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Bus service for qubits: Spin-orbit qubits are right at home in electrical circuits

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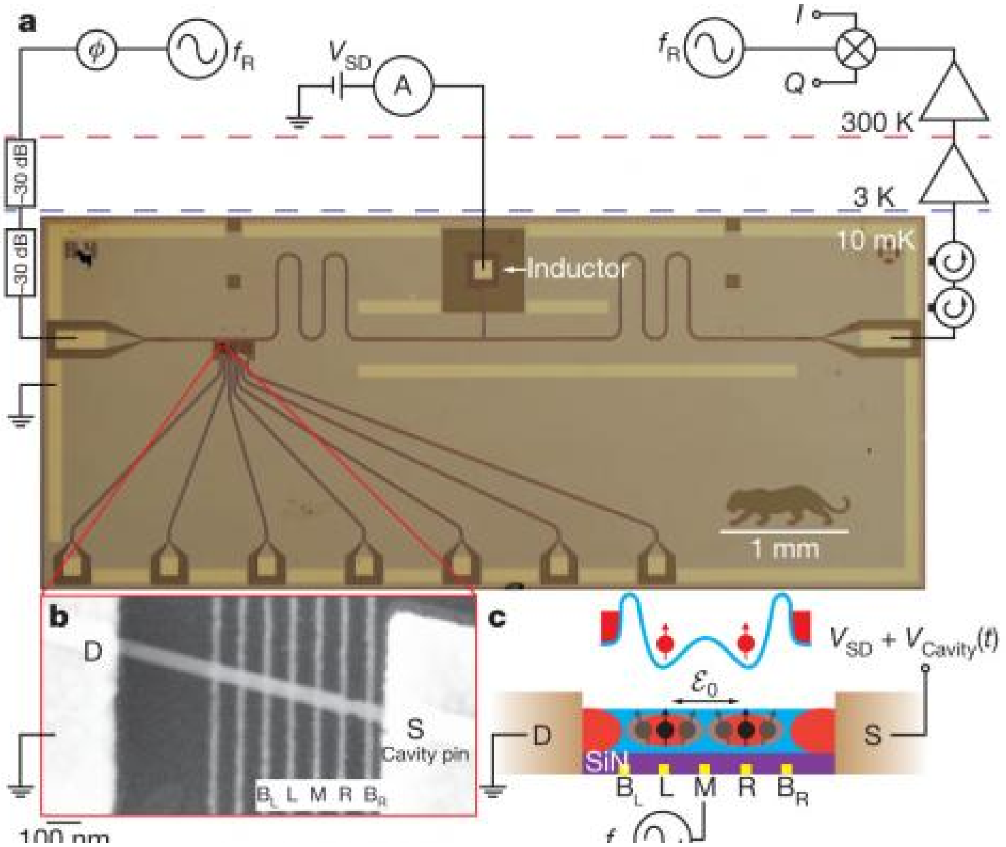

Hybrid quantum dot-superconducting resonator device. (a) Circuit schematic and micrograph of the hybrid device design. Scanning electron micrograph (b) and cross-sectional schematic view (c) of the nanowire double quantum dot (DQD). The left and right barrier gates (BL and BR), left and right plunger gates (L and R), and middle gate (M) are biased to create a double-well potential within the nanowire. The drain contact of the nanowire, D, is grounded, and the source contact, S, is connected to an antinode of the resonator, oscillating at a voltage VCavity. Credit: Petersson et. al.

Qubit-based computing exploiting spooky quantum effects like entanglement and superposition will speed up factoring and searching calculations far above what can be done with mere zero-or-one bits. To domesticate quantum weirdness, however, to make it a fit companion for mass-market electronic technology, many tricky bi-lateral and multi-lateral arrangements—among photons, electrons, circuits, cavities, etc.—need to be negotiated.

A new milestone in this forward march: a Princeton-Joint Quantum Institute (JQI) collaboration announces the successful excitation of a spin qubit using a resonant cavity. The circuit, via the cavity, senses the presence of the qubit as if it were a bit of capacitance. This result, published this week in *Nature* magazine, points toward the eventual movement of quantum information over "bus" conduits much as digital information moves over buses in conventional computers.

QUBIT CATALOG

A qubit is an isolated system—a sort of toggle—which is maintained simultaneously in a mixture of two quantum states. Qubits come in many forms, such as photons in either of two polarization states, or atoms oriented in either of two states, or superconducting circuits excited in either of two ways. One promising qubit platform is the quantum dot, a tiny speck of semiconducting material in which the number of electrons allowed in or out can be severely controlled by nearby electrodes. In a charge qubit the dot can co-exist in states where one or zero electrons are in the dot. In a spin qubit, two electrons (sitting in two neighboring dots), acting like a molecule, possess a composite spin which can be up or down.

