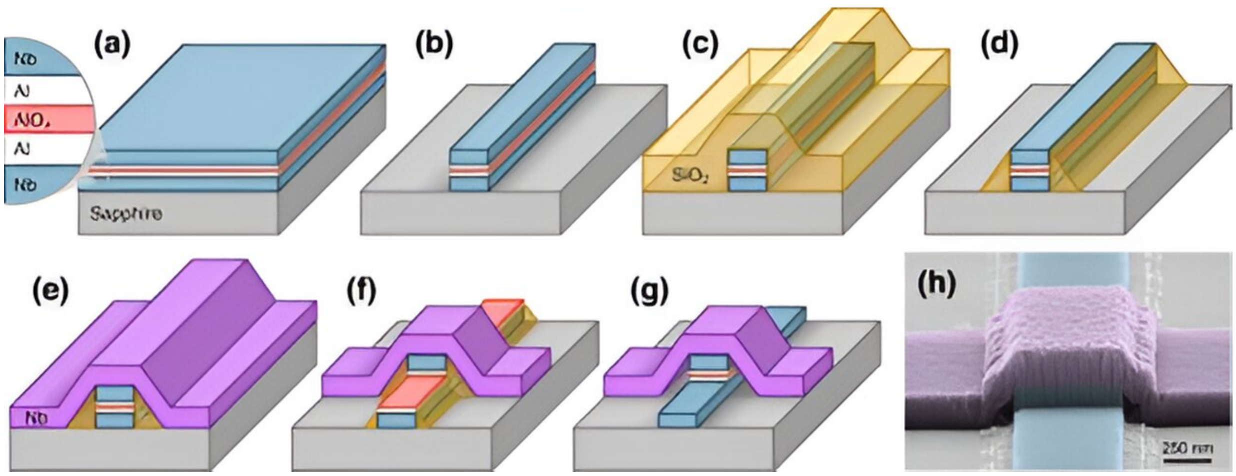
Resurrecting niobium for quantum science

February 26 2024, by Leah Hesla



Junction fabrication process. (a) The trilayer is deposited and oxidized in situ. (b) The first layer is etched with a chlorine RIE. (c) SiO_2 is grown isotropically. (d) Sidewall spacer is formed by anisotropic etching with fluorine chemistry. (e) Surface oxides are cleaned in a vacuum, and the wiring layer (purple) is deposited. (f) The second junction finger (and other circuit elements) are defined by a fluorine plasma etch selective against Al. (g) Final devices undergo a wet etch to further remove SiO_2, exposed Al, and some NbO_x. (h) Color-enhanced electron micrograph of a finished trilayer junction with dimensions 500×600 nm. Credit: *Physical Review Applied* (2024). DOI: 10.1103/PhysRevApplied.21.024047

For years, niobium was considered an underperformer when it came to superconducting qubits. Now, scientists supported by Q-NEXT have found a way to engineer a high-performing niobium-based qubit and take advantage of niobium's superior qualities.

When it comes to quantum technology, niobium is making a comeback.

For the past 15 years, niobium has been sitting on the bench after experiencing a few mediocre at-bats as a core qubit material.

Qubits are the fundamental components of quantum devices. One qubit type relies on superconductivity to process information.

Touted for its superior qualities as a superconductor, niobium has always been a promising candidate for quantum technologies. However, scientists found niobium difficult to engineer as a core qubit component, so it was relegated to the second string on Team Superconducting Qubit.

Now, a group led by Stanford University's David Schuster has demonstrated a way to create niobium-based qubits that rival the state-of-the-art for their class.

"We've shown that niobium is relevant again, expanding the possibilities of what we can do with qubits," said Alexander Anferov of the University of Chicago's Physical Science division, one of the lead scientists of the result.

The team's work is published in *Physical Review Applied*.

By harnessing niobium's standout features, scientists will be able to expand the capabilities of quantum computers, networks, and sensors. These quantum technologies draw on quantum physics to process information in ways that outclass their traditional counterparts and are expected to improve areas as varied as medicine, finance, and communication.

The niobium advantage

When it comes to superconducting qubits, aluminum has ruled the roost. Aluminum-based superconducting qubits can store information for a relatively long time before the data inevitably disintegrates. These longer coherence times mean more time for processing information.

