Silicon-based quantum dots have a path to scalable quantum computing

Two research groups demonstrate the coherent interaction between the spin of a single electron and a single microwave photon.

Ordinarily, an atom hardly notices the presence of light. But when it's placed in a highly reflective optical cavity, cavity quantum electrodynamics (QED) strengthens the interaction so much that a single photon can be coherently exchanged between the two.

In the past 15 years, modern fabrication techniques have made that strong coupling regime also accessible to mesoscopic structures. Superconducting qubits and semiconducting quantum dots can be customized to behave like artificial, two-level atoms that interact with microwaves from a transmission-line resonator on the same chip. The approach has been dubbed circuit QED (see PHYSICS TODAY, November 2004, page 25, and the article by J. Q. You and Franco Nori, November 2005, page 42).

A quantum dot in such a circuit can be configured into the quantum analogue of a transistor. By adjusting the voltage on gate, source, drain, and other electrodes, researchers can controllably pull even a single electron into the dot and store it there. The up-or-down spin of the electron makes it a natural qubit that couples to the surrounding crystal lattice with coherence-preserving weakness (see PHYSICS TODAY, March 2006, page 16).

Two groups—one led by Jason Petta of Princeton University[1] and the other led by Lieven Vandersypen of Delft University of Technology[2]—have now independently demonstrated strong coupling between a single microwave photon and the spin of a single electron placed in a double quantum dot made of silicon. The Vandersypen group's integrated device is shown in figure 1.

Both research groups and others have already built arrays of such Si qubits—albeit outside a circuit-QED context—and demonstrated two-qubit operations. Earlier this year, Petta's group demonstrated a controlled-NOT gate using two spins in Si,[3] and this month Vandersypen and colleagues also published a demonstration[4] of simple computational algorithms executed in Si. But the qubits in those implementations interacted only when the nearest-neighbor spins in an array were close enough for their wavefunctions to overlap.

The new achievement charts a course to a mechanism by which Si qubits can

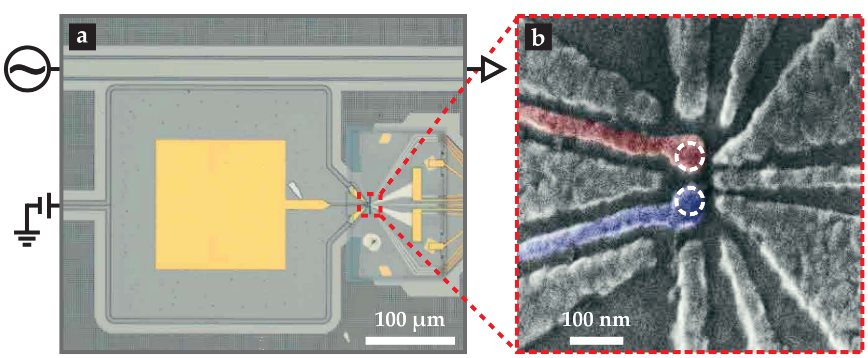

FIGURE 1. QUBIT QUANTUM ELECTRODYNAMICS. (a) The low-power source driving a microwave transmitter (top) ensures that the square cavity resonator capacitively coupled below it circulates no more than a single photon. **(b)** The resonator is connected to two gate electrodes (red and purple) atop a double quantum dot (white circles) in a heterostructure of silicon and silicon germanium. Voltages on surrounding electrodes pull a single electron into the double dot. (Adapted from ref. 2.)

