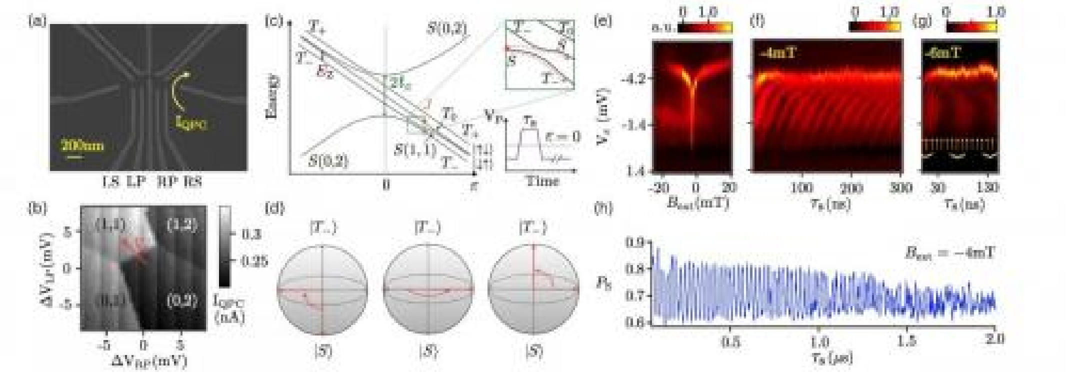
Quantum meets classical: Qubit fabricated with integrated micromagnet increases speed of quantum manipulation in silicon

