Electrically detected spin echoes of donor nuclei in silicon

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The ability to electrically probe the spin properties of solid state systems underlies a wide variety of emerging technologies. Here, we demonstrate the electrical readout of the nuclear spin states of phosphorus donors in silicon in the coherent regime with modified Hahn echo sequences. We find that while the nuclear spins have electrically detected phase coherence times exceeding 2 ms, they are nonetheless limited by the artificially shortened lifetime of the probing donor electron.

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I. INTRODUCTION

Using spin to encode and process information lies at the heart of a range of emerging technologies.1–5 While electron spins are an obvious choice for manipulating information, nuclear spins provide a robust system in which to store spin information for long periods of time.6 However, while a number of optical7,8 and quantum Hall based techniques9 exist for reading the state of small ensembles of nuclear spins, until recently there has been no technique for doing so which is compatible with conventional electronic devices, particularly those in silicon. Using pulsed spin resonance, we recently demonstrated the ability to electrically measure the nuclear spin state of phosphorus donors in silicon10 with a long spin lifetime. However, while the nuclear spin lifetime \(T_1^n\) imposes a limit on the storage of classical information, it is the nuclear spin phase coherence time \(T_2^n\) that sets a limit on the storage of quantum information, usually shorter than the spin lifetime. Here, we utilize a spin echo technique to show that electrical readout of donor nuclear spins is compatible with phase coherence times \(T_2^n\) exceeding 2 ms, nearly two orders of magnitude longer than that previously seen.11 We also determine that the artificially shortened donor electron lifetime \(T_1^e\) limits \(T_2^n\) via hyperfine coupling to the nuclei, and discuss ways to overcome this limitation.

To access the nuclear spin state of phosphorus donors in silicon, we exploit the precise hyperfine coupling between the donor nucleus and electron. By selectively exciting the donor electron dependent on the state of the nuclear spin, we obtain a sensitive probe of the nuclear spin.10,12 A variety of methods can then be used to readout the selective excitation of the electron. For example, coupling the donor electron to the island of a nearby single electron transistor can allow single spin readout,11 although readout of coherent states of the electron using this technique has not yet been reported in the literature. Hoehne et al.11 have recently shown that electrical readout of coherent nuclear spin motion could be detected using spin-dependent recombination, although phase coherence times are limited to \(T_2^n \sim 50 \mu s\) in those measurements.

Here, we utilize spin-dependent trapping of photoexcited electrons into the \(D^-\) state of the \(^{31}\)P donor13,15 [Fig. 1(a)].
To obtain a starting point for our measurements, we first polarize the nuclear spin [Figs. 2(a)–2(d)]. While this could be achieved in a number of ways,22,23 we make use of the fact that the donor electrons are nearly entirely polarized by the rf radiation used to drive nuclear spin transitions. It is nonresonant and most likely due to resistance changes from heating the sample. The current change at 20 ms is due to the electron trapping described above, and only occurs when the electron spin resonance conditions are matched (in this case for the $f_e^2$ transition).

Following nuclear spin polarization, the system is allowed to recover for $t_{\text{wait}} = 10$ ms, long enough for the electrons to relax to the ground state ($t_{\text{wait}} > T_i^e$), but still much shorter than the nuclear spin lifetime ($t_{\text{wait}} < T_i^n$) so that the polarization is maintained. A Hahn echo is then performed on the $f_e^2$ transition, consisting of a $\pi/2 - \tau - \pi - \pi' - \pi/2$ pulse sequence.27 A perfect echo should leave the nuclear spin polarization unchanged [Fig. 2(e)ii], whereas a nonoptimal echo sequence (e.g., with $\tau \neq \tau'$) should result in a decrease in the polarization, as some nuclear spin population returns to the spin-down state [Fig. 2(e)i]. To determine the resulting nuclear spin polarization, a readout pulse $\pi$ ($f_e^2$) is applied 10 ms after the start of the echo sequence. The magnitude of the change in current following the readout pulse is proportional to the nuclear spin-down population.