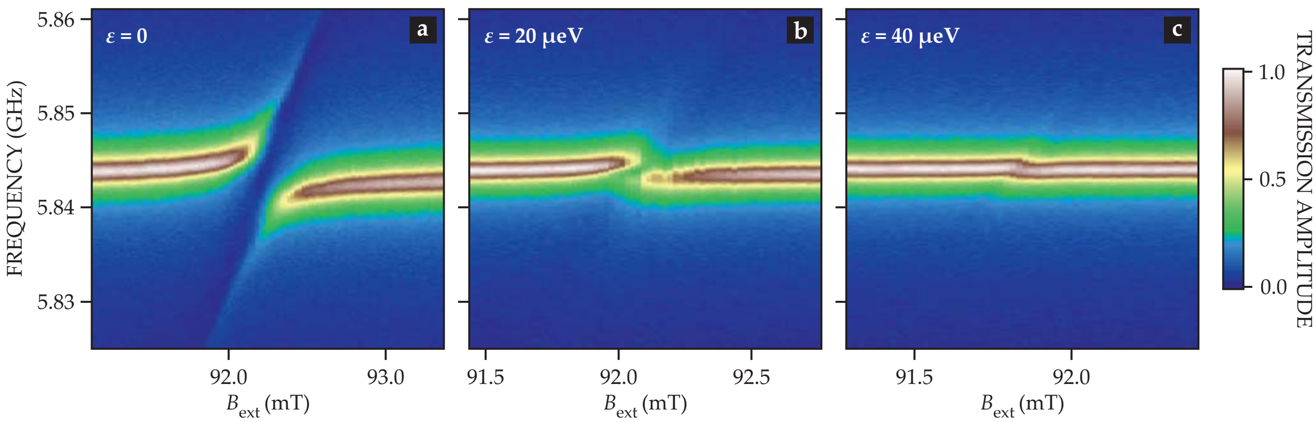

FIGURE 2. AN ELECTRON'S SPIN RESONATES WITH A PHOTON when the energy difference between the electron's spin states, set by an externally applied magnetic field $\mathbf{B}_{ext}$, matches the resonator photon energy. **(a)** Strong spin–photon coupling is evident as a discontinuity, or "avoided level crossing," in the transmission amplitude at resonance. But the energy of the electron in each potential well of the double quantum dot must be equal (their difference ε=0) for the electron and photon to reach the strong coupling regime. **(b,c)** As the potential energy of one well rises with respect to the other (ε>0), the electron localizes into the lower-energy well and loses its grip on the photon. (Adapted from ref. 1.)

instead exchange information and become entangled through a photon intermediary. The length of the microwave resonator can extend up to several millimeters on a chip, and individual Si qubits can be packed as tightly as 100 nm apart. So even though those qubits wouldn't themselves change positions in the array, circulating photons could, at least in principle, share information among any of them. And because the qubits are Si-based, engineers can leverage the more than half century of fabrication expertise on the material when they scale up to arrays containing potentially thousands of qubits.[5]

Hybridization

The strong coupling of a single electron to a single microwave photon isn't completely new. Petta's group pulled off the achievement using a Si double-dot architecture a year ago.[6] But in that earlier demonstration, he and his collaborators coupled the photon to the electron's charge, not its spin. "The trouble with a dot-embedded charge qubit," Petta explains, "is that its coherence falls apart too quickly—on the scale of nanoseconds—to be practical," because of the pervasiveness of nearby charges. The environment felt by an electron's spin, by contrast, is nearly as quiet as a vacuum, at least in isotopically pure ^{28}Si, which contains no net nuclear spin. In the purified lattice, a spin's coherence time is tens of milliseconds. That's long enough for potentially millions of gate operations to occur at the 10–100 MHz rate typical for spin qubits.

The quiet isolation cuts both ways, though. The spin's magnetic dipole is so weak that grabbing hold of a photon is practically impossible, even in a cavity. Indeed, the electric dipole interaction of the charge with the photon's electric field exceeds the spin's magnetic dipole interaction with the photon's magnetic field by five orders of magnitude. In their new work, the two teams therefore still had to rely on the charge's stronger handle to interact with a photon. They placed a cobalt micromagnet across the double dot in their circuits. The micromagnet's strong field gradient of about 10 G/nm couples the electron's spin with its position, or orbital degree of freedom.

The idea behind that hybridization was proposed more than a decade ago by the University of Tokyo's Seigo Tarucha and colleagues[7] but was not implemented in an experimental circuit-QED context until 2015. That's when Takis Kontos and colleagues at CNRS used a micromagnet to couple spins in a carbon-nanotube double quantum dot to a cavity.[8]

The appeal of the double quantum dot lies in its double-well potential, which can be adjusted electrically. The Delft and Princeton groups tuned the electrode voltages to equalize the electron's potential energy on each dot. With no energy difference, the electron is delocalized across both. The distance over which the electron's wavefunction extends, roughly 100 nm, engenders a large electric susceptibility—essentially enabling the electron to respond to the tiny oscillating electric field from a single microwave photon. When combined with the magnetic gradient, the susceptibility allows the spin to interact with the photon's electric field.

To reach the regime of strong coupling, the researchers also had to equalize the energy of a spin flip and the photon. To do so, they applied another magnetic field—a larger, tunable, external field $\mathbf{B}_{\text{ext}}$. Pointed in the same direction as the Co micromagnet's field, $\mathbf{B}_{\text{ext}}$ sets the electron's Zeeman energy—that is, the energy difference between its spin states. The two groups swept the field's magnitude while monitoring the transmission of the microwave circuit (figure 2a shows data from the Princeton group). Once the Zeeman energy and photon energy came into resonance, a pronounced "avoided level crossing" appeared—a telltale sign of strong coupling.

