

Electrically detected Rabi oscillations of phosphorus qubits in silicon

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Electrically detected magnetic resonance is a sensitive technique for studying electron spins bound to phosphorus atoms in silicon. Using a high magnetic field of 8.6 T increases this sensitivity by accessing a mechanism for spin-to-charge conversion which is different to that in the more commonly used magnetic field of ~ 0.33 T. The higher-field regime benefits from a long spin coherence time of over 100 μs because the

phosphorus spins that are detected are not coupled to dangling-bonds. Additionally, the high field permits the spin qubits to reach an equilibrium polarization of over 95% at a temperature of 2.8 K. We demonstrate electrically detected Rabi oscillations of these electron spins in the high-field regime. The Rabi frequency is proportional to the square root of the excitation power as expected.

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1 Introduction Electron spins bound to phosphorus atoms in silicon could be used as qubits in future quantum technologies [1, 2]. They benefit from very long spin lifetimes [3] and coherence times [4] at helium temperatures. A major obstacle to engineering a quantum computer in this way has been the problem of reading out a single electron spin. This has recently been achieved with an electrical measurement [5], but the single electron transistor used is 60 nm or less from the qubit and the effect of this on the spin coherence times has not yet been checked.

Our approach to spin readout uses electrically detected magnetic resonance at a high magnetic field of 8.6 T and a temperature of 2.8 K. The Pauli exclusion principle provides a spin-to-charge conversion: polarized photoelectrons are trapped if and only if they have opposite spin to the phosphorus qubits [6, 7]. We have previously presented electrically detected measurements of the electron spin coherence time in this regime, showing a relaxation time of 100 μs [7]. This is over an order of magnitude longer than similar measurements at low magnetic fields [8], where the mechanism for spin-to-charge conversion is different. In the low-field regime, a range of electrically detected magnetic

resonance experiments have been performed with phosphorus-doped silicon (Si:P) including electron spin echo envelope modulation (ESEEM) [9], electron–nuclear double resonance (ENDOR) [10–12], and electron–electron double resonance (ELDOR) [13]. We have previously demonstrated electrically detected ENDOR of Si:P in the high magnetic field regime [14, 15].

Rabi oscillations illustrate the quality of single qubit gates in a quantum computation. They are used to illustrate coherent spin manipulation and to determine the pulse length needed for a specific angle of spin rotation. The spin precesses about the magnetic field of the resonant pulse at a frequency that is proportional to this magnetic field and thus proportional to the square-root of the power in the excitation pulse. We have previously demonstrated electrically detected Rabi oscillations [16] with a different sample to the one we used for electrically detected spin echo measurements [7]. This made it difficult to compare the decay times for the Rabi oscillations and the spin echo.

2 Experimental Our experiments were performed at the National High Magnetic Field Laboratory in Tallahassee

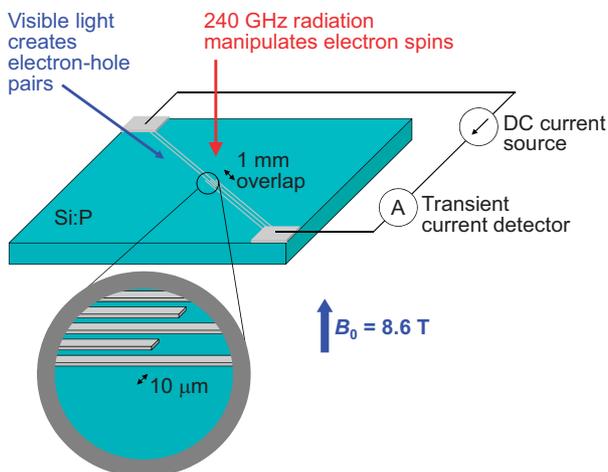


Figure 1 (online color at: www.pss-b.com) Schematic of the experimental setup. The temperature used was 2.8 K.

Florida using the quasi-optic pulsed EPR spectrometer we have described previously [17, 18]. The spin excitation was with circularly polarized 240 GHz millimetre waves, concentrated with a Fabry-Pérot resonator.

The electrical detection setup uses photoconductivity as shown schematically in Fig. 1 and has been used in the past [7, 14, 19, 20]. The device and the experimental conditions were identical to those described in Ref. [7]. The (111)-oriented, 330 μm thick, prime grade Cz-grown silicon wafer has a phosphorus concentration of $\sim 10^{15} \text{ cm}^{-3}$. Five interdigitated Al wires, 100 nm thick, were fabricated with optical lithography with a width and separation of 10 μm . An HF etch dip was used to remove the native oxide. Continuous irradiation with a filtered Xe lamp allowed a Keithley 6220 current source to drive a photocurrent of 60 nA. A SR570 current amplifier was used, which responds more slowly than the electrical circuit [7].

The power of the mm-waves was adjusted by rotating a wire grid which has previously been calibrated to provide known attenuation [18].

