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Viewpoint

Reading a single spin in silicon

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Demonstration of one-shot measurement of a single spin on a silicon quantum dot brings the prospect of quantum information processing one step closer.

Subject Areas: **Quantum Information, Spintronics**

A Viewpoint on:
Tunable Spin Loading and T1 of a Silicon Spin Qubit Measured by Single-Shot Readout
C. B. Simmons, J. R. Prance, B. J. Van Bael, Teck Seng Koh, Zhan Shi, D. E. Savage, M. G. Lagally, R. Joynt, Mark Friesen, S. N. Coppersmith, and M. A. Eriksson
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The holy grail of research in quantum computing is to simultaneously meet the DiVincenzo criteria—five obstacles that must be overcome to transform a quantum system into a scalable quantum computer [1]. Overcoming the first two, namely to have well-characterized qubits and long decoherence times can be a simple matter: Nature provides a variety of long-lived quantum systems. However, once the choice for a quantum system is made, things become quite complex since the other three criteria—qubit initialization, the implementation of quantum gates, and the qubit specific measurement capability (the so-called "quantum readout")—require a number of different well-controlled interactions with individual qubits. Attempts to engineer these interactions have defined experimental quantum information research for the past two decades. Particularly challenging in this regard has been the measurement of a single qubit in a single attempt. Turning the isolation of qubits, needed for long coherence times, on and off in a controlled manner and determining the qubit state quickly with a single probe transition is crucial for the operation of quantum computers. (After all, "write-only memory" is not too useful.) Only when a qubit readout is available, will it be possible to experimentally verify initialization and quantum-gate operations.

While many quantum systems have been proposed to realize qubits, spin states of electrons and nuclei embedded in crystalline silicon are among those with the longest coherence times [2]. The spin degree of freedom is ideal for quantum computing because it is discrete and, in contrast to other semiconductor materials, silicon seems ideal for providing the perfect quantum solitude for spins because the spin of the silicon nucleus is zero (in enriched ^{28}Si) and there is comparatively weak spin-orbit coupling. Now, in a recent paper to appear in *Physical Review Letters*, Christine Simmons and collaborators from the University of Wisconsin, Madison, have demonstrated a single-shot readout of spin in what is potentially a scalable system, namely, a Si/SiGe artificial quantum dot.

The traditional approach to spin readout has been based on the detection of radiation emitted by a spin's magnetic moment, as is used for pulsed magnetic resonance spectroscopy. However, the problem with this approach is the challenge of detecting a single photon in the microwave range, which makes single-shot spin readout inconceivable. Alternatively, optical and electrical detection schemes taking advantage of spin-selection rules in silicon have been proposed. While experimental demonstrations based on these approaches have proven significantly enhanced sensitivity [3, 4], single-spin/single-shot readout has remained elusive. The key to single-spin/single-shot detection of spin states in silicon turns out to be electrical detection via local amplification of charge-controlled currents. A first demonstration of this approach was achieved by Xiao *et al.*[5] in 2004, who demonstrated that changes of spin-dependent trapping rates at single paramagnetic interface defects in a silicon transistor can be monitored by shot noise of the transistor's channel current. At about the same time that this many-shot/single-spin detection (but not yet spin-readout) demonstration was made, spin readout schemes for materials other than silicon had advanced considerably: By observation of spin-dependent occupancy of charge states in GaAs/AlGaAs quantum dots using a quantum point contact as a probe, Elzerman *et al.* demonstrated a true single-spin/single-shot electron spin readout [6]. The intriguing idea behind this approach was to probe an electron spin in the singly occupied quantum dot by placing the dot in tunneling proximity to a metal and adjusting the Fermi level of this metal (with, say, a voltage) so that it lies between the up and down eigenstates of the probed

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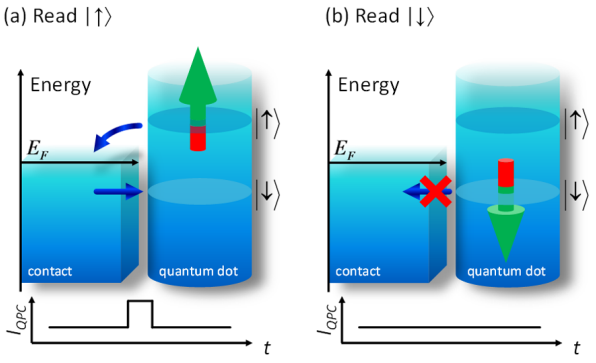

FIG. 1: Illustration of the single-shot/single-spin quantum dot readout scheme used in Ref. [7]. A tunnel contact in proximity to the quantum dot has a Fermi energy tuned between the two Zeeman states of an electron trapped in the quantum dot. The spin-up state $|\uparrow\rangle$ leads to a discharge transition of the trapped electron into the metal contact followed by a recharge transition into the energetically lower Zeeman state. The spin-down state $|\downarrow\rangle$ cannot discharge. Thus detection of the spin is possible by transient observation of discharge/recharge transitions.

electron. (Here it is assumed the up and down states are split by an external magnetic field.) An illustration of this approach is shown in Fig. 1. Depending on whether the spin occupied an eigenstate above or below the Fermi threshold, the electron would either tunnel out of the quantum dot or stay put. If it did tunnel, the empty spin state below the Fermi level would soon be recharged by an electron with opposite spin orientation. Hence the electrical detection of a discharge/recharge event gave clear evidence about the spin eigenstate of the electron before the readout.

The early successes of single-shot/single-spin readout experiments with III-V semiconductor materials were possible in part because this material class allows great control of device structures. This advantage comes with a price: Neither gallium, arsenic, or aluminum exist as nuclear spin-free stable isotopes. Thus electronic spin qubits in these materials, especially quantum dot qubits with localizations significantly exceeding atomic scales, interact with tens of thousands of nuclear spins at the same time and their quantum coherences are therefore quenched considerably.

The recent work by Simmons *et al.*[7] succeeded in combining the elegant spin readout scheme by Elzerman [6] with the preferred host material, silicon. This experiment comes shortly after the first demonstration of single-shot/single-spin detection in silicon using a single electron transistor as detector of a localized point defect spin (possibly a phosphorous donor) [8]. In contrast to this study, Simmons *et al.* conducted their experiments on spins existing on artificial charge quantum dots, which provide significantly greater control and a better understanding of the spin state's electron wave function. Due to this control, this single-shot/single-spin readout will immediately allow for the investigation of a plethora of important questions. In the study by Simmons *et al.*, the readout scheme has already been applied to the measurement of longitudinal quantum dot spin-relaxation times (T_1), revealing values on the order of seconds. Another important question is whether the coherence time promises of the silicon host material hold for the Si/SiGe quantum dots. While the predominant silicon isotope (^{28}Si) is without spin, germanium nuclear spins and interface states may still decohere the quantum dot. One also can anticipate that the new spin readout will soon lead to first demonstrations of multi-qubit quantum gating in a silicon quantum dot device. In any case, it is clear that the demonstration of the silicon quantum dot single-shot spin readout by Simmons *et al.* is not just the outcome of some quite sophisticated experimental work, but in fact the starting point of even more to come.

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