But if the double-dot potential energy landscape is tilted, with the electron at higher energy on one dot than the other, the electron localizes into the lower-energy well. Its responsiveness to the electric field then drops, which in turn saps its ability to coherently exchange energy with the photon. The voltage controls allow the groups to switch on and off the spin–photon coupling on demand. Figures 2b and 2c show the loss of the avoided crossing as the interdot potential difference increases, until the photon no longer even notices the electron's presence.

Spin readout

For double-dot devices to serve as building blocks for a quantum processor, it's necessary to prepare, control, and read out the spin state of the trapped electron deterministically. The first two steps are straightforward: Use microwave pulses to initialize a qubit's state and flip it on cue. But to read a spin state, researchers have historically had to sacrifice the electron in the process.

Petta realized that circuit-QED measurements could avoid such destruction. Ordinarily, one thinks of the cavity's resonance frequency as unchanging—set by the cavity's length, the dielectric constant of the material, and the speed of light. But strong coupling entangles light and matter. His group showed that the spin state of the single electron could be nondestructively read out by measuring the phase shift experienced by microwaves transmitted through the resonator.

With the tools of circuit QED, both groups are preparing to add multiple qubits to their resonator circuits. They're also working to improve the quality of their Si: more uniform, fewer defects, and purified of isotopes that contain nuclear spin. But they and others might also consider using submicron circuit integration to add another computer building block to the circuits—a local quantum memory. To that end, the University of Chicago's David Awschalom suggests it may be interesting to retain some remnant nuclear spins or implant them into a purified sample. "The physics of building subatomic memories using nuclear spins has been explored in a number of materials, including silicon, silicon carbide, and diamond," he notes. "I think it's reasonable to imagine integrating this capability within these classes of devices." Whereas electron spin states can remain coherent for milliseconds, nuclear spins remain so for hours.

Mark Wilson

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Lab experiments mimic the origin and growth of astrophysical magnetic fields

A turbulent, laser-generated plasma can amplify magnetic fields to cosmic scales.

Magnetic fields permeate the space between objects throughout the universe, from galaxy clusters to protogalaxies to nebulae like the one shown in figure 1. It's not difficult to explain how those fields might be initiated: Weak fields originate in astrophysical plasmas through various mechanisms—for example, temperature or density gradients in the plasma that alter electron trajectories.

But it remains challenging to demonstrate how seed fields of 10^{-21} gauss in intergalactic space grow to their measured astronomical values of several microgauss. Theory suggests that turbulent motion in an astrophysical plasma amplifies tiny magnetic fields by converting kinetic energy into magnetic energy. Such a self-sustaining energy conversion mechanism is called a dynamo.

Dynamos are often distinguished between large scale and small scale. The familiar large-scale geodynamo relies on Earth's symmetry-breaking rotation to generate a magnetic field that grows at scales larger than those of the liquid-core motion. But in a small-scale dynamo, the magnetic field grows below the length scales of fluid motion. There, turbulence operates first at the smallest length scales, where it rapidly amplifies the fields. The mechanism works even in isotropic conditions.

FIGURE 1. NGC 604, A VAST STAR-FORMING REGION in a spiral galaxy 2.7 million light-years away in the constellation Triangulum, as imaged by the *Hubble Space Telescope*. The hot plasma fluoresces and highlights the nebula's shape. (Image courtesy of Hui Yang [University of Illinois] and NASA.)

Now Gianluca Gregori (Oxford University), Petros Tzeferacos (University of Chicago), and colleagues have measured the amplification of a magnetic field in a turbulent laboratory plasma and provided the first physical demonstration of a dynamo resulting from turbulent motion.[1] The study shows that the turbulent dynamo could be a viable mechanism for magnetic field amplification in the lab and in astrophysical settings.

Galaxies far, far away

To sustain a dynamo, a fluid needs to be electrically conductive, and its motion cannot be too symmetric. Dynamo conditions also require that the magnetic field lines stay in the plasma, rather than diffusing away. Those conditions are easily satisfied by the turbulent, high-temperature, high-velocity plasma that fills intergalactic space.

Even though conditions favorable for dynamos are common in astrophysical settings, the strong turbulence is extremely difficult to replicate in the lab. (See the article by Daniel Lathrop and Cary Forest, PHYSICS TODAY, July 2011, page 40.) Astronomical x-ray observations provide information about the temperature, density, and composition of hot plasmas in the universe. But observations cannot convey the geometry and