August 25 2014, by Stuart Mason Dambrot

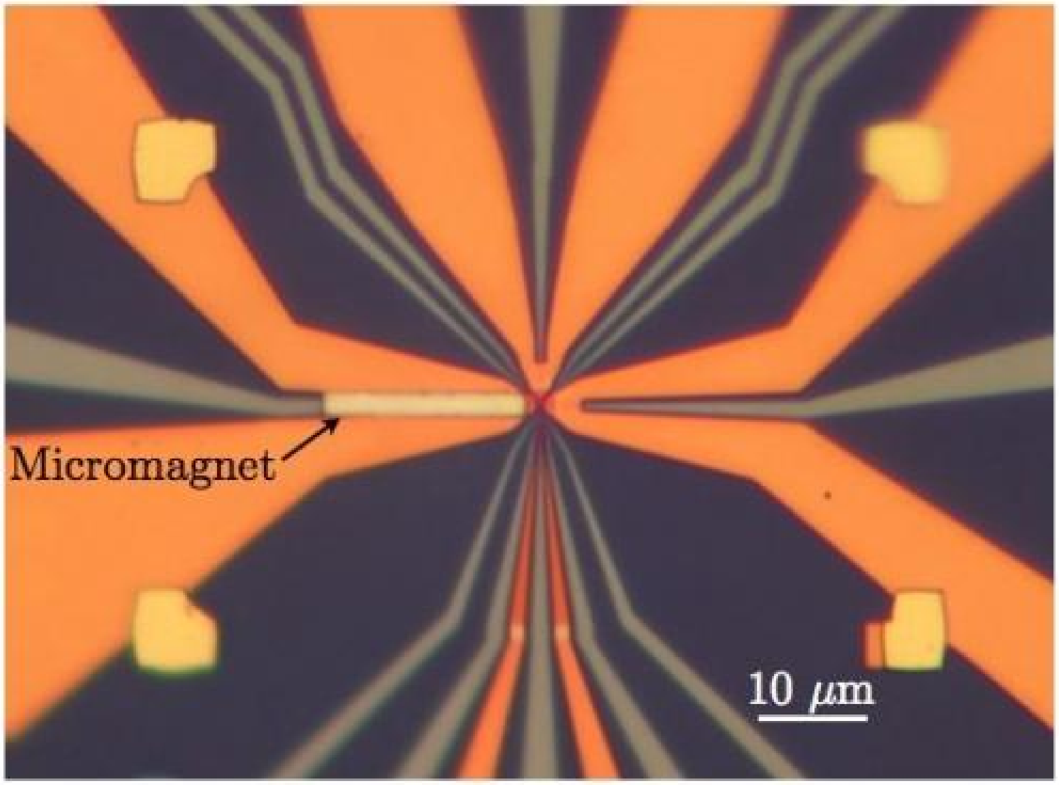


(A) Scanning electron micrograph of a device identical to the one used in the experiment before deposition of the gate dielectric and accumulation gates. An optical image of a complete device showing the micromagnet is included in SI Appendix. Gates labeled left side (LS) and right side (RS) are used for fast pulsing. The curved arrow shows the current path through the QPC used as a charge sensor. (B) IQPC measured as a function of VLP and VRP yields the double-dot charge stability diagram. Electron numbers in the left and right dot are indicated on the diagram. The red arrow denotes the direction in gate voltage space Vε = √(ΔV2LP +ΔV2RP) that changes the detuning ε between the quantum dots. (C) Schematic energy diagram near the (0, 2) to (1, 1) charge transition, showing energies of singlet S and triplet T states as functions of ε. The exchange energy splitting J between S and T0, the Zeeman splitting EZ between T− and T0, and the tunnel coupling tc are also shown. At large ε, in the presence of a field difference between the two dots, S and T0 mix, and the corresponding energy eigenstates are |↑↓⟩ and |↓↑⟩. At small ε, the small transverse field from the micromagnet and the nuclear fields turns the S-T− crossing into an anticrossing (zoom in). Pulsing through this anticrossing with intermediate velocity transforms S into a superposition of S and T−, leading to Landau–Stückelberg–Zener oscillations at the frequency corresponding to the S-T− energy difference (22). The pulse used to observe the spin funnel and S-T− oscillations shown in E is also shown, where the pulse voltage VP is applied along the detuning axis. (D) Bloch sphere representation of π rotation of S and T− states with 50% initialization into each state. (E) Spin funnel (2) measurement of the location of the S-T− anticrossing as a function of external magnetic field Bext and Vε. The data were acquired by sweeping along the detuning direction with the pulse on, with the vertical axis reporting the value of the detuning at the base of the pulse. The spin funnel occurs when S-T− mixing is fast, which locates the relevant anticrossing. (F and G) S-T− oscillations acquired at different external B fields. The oscillation frequency increases with increasing Bext. The slower oscillations in G with period ~80 ns and labeled with the curly brackets are S-T0 oscillations, which are investigated in more detail in Figs. 2 and 3. The S-T− oscillations in G are labeled with arrows. (H) Singlet probability as a function of pulse duration τs at external magnetic field B = −4 mT and base detuning Vε ≃ −2.8 mV. Credit: Copyright *PNAS*, doi:10.1073/pnas.1412230111

(Phys.org) —The ubiquitous classical digital computer encodes data in bits (a portmanteau of *binary* and *digits*) in either a 0 or 1 state. On the other hand, while a quantum computer also uses 0/1 data representation, these *qubits* (from *quantum* and *bits*), qubit states 0 and 1 can be simultaneously in what is known as a superposition – and a quantum computer can also make use of entanglement. For these reasons, quantum computers can potentially solve problems whose complexity is too resource-intensive for classical computation. That being said, quantum computers are very difficult to construct. Recently, however, scientists at University of Wisconsin, Madison have fabricated a qubit in a silicon double-quantum dot in which the qubit basis states are the singlet state and the spin-zero triplet state of two electrons. (A double quantum dot links two quantum dots – semiconductor nanostructures that confine the motion of conduction band electrons, valence band holes, or excitons in all three spatial directions.) Moreover, the researchers have for the first time integrated a proximal micromagnet, allowing them to create a large local magnetic field difference between the two sides of the quantum dot - thereby greatly increasing their ability to manipulate the qubit without injecting noise that would induce superposition decoherence.

Prof. Susan Coppersmith and Prof. Mark Eriksson discuss the paper they and their co-authors published in *Proceedings of the National Academy of Sciences* with *Phys.org*, noting that overall goal of the research program is to develop quantum bits for a quantum computer using technology that is similar to that used for current classical computers. "The advantages of this strategy arise for two main reasons." Coppersmith tells *Phys.org*. "First, enormous investments have been made to develop large-scale classical electronics, and one hopes that this investment can be leveraged to facilitate scale-up of quantum electronics. Second, the similarity in technology facilitates integration of quantum and classical processors." Integration is important, Eriksson adds, because a large-scale classical computer will almost certainly be necessary to control the operation of a quantum computer.