Quantum dots are easy to fabricate using established semiconductor technology. This gives them an advantage over many other qubit modes, especially if you want to build an integrated qubit chip with many qubits in proximity. One drawback is that qubits in a dot are harder to protect against outside interference, which can ruin the delicate quantum processing of information. An example of this unwanted decoherence is the magnetic interaction of the electron "molecule" with the nuclei of the very atoms that make up the dot.

Another challenge is to control or excite the qubit in the first place. That is, the qubit must be carefully incited into its two-states-at-once condition, the technical name for which is Rabi oscillation. The Princeton-JQI work artfully addresses all these issues.

CIRCUIT QED

Indeed, the present work is another chapter in the progress of knowledge about electromagnetic force. In the 19th century James Clerk Maxwell set forth the study of electrodynamics in its classic form. In the early and mid 20th century a quantum version of electrodynamics (QED) was established which also, incidentally, accommodated the revolutionary idea of antimatter and of the creation and destruction of elementary particles.

More recently QED has been extended to the behavior of electromagnetic waves within metal circuits and resonant cavities. This cavity-QED or circuit-QED (cQED), provides a handy protocol for facilitating a traffic between qubits and circuits: excitations, entanglement, input and readout, teleportation (movement of quantum information), computational logic, and protection against decoherence.

Forty years ago this effort to marry coherent quantum effects with electronics was referred to as quantum electronics. The name used nowadays has shifted to quantum optics. "With the advent of the laser, the focus moved into the optical domain," says Jacob Taylor, a JQI fellow and NIST physicist. "It is only in the past few years that the microwave domain – where electronics really function – has come into its own, returning quantum optics to its roots in electrical circuits."

Cavities are essential for the transportation of quantum information. That's because speed translates into distance. Qubits are ephemeral; the quantum information they encode can dissipate quickly (over a time frame of nanoseconds to seconds) and all processing has to be done well before then. If, moreover, the information has to be moved, it should be done as quickly as possible. Nothing goes faster than light, so transporting quantum information (at least for moving it from one place to another within a computer), or encoding the information, or entangling several qubits should be done as quickly as possible. In this way information or processing in more distant nodes can take place.

SPIN-ORBIT COUPLING

The JQI part of this spin-qubit collaboration, Jacob Taylor, earlier this year participated in research that established a method for using a resonant cavity to excite a qubit consisting of an ion held simultaneously in two spin states. The problem there was a mismatch between the frequency at which the circuit operated and the characteristic frequency of the ion oscillating back and forth between electrodes. The solution was to have the circuit and ion speak to each other through the intermediary of an acoustic device. (See story at http://phys.org/news/2012-03-electrical-circuits-atoms.html)

The corresponding obstacle in the JQI-Princeton experiment is that the circuit (in effect a microwave photon reflecting back and forth in a resonant cavity) exerts only a weak magnetic effect upon the electron doublet in the quantum dot. The solution: have the cavity influence the physical movement of the electrons in the dot—a more robust form of interaction (electrical in nature)—rather than the interact with the electrons' spin (magnetic force).

Next this excitation is applied to the spin of the electron doublet (the aspect of the doublet which actually constitutes the quantum information) via a force called spin-orbit coupling. In this type of interaction the physical circulation of the electrons in the dot (the "orbit" part) tangles magnetically with the spins of the nuclei (the "spin" part of the interaction) in the atoms composing the dot itself.

It turns out this spin-orbit coupling is much stronger in indium-arsenide than in the typical quantum dot material of gallium-arsenide. This it was that material science was an important ingredient in this work, in addition to contributions from the physics and electrical engineering departments at Princeton.

To recap: an electrical circuit excites the dot electrically but the effect is passed along magnetically to the qubit in the dot when the electrons in the dot move past and provoke an interaction with the nuclei in the InAs atoms. Thus these qubits deserve to be called the first spin-orbit qubits in a quantum dot.

The influence works both ways. Much as the presence of a diver on the end of a diving board alters the resonant frequency of the board, so the presence of the spin qubit alters the resonant frequency of the cavity, and so its presence can be senses. Conversely, the alteration, effected by the spin-orbit interaction, can be used to excite the qubit, at rates of a million per second or more.

Previously a quantum-dot-based charge qubit was excited by a cavity. So why was it important to make a quantum-dot qubit based on spin? "The spins couple weakly to the electrical field, making them much harder to couple to than a charge," said Taylor. "However, it is exactly this property which also makes them much better qubits since it is precisely undesired coupling to other systems, which destroys quantum effects. With a spin-based qubit, this is greatly suppressed."

More information: "Circuit Quantum Electrodynamics with a Spin Qubit," K. D. Petersson, L. W. McFaul, M. D. Schroer, M. Jung, J. M. Taylor, A. A. Houck, and J. R. Petta. *Nature*, 18 October 2012.

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