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Major Goals: Single electron spins, either bound to donors or held in gated quantum dots, have long been considered excellent candidate qubits because the basic properties of silicon could enable extremely long coherence in a materials system with the advanced manufacturing capability of the microelectronics industry. Our goal is to understand the limits of electron spin coherence in silicon, and use that knowledge to guide the development silicon-based quantum devices. Bulk donors can exhibit spin coherence of a second, and longer, but one of our tasks is to understand decoherence processes for near-surface donors. This will require the development of new methods for higher sensitivity electron spin resonance (ESR), including low-power on-chip superconducting microresonators and ultra-low temperature (~100 mK, or lower) measurements. New approaches to detecting the spin state of electrons are being developed. In addition to donor-electron spins, new quantum dot structures are being studied to understand what is limiting the relaxation and coherence of electrons bound in dots, and to obtain longer spin coherence in these structures. The possibility of integrating quantum dots with donors, to harness the unique capabilities of both variety of qubit, is being investigated.

Accomplishments: A pdf has been uploaded.

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Authors: B.C. Rose, A.M. Tyryshkin, H. Riemann, N.V. Abrosimov, P. Becker, H.-J. Pohl, M.L.W. Thewalt, K.M. It
Keywords: Mesoscopics, Quantum Physics, Strongly Correlated Materials
Abstract: We achieve the strong-coupling regime between an ensemble of P-donor spins in a highly enriched 28Si crystal and a 3D dielectric resonator. Spins are polarized beyond Boltzmann equilibrium using spin-selective optical excitation of the no-phonon bound exciton transition resulting in N = 3.6 × 10^13 unpaired spins in the ensemble. We observe a normal mode splitting of the spin-ensemble–cavity polariton resonances of 580kHz (where each spin is coupled with strength g) in a cavity with a quality factor of 75000 (? ? ? ? 60 kHz, where ? and ? are the spin dephasing and cavity loss rates, respectively).The spin ensemble has a long dephasing time (T2* = 9 ?s) providing a wide window for viewing the dynamics of the coupled spin-ensemble–cavity system. The free-induction decay shows up to a dozen collapses and revivals revealing a coherent exchange of excitations between the superradiant state of the spin ensemble and the cavity. The ensemble is found to evolve as a single large pseudospin.
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Article Title: Multi-frequency spin manipulation using rapidly tunable superconducting coplanar waveguide microresonators
Authors: A. T. Asfaw, A. J. Sigillito, A. M. Tyryshkin, T. Schenkel, S. A. Lyon
Keywords: tunable resonator, DEER, superconducting resonator, NbTiN, electron spin resonance
Abstract: In this work, we demonstrate the use of frequency-tunable superconducting NbTiN coplanar wave-guide microresonators for multi-frequency pulsed electron spin resonance (ESR) experiments. By applying a bias current to the center pin, the resonance frequency (~7.6GHz) can be continuously tuned by as much as 95MHz in 270ns without a change in the quality factor of 3000 at 2K. We demonstrate the ESR performance of our resonators by measuring donor spin ensembles in silicon and show that adiabatic pulses can be used to overcome magnetic field inhomogeneities and micro- wave power limitations due to the applied bias current. We take advantage of the rapid tunability of these resonators to manipulate both phosphorus and arsenic spins in a single pulse sequence, demonstrating pulsed double electron-electron resonance. Our NbTiN resonator design is useful for multi-frequency pulsed ESR and should also have applications in experiments where spin ensembles areused as quantum memories.
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Authors: Anthony J. Sigillito, Alexei M. Tyryshkin, Thomas Schenkel, Andrew A. Houck, Stephen A. Lyon
Keywords: qubit, superconducting resonator, nuclear spin, donor, silicon
Abstract: The electronic and nuclear spin degrees of freedom of donor impurities in silicon form ultra-coherent two-level systems 1,2 that are potentially useful for applications in quantum information 3 and are intrinsically compatible with industrial semiconductor processing. However, because of their smaller gyromagnetic ratios, nuclear spins are more difficult to mani- pulate than electron spins and are often considered too slow for quantum information processing. Moreover, although alternating current magnetic fields are the most natural choice to drive spin transitions and implement quantum gates, they are difficult to confine spatially to the level of a single donor, thus requiring alternative approaches. In recent years, schemes for all-electrical control of donor spin qubits have been proposed 4,5 but no experimental demonstrations have been reported yet. Here, we demonstrate a scalable all-electric method for controlling neutral 31 P and 75 As donor nuclear spins in silicon.
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Authors: J.-S. Kim, A. M. Tyryshkin, S. A. Lyon
Keywords: MOS, shallow traps, qubit, Si/SiO2 interface
Abstract: Electron-beam (e-beam) lithography is commonly used in fabricating metal-oxide-silicon (MOS) quantum devices but creates defects at the Si/SiO 2 interface. Here, we show that a forming gas anneal is effective at removing shallow defects (<4meV below the conduction band edge) created by an e-beam exposure by measuring the density of shallow electron traps in two sets of high- mobility MOS field-effect transistors. One set was irradiated with an electron-beam (10keV, 40uC/cm 2) and was subsequently annealed in forming gas while the other set remained unexposed. Low temperature (335 mK) transport measurements indicate that the forming gas anneal recovers the e-beam exposed sample's peak mobility (14000cm 2 /Vs) to within a factor of two of the unex- posed sample's mobility (23000cm 2 /Vs). Using electron spin resonance (ESR) to measure the den- sity of shallow traps, we find that the two sets of devices are nearly identical, indicating the forming gas anneal is sufficient to anneal out s
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Authors: Anthony Sigillito
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Our original plan for the work we performed under this grant was divided into four parts. Here we discuss the research and results we obtained in that framework.