3 Results and discussion Figure 2 shows the current transients following a mm-wave pulse with the magnetic field both on and off the ^{31}P EPR resonance. Of the two ^{31}P hyperfine resonances, the higher-field one was used for these measurements. With off-resonant excitation, no current transients are seen, in contrast to experiments at low magnetic field [21]. The current recovers with an exponential time constant of $2.5 \pm 0.1 \text{ ms}$ in our measurements here; this is not limited by the detection electronics, but is the same as the electron spin lattice relaxation time, T_1 , measured with the same illumination using traditional EPR, with no electrical measurement [7].

The correct length for a π pulse was found to be 480 ns with full mm-wave power from the Rabi oscillations shown in Fig. 3. For these measurements, the current transient after a single pulse was integrated for pulse lengths between 0 and

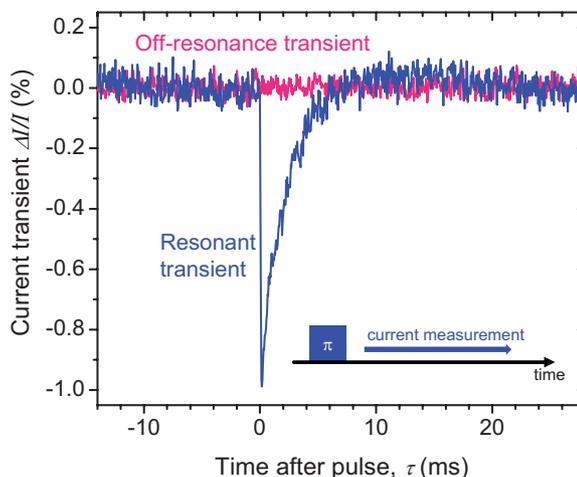


Figure 2 (online color at: www.pss-b.com) Electrical transients with on and off resonance excitation using a 480 ns pulse and full mm-wave power, P^{max} . The resonant data have been published previously [7] and are used with permission of the APS.

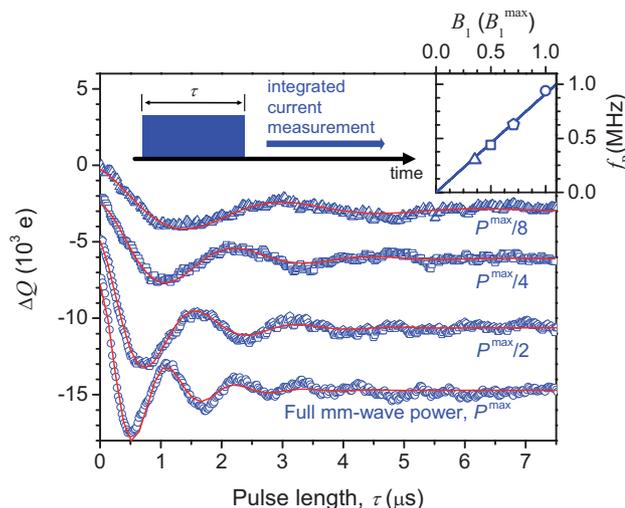


Figure 3 (online color at: www.pss-b.com) Electrically detected Rabi oscillations. The Rabi frequencies (inset) were obtained by Fourier transforming the oscillations. The fits to the data are with an exponentially decaying cosine function. The time constant for the decays are shown in Table 1.

8 μs . This was repeated for four different microwave powers and the Rabi frequency is proportional to the microwave magnetic field, B_1 . These oscillations are evidence that the spins are being coherently manipulated and detected. The coherence decays after a few μs due to inhomogeneities in the mm-wave field. The thickness of the silicon wafer is similar to the $\sim 360 \mu\text{m}$ wavelength of 240 GHz radiation in silicon. By refocusing the inhomogeneities with an electrically detected spin echo sequence [7] we measured a spin coherence time of over 100 μs .

Table 1 Fitted Rabi decay time constants from Fig. 3.

mm-wave power (P^{\max})	Rabi decay time constant (μs)
1/8	1.84
1/4	1.35
1/2	0.98
1	0.74

We estimate that there are 10^9 ^{31}P electron spins contributing to the signals measured here. Using contacts separated by 100 nm may enable single spin measurements with this technique [7].

In conclusion, we have presented our electrically detected coherent manipulation of phosphorus electron spins in silicon. The high magnetic field of 8.6 T allows us to study phosphorous dopants that are not coupled to other spins. The relative Rabi frequencies follow the expected behaviour.

Several proposals for quantum computing require two different qubit species [22–24]. Bismuth atoms in silicon could be used as spin qubits as their electrons have long coherence times [25, 26] and the nuclear spin of 9/2 provides a large Hilbert space that could be used for storing quantum information [25–29]. Pulsed EDMR with Si:Bi samples at high magnetic fields is needed to find out whether the spin-to-charge mechanism found for Si:P dominates in Si:Bi also.

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