. The inset shows the modulated form of these echoes collected purposely slightly off resonance.



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 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 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. The set up to get light down into the ESR resonator located on the cold finger of the dilution refrigerator is shown in Figure 1. An illustration of the effectiveness of the light pulses in circumventing T_1 problems is shown in Figure 2. Initial coherence measurements on the millikelvin system were completed early in 2008. Firstly, for natural silicon (~4.7% ^{29}Si) bulk doped with 10^{15} cm^{-3} phosphorus donors, for which the lowest measurement temperature was 0.9 K at which T_2 reached a limit governed by ^{29}Si spin flips of ~ 4 ms as determined by the extraction method or 5.6 ms via projection. Secondly, for isotopically pure ^{28}Si (~ 0.1 % ^{29}Si) with (bulk doped) phosphorus concentration of 10^{16} cm^{-3}, from which the projection method gave a value of $T_2 \approx 10$ ms. Since it is expected that T_2 should scale inversely with donor concentration, one might expect an isolated spin coherence time of approximately 100 ms for a sample with 10^{15} cm^{-3} phosphorus donors at 1 K and to do even better at lower temperature. What is required to achieve such coherence times in practice, are a high quality ^{28}Si hosts lightly doped with phosphorus. Some measurements on bulk ^{28}Si doped at 5×10^{15} cm^{-3} phosphorus are promising. For example the data in Figure 3, using a standard ESE pulse sequence yields an ensemble T_M coherence time of 4.8 ms. Sequences with shorter second pulses give T_M's out to 15 ms. These ensemble coherence times are some order of magnitude longer than for the ^{28}Si epilayer examined earlier. However, because these measurements where made off resonance to avoid radiation damping issues, it is not possible to derive the isolated spin coherence time T_2 with any confidence. Ironically the quality of this material, reflected in the narrowness (in the frequency domain) of the ESR linewidth, means that a new lower Q resonator will be required to extract the ultimate coherence times. Such a resonator is under development.

2. 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. Figure 4 is an example compilation of data showing a range of P_b signal intensities from silicon samples with a range of surface finishes. The ESR spectrum of Figure 5 is for a shallow P^+ implant (14 keV) into a silicon wafer with a good quality thermal oxide that was carefully annealed. The fluence was relatively high and is reflected in large central line from clustered P donors which never-the-less dwarfs the signal from active P_b centres.

FIGURE 4

Comparison of ESR signals, extensively from P_b type charge traps, from nominally 'blank' high resistivity silicon samples with various surface capping.

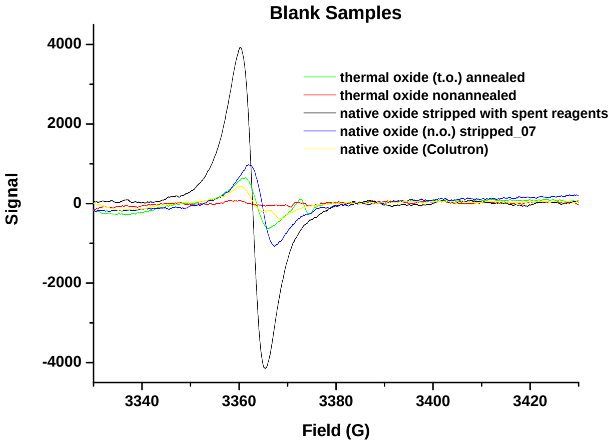


FIGURE 5

ESR spectrum of a silicon wafer which has been implanted with P_2^+ ions at 14 keV and a fluence of 6.0×10^{12} cm^{-2} using the UM colutron. The triplet spectrum indicates exchange coupled P donors.