1. Understanding spin coherence in bulk Si and near surfaces and interfaces

In previous studies we had found that the coherence of electron spins bound to donors in bulk Si (as measured by in a 2-pulse Hahn echo experiment) could be very long, but the ultimate limits of the coherence were not known, and the coherence of spins near a surface were shorter than those in the bulk of a high-quality Si crystal. Our goal has been to understand what is limiting the spin coherence in these cases. When we began this work, one common argument was that the coherence was limited by the presence of other nearby donors or other spins, and the resulting flip-flops between spins. According to this picture, if the spins could be fully polarized, there would be no flip-flops, and the spin coherence could become much longer. We on the other hand suspected that other processes, such as electric field noise, was leading to the decoherence.

We have taken several approaches to attempt to answer these questions. Our conclusion is that there are, in fact, other processes leading to substantial decoherence, even after the effects of spin flip-flops are eliminated. It is likely that these effects are associated with fluctuating electric fields, though we have not directly proven this.

One way to achieve full spin polarization would be to cool the materials to low enough temperature that the spins almost all freeze into their ground state. That is one avenue we have pursued, but it introduces complications, as we discuss more in the next section. The fundamental complication is that the microwave power dissipation must be kept low, to avoid heating, and that largely has forced the use of thin-film superconducting microresonators. These resonators only see the spins within the first few microns (up to a few tens of microns). Instead, we combined two experimental approaches; first using a laser tuned to a bound exciton line to hyperpolarize the donor spins, and second using ^{28}Si:Bi at a clock transition where the spin frequency is insensitive to the magnetic field. The clock transition does not, by itself, eliminate flip-flops, though it does further reduce their rate by a factor of 4. In our most lightly-doped ^{28}Si:Bi crystal we obtained a Hahn echo coherence time of ~4.5 seconds using these techniques (along with magnitude detection to eliminate residual effects of magnetic field noise). This is the longest Hahn-echo T_2 ever measured, as far as we know, but it is not as long as one would expect if only electron spin flip-flops were controlling the coherence. An important hint as to what is limiting the coherence was our observation that immediately after turning off the laser exciting the bound excitons (and polarizing the spins), the measured T_2 was under 1 s. We found that a short illumination with an above-gap LED, which would thermalize the spins if left on longer, reduced the noise that was limiting T_2 and gave the 4.5 s result. Our interpretation of this data is that after illumination with the bound-exciton laser, charges were moving between defects in the crystal and causing electrical noise which limited T_2. The brief above-gap illumination neutralized most of these defects, thus reducing the noise.

We have also recently obtained other data pointing towards significant decoherence from processes other than flip-flops in bulk ^{28}Si:P. These data come from modeling the effect of electron spin flip-flops on the decay of the coherence of the phosphorus nuclear spins. The nuclear spin decays can be fit by a combination of a term with a time dependence ~exp[-$(t/T_{2ff})^{0.6}$] and one whose time dependence is exp[-t/T_2]. From our modeling, the first term can be seen to arise from the electron spin flip-flops, and those dominate the decoherence of the nuclear spins in more heavily doped crystals (where flip-flops are more important). However, the simple exponential decay from the second term dominates the decay for more lightly doped crystals. While we cannot prove that this second term arises from electric field noise, it seems to be the most likely candidate. If we make that assumption, we can estimate the magnitude of the electric field noise, and it is about 30x less than that which has been reported for devices at interfaces.[1] That factor of 30 is not unreasonable for the difference between the electrical noise at a surface and the noise in the bulk of a Si crystal (the bulk electric field noise probably is dominated by donor-acceptor pair recombination following the optical pulse which thermalizes the spins). This work will be submitted for publication shortly.

