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Rebuilding the heart of a quantum computer

After decades of advances in quantum computing, one of the obstacles standing between today's experimental machines and far more capable processors may come down to a layer of material only a few atoms thick.

It sits inside the Josephson junction, the tiny circuit element at the heart of superconducting quantum bits, or qubits. The basic design used in most systems today has changed remarkably little in roughly a quarter century: two layers of aluminum separated by an ultrathin layer of aluminum oxide.

That design helped enable enormous progress. Now, researchers believe the junction itself may be limiting what comes next.

A trio of UC Santa Barbara researchers will help take on that problem through a new institute titled MARQUIS: Manufacturable and Resilient Superconducting Quantum Information Systems. Led by Princeton University, the institute will receive $27.9 million from the National Science Foundation over five years and bring together roughly two dozen laboratories across nine institutions, spanning materials science, quantum devices and semiconductor processing.

UCSB’s team includes Nobel laureate and physics professor Michel Devoret, a pioneer in superconducting circuits; Herbert Kroemer Distinguished Professor Chris Van de Walle, whose computational work reveals the behavior of materials at the

atomic scale; and Distinguished Professor Chris Palmstrøm, an expert in growing and characterizing complex combinations of materials. MARQUIS is one of eight institutes established by NSF as part of a $290 million round of funding in the Quantum Leap Challenge Institutes program. Three of the eight institutes involve UCSB researchers.

“Professors Devoret, Palmstrøm and Van de Walle bring together three capabilities that rarely exist in one place: understanding how quantum devices behave, seeing what is happening at the atomic level and being able to build entirely new material structures,” said Umesh Mishra, dean of the Robert Mehrabian College of Engineering. “That is very much the UCSB model. We bring people across disciplines together around a difficult problem and give them the freedom and tools to attack it from fundamentally different directions.”

For much of the history of superconducting quantum computing, researchers had other limitations to overcome, including electromagnetic noise, quasiparticle losses and losses associated with wiring. As those obstacles have receded, scientists have gained a clearer view of the junction.

“The Josephson tunnel junction is now, finally, the weakest element in a superconducting quantum processor,” Devoret said.For decades, many other roadblocks had to be cleared.We can now offer material scientists a testbed to evaluate experimental junctions without as much interference from shortcomings elsewhere in the device.”

Devoret shared the 2025 Nobel Prize in Physics with John Clarke and John Martinis, a UCSB professor of physics, for experiments demonstrating macroscopic quantum mechanical tunneling and energy quantization in an electrical circuit, foundational work for today's superconducting quantum technologies.

MARQUIS now returns to one of the basic components involved in that physics and asks whether the design can be improved.

Disorder only atoms wide

A conventional Josephson junction sandwiches an insulating layer of aluminum oxide between two superconducting aluminum electrodes. The oxide is roughly a nanometer thick, thin enough for electrons to cross it through quantum tunneling.

Unlike a crystal, however, the oxide lacks a regular atomic arrangement. That disorder can give rise to two-level systems, microscopic configurations capable of absorbing energy at frequencies used to control a qubit. Those losses shorten the time its quantum state can survive.

Palmstrøm's group will investigate whether more orderly structures could reduce those losses.

“What would be ideal is to have single crystal superconductors and dielectric heterostructures so that there is no disorder in the dielectric and at the interfaces,” he said.

Creating them is difficult because superconductors and insulators can have very different crystal structures, chemical bonds and surface properties. Palmstrøm's laboratory specializes in combining such dissimilar materials.

Using molecular beam epitaxy, or MBE, his group can grow structures layer by layer and interfaces as they form. Samples can move under ultrahigh vacuum among seven interconnected MBE systems dedicated to different classes of materials.

One possibility Palmstrøm and Van de Walle are exploring replaces aluminum oxide with exceptionally pure single-crystal silicon. Its lower tunneling barrier would allow a thicker insulating layer, reducing the effects of minute variations in thickness.

The concept may also allow much smaller qubits.

