Electrical Readout of $^{31}$P Spin Qubits in Crystalline Silicon at High Magnetic Fields

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Introduction
Phosphorus ($^{31}$P) doped silicon (Si:P) is a technologically important material with possible uses in spintronic and quantum information processing devices. The goal of the work described in the following was to carry out pulsed electrically detected magnetic resonance (EDMR) experiments at high magnetic fields in order to (i) understand the sensitivity limitations of electrical spin measurements on $^{31}$P and (ii) demonstrate electrically detected nuclear magnetic resonance by combination of pulsed EDMR and electron nuclear double resonance.

Improving the sensitivity of pulsed EDMR
EDMR was measured in Si:P devices with contacts patterned with electron beam lithography to have active areas of 50 nm × 50 nm. These measurements generally reproduced the features described in our previous research on devices with larger active areas [1-3], and used the same spectrometer [4,5].

Figure 1 shows a spectrum recorded with a device having a thickness of 500 μm and a phosphorus concentration of $1-3 \times 10^{15}$ cm$^{-3}$. To estimate the number of spins participating we use $50 \text{ nm} \times 50 \text{ nm} \times 500 \mu \text{m} \times 2 \times 10^{15} \text{ cm}^{-3} \approx 10^3$ spins. The real active volume will be wider than 50 nm × 50 nm, but less than 500 μm thick [3]. High field EDMR has not previously been demonstrated with fewer than $\sim 10^8$ spins [2] so it is encouraging that the signal-to-noise is similar after scaling the experiment down by more than four orders of magnitude. Similar scaling was suggested by a series of low-field EDMR experiments with Si:P [6]. To scale down further we will use a silicon-on-insulator (SOI) wafer with a device thickness of 100–300 nm.

Electrical nuclear spin detection
We have also demonstrated pulsed, electrically-detected electron nuclear double resonance (pEDENDOR) on Si:P. Figure 2 shows both a conventionally detected and electrically detected signal obtained from a pulsed ENDOR experiment. A resonance is seen at $\sim 206.7$ MHz in both cases. pEDENDOR of the $^{29}$Si nuclear spins in the naturally abundant silicon host were also observed. Neither signal has the expected Gaussian lineshape. This is due to the extremely long nuclear spin lifetimes ($\sim$minutes) of the $^{31}$P donors, which lead to passage effects even at very slow sweep rates. Our proof-of-principle demonstration of electrical readout of coherently controlled nuclear spins at high fields provides a pathway towards the electrical readout of nuclear spin qubits. This technique will also be of wider use as a tool for investigating nuclear spins in macroscopic electrical devices, which are usually too small to be investigated with conventional resonance techniques.

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References