2. Experimental technique development

We have pursued research in three major areas: (1) high-sensitivity ultra-low power superconducting microresonators, (2) a bound-exciton laser for polarizing and measuring the spin of electrons bound to donors, (3) strong-coupling a spin ensemble to a resonator. In addition we have investigated approaches to eliminating global magnetic field noise (or at least eliminating its effects on the spins).

The superconducting microresonator work has been very successful. We first demonstrated extremely high sensitivity in such a structure (single-shot sensitivity of ~10^7 spins) as well as extremely low microwave power (400 nW peak power for a 400 ns π-pulse).[2] With their low power requirements, these sorts of resonators are ideal for operation at dilution refrigerator temperature. We conducted experiments along those lines in collaboration with other groups (Prof. David Schuster at U. Chicago and Prof. Jason Petta at Princeton) who had fridges which were already set up for these experiments. Recently with Prof. Petta (the experimental work was all done by his students and postdocs – we supplied the sample and helped with the resonator design) we demonstrated a single-shot sensitivity of about 2 x 10^4 spins[3] in ^{28}Si:P.

More recently we showed how photonic bandgap resonators could be used to excite both electron and nuclear spin resonance in the same device. This work has culminated in our discovery of direct electrical excitation of donor nuclear spins in silicon.[4] We have also recently published a demonstration of experiments employing the photonic bandgap resonators made of NbTiN, where the kinetic inductance of the superconductor can be used to rapidly tune the resonator.[5]

The bound-exciton laser work has proven to be partially successful. We have been able to optically polarize spins, as we used for the Si:Bi experiments discussed previously, and in the strong-coupling experiments discussed next. However, using the laser to detect small numbers of spins (ideally down to single spins) has proven to be more difficult. Together with a long-term collaborator, Prof. John Morton at University College London, we showed that laser excitation and electrical detection for relatively small numbers of spins was possible.[6] However, the applicability of this approach appears to be limited by local strains near the silicon surfaces and interfaces. When we have attempted to make small devices, the optical resonances appear to be excessively broadened, to the point that no resonance can be found. We have tried using polysilicon gates, to reduce the local strains, but the resonances are still washed out. The upper state of the optical transition (the bound exciton) is much more sensitive to strain than the donor, and that is probably what leads to these issues.

As noted in the last paragraph, optical polarization of donor electron spins in bulk Si has been successful, and one application of that technique has made it possible for us to study large spin ensembles strongly coupled to a resonator. This allowed us to perform, for the first time, experiments with large ensembles in which all the spins are uniformly coupled to the resonator as assumed by the Tavis-Cummings model. We are able to follow about a dozen oscillations of the energy back and forth between the cavity photons and the spins, with excellent signal/noise. This work was recently published.[7]

This strong-coupling work is also related to the possibility of using spin ensembles as a quantum memory, where a strongly coupled ensemble would be required. In the simplest approach the spins are able to store the quantum information for a time, T_2^*, which is generally quite short. However, refocusing the spins with a π-pulse would trigger the avalanche that we studied in these experiments. An approach must be found to rapidly switch the coupling between strong and weak for the refocusing to work as desired. The tunable resonators, discussed above, might provide a route to a long-lived spin-ensemble quantum memory.

Another experimental enhancement we pursued was an attempt to mitigate the effects of global magnetic field noise. This noise plagues all spin experiments which cannot utilize a clock transition or a field-cancelling decoherence-free subspace. Our approach was to lock the microwave source driving the electron spins to a strong nuclear spin signal. In our initial experiments we locked to the proton signal in a water cell. However, the noise in the NMR measurement was too large to cancel the global field noise above about 100 Hz, while the global field noise extends to at least 1 kHz. We shifted to a liquid ^{3}He NMR cell, since eventually the experiments would need to be performed at low temperature, anyway. The signal/noise was better (larger spin polarization at low temperature), but still not sufficient. The main limitation was the long T_1 of the ^{3}He (~30 s, or longer). At this point we decided to take a break from that work, but expect to return to it since we believe that it can be engineered to work.