The longest coherence times for an aluminum-based superconducting qubit are a few hundred-millionths of a second. By contrast, in recent years, the best niobium-based qubits yielded coherence times that are 100 times shorter—a few hundred billionths of a second.

Despite that short qubit lifetime, niobium held attractions. A niobium-based qubit can operate at higher temperatures than its aluminum counterpart, and so would require less cooling. It can also operate across an eight-times-greater frequency range and a massive 18,000-times-wider magnetic field range compared to aluminum-based qubits, expanding the menu of uses for the superconducting-qubit family.

In one respect, there was no contest between the two materials: Niobium's operating range trounced aluminum's. But for years, the short coherence time made the niobium-based qubit a nonstarter.

"No one really made that many qubits out of niobium junctions because they were limited by their coherence," Anferov said. "But our group wanted to make a qubit that could work at higher temperatures and a greater frequency range—at 1 K and 100 gigahertz. And for both of those properties, aluminum is not sufficient. We needed something else."

So, the team had another look at niobium.

Losing the lossiness

Specifically, they had a look at the niobium Josephson junction. The Josephson junction is the information-processing heart of the superconducting qubit.

In classical information processing, data comes in bits that are either 0s or 1s. In quantum information processing, a qubit is a mixture of 0 and 1. The superconducting qubit's information "lives" as a mixture of 0 and 1 inside the junction. The longer the junction can sustain the information in that mixed state, the better the junction and the better the qubit.

The Josephson junction is structured like a sandwich, consisting of a layer of nonconducting material squeezed between two layers of superconducting metal. A conductor is a material that provides easy passage for electrical current. A superconductor kicks it up a notch: It carries electrical current with zero resistance. Electromagnetic energy flows between the junction's outer layers in the mixed quantum state.

The typical, trusty aluminum Josephson junction is made of two layers of aluminum and a middle layer of aluminum oxide. A typical niobium junction is made of two layers of niobium and a middle layer of niobium oxide.

Schuster's group found that the junction's niobium oxide layer sapped the energy required to sustain quantum states. They also identified the niobium junctions' supporting architecture as a big source of energy loss, causing the qubit's quantum state to fizzle out.

The team's breakthrough involved both a new junction arrangement and a new fabrication technique.

The new arrangement called on a familiar friend: aluminum. The design did away with the energy-sucking niobium oxide. And instead of two distinct materials, it used three. The result was a low-loss, trilayer junction—niobium, aluminum, aluminum oxide, aluminum, niobium.

"We did this best-of-both-worlds approach," Anferov said. "The thin layer of aluminum can inherit the superconducting properties of the niobium nearby. This way, we can use the proven chemical properties of aluminum and still have the superconducting properties of niobium."

The group's fabrication technique involved removing scaffolding that supported the niobium junction in previous schemes. They found a way to maintain the junction's structure while getting rid of the loss-inducing, extraneous material that hampered coherence in previous designs.

"It turns out just getting rid of the garbage helped," Anferov said.

A new qubit is born

After incorporating their new junction into superconducting qubits, the Schuster group achieved a coherence time of 62 millionths of a second, 150 times longer than its best-performing niobium predecessors. The qubits also exhibited a quality factor—an index of how well a qubit stores energy—of 2.57×10^5, a 100-fold improvement over previous niobium-based qubits and competitive with aluminum-based qubit quality factors.

"We've made this junction that still has the nice properties of niobium, and we've improved the loss properties of the junction," Anferov said. "We can directly outperform any aluminum qubit because aluminum is an inferior material in many ways. I now have a qubit that doesn't die at higher temperatures, which is the big kicker."

The results will likely elevate niobium's place in the lineup of superconducting qubit materials.

"This was a promising first foray, having resurrected niobium junctions," Schuster said. "With niobium-based qubits' broad operational reach, we open up a whole new set of capabilities for future quantum technologies."

More information: Alexander Anferov et al, Improved coherence in optically defined niobium trilayer-junction qubits, *Physical Review Applied* (2024). DOI: 10.1103/PhysRevApplied.21.024047. On *arXiv*: DOI: 10.48550/arxiv.2306.05883

Provided by Argonne National Laboratory