An early step towards this goal is to fabricate high-fidelity individual qubits. This paper focuses on the so-called *singlet-triplet* qubit, which was first fabricated in gallium arsenide (GaAs) devices. "The operation of a singlet-triplet qubit in GaAs is complicated by strong coupling between the electron spins and nuclear spins, Eriksson explains. "Silicon has much weaker coupling between the electron spins and nuclear spins, and most of the nuclei in silicon have spin zero, so the electron spins in silicon can stay coherent much longer than in GaAs." In fact, measurements of a singlet-triplet qubit in natural silicon indeed yield much longer coherence times than in GaAs, but because the qubit operations themselves rely on having a magnetic field difference between the dots – a difference that also arises from the nuclei themselves – the qubit operations in that work were much slower than in GaAs. "Our work shows that using an integrated micromagnet enables faster gate operations by imposing a larger magnetic field difference between the quantum dots," Coppersmith points out, "and it does so without introducing measurable additional decoherence, which improves the overall performance of the qubit."



Optical micrograph of the device, with the location of the micromagnet marked on the figure. Credit: Copyright *PNAS*, doi:10.1073/pnas.1412230111

Specifically, the paper states that the integrated micromagnet provides a promising path toward fast manipulation in materials with small concentrations of nuclear spins, including both natural silicon (Si) and isotopically enriched ^{28}Si. "Nuclear spins in GaAs and other materials, such as InSb (Indium Antimonide), reduce qubit coherence – but this strong coupling also enables fast manipulation," Eriksson tells *Phys.org*. "However, if the decoherence effects are reduced by using a material with weaker coupling to nuclear spins, it's necessary to find another way to create a large magnetic field difference between the quantum dots – and the integrated micromagnet enables this."

"One big challenge was fabricating a suitable device, that being a double quantum dot in which a micromagnet is incorporated," Coppersmith continues. Devices with incorporated micromagnets had previously been investigated in GaAs in a slightly different context, but the fabrication procedure in the University of Wisconsin devices differs from that used in the GaAs devices, requiring novel processes to be developed. "A further challenge arose because the micromagnetic field was somewhat different than what was expected based on measurements of cobalt films and our numerical calculations," notes Eriksson. "Therefore, to perform the experiments we had to use the properties of the qubit itself to figure out what the actual fields on the quantum dots were." By so doing, the researchers found that the field from the micromagnet depended on the applied uniform field, which enabled them to investigate the qubit properties for two magnitudes of the micromagnet field.

Interestingly, the paper states that the scientists' fabrication techniques being similar for both quantum dot-based qubits and donor-based qubits in semiconductors suggests that micromagnets should also be applicable to donor-based spin qubits. "The micromagnet in the device that we measured is created by depositing the metal cobalt by Electron Beam Physical Vapor Deposition (EBPVD), onto the top of the sample," Coppersmith says. "Therefore, applying the technique to other semiconducting qubit architectures in which the qubits are defined by evaporated metal top gates is rather straightforward." (EBPVD uses an electron beam to bombard a target and convert some of its atoms into a gas, which then precipitate and coat all surfaces in the vacuum chamber.)

In practice, however, some of the gates on these devices will be made of non-magnetic materials – typically aluminum or gold –resulting in a small number of cobalt gates.

The researchers also describe the unique characteristics of a large-scale quantum computer based on their approach: Once high-quality single qubits and two-qubit gates are achieved, then because the technology is close to that already used in classical electronics and the qubit size (

"The next steps in our research are to increase both the magnitude of the field difference between the quantum dots, and the number of qubits by increasing the number of quantum dots," Coppersmith tells *Phys.org*. "Both steps are being implemented in new devices that have been designed and are currently being fabricated. We're also working on other qubit implementations in silicon quantum dots[1,2], all of which use electrical initialization, manipulation and readout, and therefore have the potential advantages of integrability and scalability." Moreover, Eriksson points out that being able to control local magnetic fields in a nanoelectronic device could be very useful for spintronics.

More information: Two-axis control of a singlet–triplet qubit with an integrated micromagnet, *Proceedings of the National Academy of Sciences*, Published online before print August 4, 2014, doi:10.1073/pnas.1412230111

Related:

[1] Quantum control and process tomography of a semiconductor quantum dot hybrid qubit, *Nature* 511, 70–74 (03 July 2014), doi:10.1038/nature13407
[2] Electrical control of a long-lived spin qubit in a Si/SiGe quantum dot, *Nature Nanotechnology* (2014), doi:10.1038/nnano.2014.153

Citation: Quantum meets classical: Qubit fabricated with integrated micromagnet increases speed of quantum manipulation in silicon (2014, August 25) retrieved 27 April 2024 from https://phys.org/news/2014-08-quantum-classical-qubit-fabricated-micromagnet.html