3. Spin coherence in Si-based quantum dots

We used large ensembles of Si/SiGe quantum dots (~10^8) to investigate the electron T_1 and T_2. From our previous work we had shown that T_2 could be >200 μs, but it was T_1-limited in those structures. We had proposed to fabricate smaller dots, which we did, and were able to obtain T_1 as long as 1.4 ms, and T_2 ~ 350 μs. Thus, T_2 was no longer limited by T_1. It is unclear what was limiting the T_2 at that point. That time is within a factor of two of the expected limit imposed by the natural abundance of ^{29}Si.[8] We were not able to obtain ^{28}Si/SiGe to determine whether the ^{29}Si was limiting our spin coherence.

Typically in these devices we would measure a short T_2 (~10 μs) as well as a long T_2. It is unclear what caused the short T_2. One possibility is that some areas of the device had larger valley splitting than in other areas. Since these devices were ~1 cm^2 in area, such variations would easily be possible. The regions with short T_2 might have arisen from the areas in the device with small valley splitting, but we did not find a way to confirm or refute that conjecture. The different times could also have arisen from potential variations leading to multiple electron occupancy of the dots in some areas.

We had originally planned to repeat these experiments with MOS quantum dots, since that would also tie in with the donor/dot devices we investigated in the fourth part of this work. However, first it was necessary to develop device processing techniques which would minimize the production of shallow electron traps at the Si/SiO_2 interface. At the conclusion of that work (discussed below), we decided that our effort would be better directed towards fabricating and measuring individual dots, rather than large ensembles, and we concentrated our efforts in that direction.

4. Develop donor/dot devices

It has become clear to most of the community that the length scales imposed by direct exchange interactions between donors, as in the Kane scheme for a Si-based quantum computer,[9] are not currently practical (may never be). Our suggestion for circumventing this device size problem is to combine donors with quantum dots.[10] Placing donors only into the Si layer of a Si/SiGe heterostructure is difficult, and thus we proposed to investigate MOS structures. Our original plan was to combine ensemble measurements with optical (bound-exciton excitation) readout, but as discussed earlier, the optical readout proved to be problematical. Thus, we decided that experiments on single dots would be a better approach. However, we did two sets of ensemble experiments to better understand how to fabricate these devices.

First, we had proposed using the multiple states of Si:Bi (a total of 20 states with the 9/2 nuclear spin of the Bi donor) as qubits. In particular, we had previously shown that there are two nearby pairs of states at every clock transition (termed the "allowed" and "forbidden" transitions).[11] In one set of experiments we showed that we could selectively excite one or the other transition using circularly polarized microwaves.[12]

As mentioned earlier, one issue when working with MOS quantum dots is that there are many more defects and electrons traps than in Si/SiGe heterostructures. Of particular concern are the shallow (< 10 meV trap depth) traps which are not detectable by conventional CV (capacitance-voltage) measurements, since they are numerous and might change charge state during the operation of the dot device. Our first goal was to obtain material and develop processes which would minimize the number of these defects. We used an ESR-based technique which we had developed previously to quantify the density of shallow electron traps.[13] One of the most damaging processes is electron-beam lithography, since that is a very efficient way to introduce radiation damage into the oxide. However, we obtained commercial oxides capped with polysilicon (to protect the oxide from contaminants and form a gate), and showed that a forming gas anneal was sufficient to eliminate the defects introduced during ebeam lithography.[14] We also showed that our ESR-based measurement quantitatively agreed with a percolation-model analysis.[15]

Individual quantum dots were fabricated using Petta's "dual rail" arrangement,[16] and measured at higher temperatures (2K). The dots are relatively large (30 nm gate oxide, and similar gate widths), but with the high-quality interfaces we expect that they will be less affected by traps than in other MOS structures They show evidence of Coulomb blockade at 2K, which is encouraging given the dot size. Importantly, the gate voltages where the blockade effects appear are relatively symmetrical (gate-to-gate), indicating that they are not dominated by random potential variations. Work on these dots is still ongoing, under other funding. Lower temperature measurements will be required to properly judge the performance of the dots, and preparations are being made to measure them at mK. Donors have not yet been implanted into these devices, but those experiments will be done after the quantum dots are fully characterized.

References

1. Z. Qi, X. Wu, D.R. Ward, J.R. Prance, D. Kim, J.K. Gamble, R.T. Mohr, Z. Shi, D.E. Savage, M.G. Lagally, M.A. Eriksson, M. Friesen, S.N. Coppersmith and M.G. Vavilov, *Effects of charge noise on a pulse-gated singlet-triplet* $S-T_-$ *qubit,* arXiv:1701.06971v2 (2017).

