Semiconductor-inspired superconducting quantum computing devices

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Builders of future superconducting quantum computers could learn a thing or two from semiconductors, according to a report in *Nature Communications* this week. By leveraging the good ideas of the natural world and the semiconductor community, researchers may be able to greatly simplify the operation of quantum devices built from superconductors. They call this a "semiconductor-inspired" approach and suggest that it can provide a useful guide to improving superconducting quantum circuits.

Superconducting quantum bits, or qubits, are circuits made from superconducting components—such as wires, capacitors or non-linear inductors—that have zero resistance to electrical current. Designing these circuits from scratch offers tremendous flexibility, and has gone a long way toward realizing a full-scale quantum computer. On the other hand, qubits found in semiconductor materials like ultra-pure silicon offer good properties for quantum computing, like long quantum memory times and fast two-qubit gates. These benefits come with constraints, but those constraints have led to creative solutions from the semiconductor community.

Yun-Pil Shim and Charles Tahan at the Laboratory for Physical Sciences and the University of Maryland in College Park are exploring whether ideas gleaned from semiconductor qubits may be useful in designing better approaches to superconducting quantum computers. As a first step, they considered applying novel control approaches to state-of-the-art superconducting qubits. They found that they could eliminate one of the most costly overheads for control—microwave sources—by using a solution developed in the semiconductor qubit community. Notably, they found an even more efficient implementation in superconducting qubits, making the approach easier to realize than the semiconductor original.

"If the community could mimic the great properties of semiconductor qubits in man-made superconducting circuits, they might be able to have the best of both worlds," Tahan says. "In a large sea of parameters sometimes the best guide is nature."

Qubits can be realized in many different physical platforms, such as a superconducting circuit or an electron's spin. Spin is a quantum property of particles that physicists often think of as a small magnet that will point along the direction of an applied magnetic field. A spin can point up or down, corresponding the the 0 or 1 of conventional bits, but it can also point horizontally. This results in a quantum "superposition" of 0 and 1, a key feature of qubits. In some systems, these spin qubits can carry quantum information robustly because they are unaffected by electrical charge, a common source of noise.

Spins and superconducting qubits are controlled in similar ways. In both, microwave radiation can drive transitions between the two levels of the qubit allowing for quantum logic gates. But semiconductor spin qubits are also different. They often have weak coupling to the environment, leading to long memory times but slow quantum gates. Additionally, spin qubits are quite small, making them susceptible to inadvertent crosstalk from nearby spins.

The semiconductor community has dealt with both problems by developing "all-electrical" approaches to quantum computation that represent one qubit with multiple physical spins. Operations on this "encoded" qubit are performed by pairwise interactions between the physical spins. This requires at least three spins per encoded qubit and a large number of physical pulses to achieve a single encoded gate—a costly overhead for quantum computing, especially when pulses aren't perfect.

Shim and Tahan show that an encoded qubit approach can work even better with superconducting qubits. In fact, they show that modern superconducting qubits called transmons or fluxmons, which can be tuned individually, require only two physical qubits per encoded qubit. More importantly, the encoded gate time and gate error don't change much. For example, while a controlled-NOT gate may take roughly 20 qubit-qubit interactions to accomplish in semiconductor spins, Shim and Tahan show that a similar two-qubit gate can be accomplished using only one two-qubit pulse. This means that all quantum logic gates can be performed with fast DC pulses instead of relying on microwave-driven qubit rotations.

The authors claim that their scheme can be implemented with current superconducting qubits and control methods, but there are still open questions. In the encoded scheme, initializing qubits may be noisy. And ubiquitous "transmon" qubits maybe be outperformed by newer qubit types like the "fluxmon" or "fluxonium."

Quantum computers must preserve qubits from outside interference for as long as a calculation proceeds. Despite rapid progress in the quality of superconducting qubits (qubit lifetimes now surpass 100 microseconds, up from tens of nanoseconds a decade ago), qubit gate error rates are still limited by loss in the metals, insulators, substrates and interfaces that make up these devices. These limitations will also limit the performance of the encoded scheme as proposed, and more progress on these fundamental device issues is still needed.

A major goal on the path to a full-scale quantum computer is the demonstration of "fault-tolerant" quantum error correction, where the error of physical quantum gates is reduced by repeated error correction on a "logical" qubit consisting of many physical qubits. Removing the need for microwave control, along with the other benefits of the encoded qubit proposal, could make realizing a logical qubit with superconducting qubits easier. While the authors believe that this work represents an advance, they suggest that additional progress can be made by looking closer still at spin qubits.

More information: Yun-Pil Shim et al. Semiconductor-inspired design principles for superconducting quantum computing, *Nature Communications* (2016). DOI: 10.1038/NCOMMS11059

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