Palmstrøm's group is developing a design in which a tiny fin is etched from a single-crystal silicon wafer and superconducting material is deposited along its sides. The silicon forms the insulating barrier of the Josephson junction, an approach that Palmstrøm said could reduce the footprint of a transmon, a widely used type of superconducting qubit, by more than two orders of magnitude.

Finding the atoms that cause the trouble

Building a promising structure is only part of the challenge. Researchers also need to determine which microscopic imperfections interfere with a qubit and why.

Van de Walle's group uses first-principles calculations grounded in quantum mechanics to predict how individual atoms and interfaces influence electronic

behavior. His team has spent years applying similar methods to semiconductor devices, including LEDs.

The work illustrates how even extremely rare imperfections impact results.

“In our work on defects in LEDs, we find that even at concentrations of less than one in a million atoms certain defects can measurably lower the light-emission efficiency,” Van de Walle said.

For MARQUIS, those calculations can help identify which material combinations warrant further experiments and explain why some perform better than others.

The partnership between calculation and experiment is already established at UCSB. In previous work with Palmstrøm, Van de Walle's predictions helped guide the development of higher-quality Josephson junctions.

MARQUIS adds another piece: Devoret's ability to determine whether those changes translate into a better quantum circuit.

Knowing when something is actually better

An encouraging result can be misleading if a limitation elsewhere in the circuit or measurement system is responsible for what researchers observe.

Devoret said that such complications hampered previous attempts to move beyond conventional junction materials. Within MARQUIS, he will help establish experimental “guardrails” that distinguish changes in the junction itself from unrelated effects. His group will also investigate nitride-based junctions.

“It is only now in 2026 that we know how to mitigate all other possible failure modes that we can attack the problem of making the best possible junction,” Devoret said.

The stakes extend beyond improving an individual component. Quantum computers capable of running useful algorithms are expected to rely on error correction, which compensates for mistakes that accumulate while quantum information is stored and manipulated.

“The useful algorithms require quantum error correction of 2-qubit quantum operations, which itself requires improvement of Josephson tunnel junction quality by a factor 10,” Devoret said.

Greater reliability at the junction could affect the entire machine. Fewer physical qubits may be needed to construct an error-corrected logical qubit, reducing the accompanying control wiring and refrigeration requirements.

From exceptional devices to repeatable ones

MARQUIS is not simply trying to produce an exceptional junction in one laboratory. The larger aim is to understand the physics and fabrication well enough to consistently make high-quality devices.

Princeton's Nathalie de Leon, who directs the institute, has noted that superconducting quantum researchers have relied on essentially the same junction technology for roughly 25 years. It has served experimental systems well, but processors containing far larger numbers of qubits will require greater control.

At UCSB, that transition from promising laboratory devices to reproducible technologies has deep roots. For decades, the campus has helped shape modern semiconductor research, from compound-semiconductor materials and epitaxial growth to electronic and photonic devices. Much of that progress grew from close interaction among material scientists, device physicists, and fabrication experts, the same disciplines that MARQUIS is bringing together around superconducting quantum hardware.

The parallel is especially relevant to Palmstrøm and Van de Walle, whose work draws directly on methods and lessons developed through semiconductor research. Palmstrøm's group is designing processes that, where possible, could be compatible with tools used in semiconductor manufacturing, including 300-millimeter silicon production facilities.

Van de Walle sees semiconductor technology as evidence of what can happen when scientists understand materials well enough to control them at scale.

“For the Josephson junctions themselves, it would be a huge success if they could be manufactured with the same level of consistency and quality as has been achieved in semiconductor technology,” he said.

If MARQUIS succeeds, UCSB researchers could help bring a similar progression to superconducting quantum hardware: from understanding atomic-scale behavior, to building better devices, to developing processes that can be repeated reliably and to

building devices that can be consistently reproduced.

The effort could also answer a question whose significance reaches beyond quantum computing.

“Identifying the microscopic origin of two-level systems has remained a great challenge in condensed-matter physics,” Van de Walle said. “Success on this front would have an impact well beyond the goals of this specific program.”

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