2. A.J. Sigillito, H. Malissa, A.M. Tyryshkin, H. Riemann, N.V. Abrosimov, P. Becker, H.-J. Pohl, M.L.W. Thewalt, K.M. Itoh, J.J.L. Morton, A.A. Houck, D.I. Schuster and S.A. Lyon, *Fast, low-power manipulation of spin ensembles in superconducting microresonators,* Appl Phys Lett **104**, 222407 (2014).

3. C. Eichler, A.J. Sigillito, S.A. Lyon and J.R. Petta, *Electron Spin Resonance at the Level of* 10^4 *Spins Using Low Impedance Superconducting Resonators,* Phys Rev Lett **118**, 037701 (2017).

4. A.J. Sigillito, A.M. Tyryshkin, T. Schenkel, A.A. Houck and S.A. Lyon, *All-electric control of donor nuclear spin qubits in silicon,* Nat Nano **advance online** (2017).(10.1038/nnano.2017.154)

5. A.T. Asfaw, A.J. Sigillito, A.M. Tyryshkin, T. Schenkel and S.A. Lyon, *Multi-frequency spin manipulation using rapidly tunable superconducting coplanar waveguide microresonators*, Appl Phys Lett **111**, 032601 (2017).

6. C.C. Lo, M. Urdampilleta, P. Ross, M.F. Gonzalez-Zalba, J. Mansir, S.A. Lyon, M.L.W. Thewalt and J.J.L. Morton, *Hybrid optical–electrical detection of donor electron spins with bound excitons in silicon*, Nat Mater **14**, 490 (2015).

7. B.C. Rose, A.M. Tyryshkin, H. Riemann, N.V. Abrosimov, P. Becker, H.J. Pohl, M.L.W. Thewalt, K.M. Itoh and S.A. Lyon, *Coherent Rabi Dynamics of a Superradiant Spin Ensemble in a Microwave Cavity*, Physical Review X **7**, 031002 (2017).

8. W.M. Witzel, R. Rahman and M.S. Carroll, *Nuclear spin induced decoherence of a quantum dot in Si confined at a SiGe interface: Decoherence dependence on* ^{73}*Ge*, Phys Rev B **85**, 205312 (2012).

9. B.E. Kane, *A silicon-based nuclear spin quantum computer,* Nature **393**, 133 (1998).

10. G. Pica, B.W. Lovett, R.N. Bhatt, T. Schenkel and S.A. Lyon, *Surface code architecture for donors and dots in silicon with imprecise and nonuniform qubit couplings,* Phys Rev B **93**, 035306 (2016).

11. G. Wolfowicz, A.M. Tyryshkin, R.E. George, H. Riemann, N.V. Abrosimov, P. Becker, H.-J. Pohl, M.L.W. Thewalt, S.A. Lyon and J.J.L. Morton, *Atomic clock transitions in silicon-based spin qubits,* Nat Nano **8**, 561 (2013).

12. T. Yasukawa, A.J. Sigillito, B.C. Rose, A.M. Tyryshkin and S.A. Lyon, *Addressing spin transitions on Bi-209 donors in silicon using circularly polarized microwaves,* Phys Rev B **93**, 121306 (2016).

13. R.M. Jock, S. Shankar, A.M. Tyryshkin, J. He, K. Eng, K.D. Childs, L.A. Tracy, M.P. Lilly, M.S. Carroll and S.A. Lyon, *Probing band-tail states in silicon metal-oxide-semiconductor heterostructures with electron spin resonance,* Appl Phys Lett **100**, 023503 (2012).

14. J.-S. Kim, A.M. Tyryshkin and S.A. Lyon, *Annealing shallow Si/SiO2 interface traps in electron-beam irradiated high-mobility metal-oxide-silicon transistors,* Appl Phys Lett **110**, 123505 (2017).

15. L.A. Tracy, E.H. Hwang, K. Eng, G.A. Ten Eyck, E.P. Nordberg, K. Childs, M.S. Carroll, M.P. Lilly and S. Das Sarma, *Observation of percolation-induced two-dimensional metal-insulator transition in a Si MOSFET,* Physical Review B **79**, 235307 (2009).

16. D.M. Zajac, T.M. Hazard, X. Mi, K. Wang and J.R. Petta, *A reconfigurable gate architecture for Si/SiGe quantum dots,* Appl Phys Lett **106**, 223507 (2015).