Figure 2(g) shows the current through the sample during one such polarization-echo-readout sequence. The transient behavior at 0 and 10 ms results from the application of the rf radiation used to drive nuclear spin transitions. It is nonresonant and most likely due to resistance changes from heating the sample. The current change at 20 ms is due to the electron trapping described above, and only occurs when the electron spin resonance conditions are matched (in this case for the $f_e^2$ transition).

To observe the spin echo, the transient current $\Delta I$ following the readout pulse is measured26 as a function of $\tau - \tau'$ for a fixed $\tau$. Figure 3(a) shows $\Delta I$ during an echo sequence with
coupled donor electron,\textsuperscript{6,23} i.e., $T^*_n \lesssim 2T^*_e$. In the experiments reported here, the nuclear coherence time measured is indeed very close to twice the spin lifetime of the coupled donor electron, $T^*_n = 2.8 \pm 0.4 \text{ ms} \approx 2T^*_e = 3.72 \pm 0.04 \text{ ms}$ [dashed line, Fig. 3(b)], indicating that this process is also the dominant dephasing mechanism in this work. The mechanism by which the nuclear spin is decohered by electron relaxation is described in Ref. 6, and we anticipate that increasing $T^*_e$ should lead to longer $T^*_n$.

It is important to note that the electron spins in these experiments have artificially shortened lifetimes due to their interaction with the photoexcited conduction electrons required for readout. Figure 4 shows $T^*_e$ measured by conventional pulsed electron spin resonance both in the dark and with the illumination required for electrical readout. In these experiments, the light intensity was optimized to maximize the reduction in $T^*_e$ and resulted in a nearly two order of magnitude reduction at $T = 4 \text{ K}$.

A number of modifications to the experiment described here would assist in obtaining these longer coherence times. A pulsed photoexcitation scheme could be utilized to enable readout only when required, retaining longer coherence times useful for computing and storage otherwise. Utilizing a MOSFET structure\textsuperscript{29–31} would also allow this modification, as well as provide more accurate control of the free carrier density (and thus scattering time between free and donor electrons), which could be used to tune the nuclear spin lifetime.\textsuperscript{32}

\section*{IV. SUMMARY}

To summarize, we have demonstrated electrically measured spin echoes from phosphorus donor nuclear spins in silicon. We find a spin phase coherence time $T^*_n = 2.8 \pm 0.4 \text{ ms}$. Evidence suggests that $T^*_n$ is limited by the lifetime of the hyperfine coupled donor electron, which bodes well for increasing this time by utilizing methods to reduce the free electron density when readout is not required, for example, by utilizing pulsed photoexcitation or MOSFET style devices. Finally, we note that, as well as the relevance to technological devices based on spin, the techniques used here may find

\begin{figure}[h]
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\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{(Color online) Nuclear echoes. (a) The change in photocurrent following the readout pulse for an echo sequence with $\tau = 1 \text{ ms}$. A clear echo is seen when $\tau = \tau'$. The data are fit with a simple exponentially decaying function, yielding a nuclear spin coherence time $T^*_n = 2.8 \pm 0.4 \text{ ms}$ (red solid line). The data are fit nearly as well if $T^*_n$ is fixed to be $2T^*_e$ (green dashed line). Note the logarithmic scale on the x axis.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4.png}
\caption{Spin lifetime $T^*_e$ of phosphorus donor electrons measured with an inversion recovery sequence at a resonance frequency of 240 GHz with conventional pulsed electron spin resonance. The measurements are performed both in the dark (closed data points) and while shining light onto the sample (open data points).}
\end{figure}
applications as tools for investigating the physics of systems comprised of a small number of spins, where conventional spin resonance techniques are not suitable.

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16The pulse times used in this work (in μs) are \( \pi(f_{n}^{*}) = 2.1 \), \( \pi(f_{e}^{*}) = 25.0 \), \( \pi/2(f_{n}^{0}) = 15 \), and \( \pi(f_{e}^{0}) = 50 \). Approximately 10% of donor nuclear spins are rotated following a \( \pi/2 \) pulse.
16We average the change in current for 300 μs following the readout pulse. Each point averaged 20 times, with a repetition rate of 30 ms.