High-quality superconducting qubits fabricated with CMOS-compatible technologies

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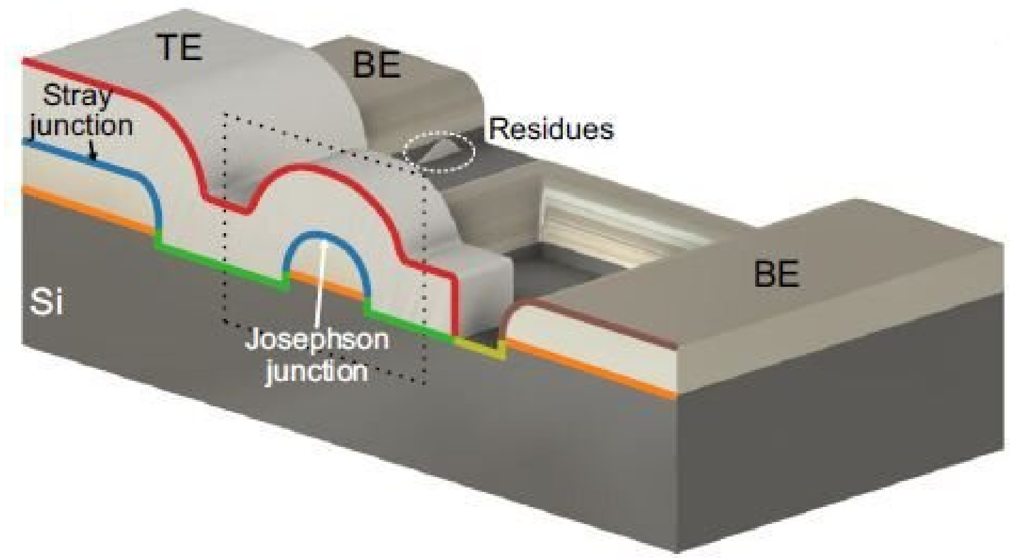


Cross-sectional illustration of the overlap junction. The overlap between the bottom electrode (BE) and the top electrode (TE) defines the Josephson junction (and a parasitic stray junction). Sidewall residues can be present due to subtractive etching steps. The green layer represents the Ar-milling induced damaged amorphous Si layer. Credit: imec

Quantum computers promise to dramatically affect selected application fields, including materials synthesis, pharmaceutical drug development, and cybersecurity—to name a few.

In the quantum circuit model of computation, a quantum logic gate (or simply quantum gate) is a basic operation on a small number of qubits, which is analogous to a classical logic gate for conventional digital circuits. Qubits are the building blocks of quantum circuits. Different quantum computing platforms with diverse types of qubits are being developed and worldwide efforts are ongoing to bring them from the lab to the world.

One of the promising technologies for quantum computing makes use of superconducting circuits. Anton Potočnik, senior researcher in quantum computing at IMEC, says, "The energy states of superconducting qubits are relatively easy to control, and, throughout the years, researchers have been able to couple an increasing number of qubits together. This enables an ever-higher level of entanglement—which is one of the pillars of quantum computing. On top of that, research groups worldwide have demonstrated superconducting qubits with long coherence times (up to several 100 µs) and sufficiently high gate fidelities—two important benchmarks for quantum computation."

While coherence time gives us information on how long a qubit retains its quantum state (and hence, its information), gate fidelity quantifies the difference in operation between an ideal gate and the corresponding physical gate in quantum hardware.

Large-scale implementation hindered by variability issues

The encouraging results mentioned above have so far only been obtained at lab scale, using double-angle evaporation and lift-off techniques for making the most critical element: the Josephson junction. "The superconducting qubit is essentially a non-linear LC resonator circuit, containing a non-linear inductor (L) and a capacitor (C)," explains Anton Potočnik.

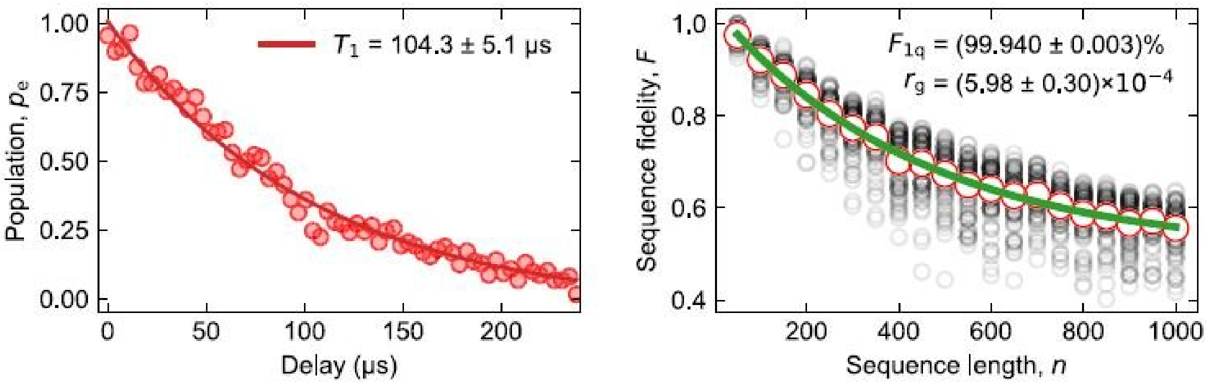
"The Josephson junction takes the role of a non-linear, non-dissipating inductor, which allows us to manipulate qubit energy states to represent, for example, a superposition of |0> and |1>. To minimize any losses of energy or, in other words, maximize coherence time, the various interfaces contained in the structures that make up the junction and the capacitor must be as clean as possible. Even one atomic defect present at one of the interfaces can cause the qubit to lose energy. And that's why double-angle evaporation and lift-off are the preferred fabrication techniques: they can provide these extremely clean interfaces."

But these fabrication techniques have a serious downside: they challenge a further upscaling towards larger numbers of qubits. Large-scale implementation is hindered by the variability in Josephson energy of the evaporated junction. In addition, the fabrication technique limits the choice of the superconducting material, and hence, the potential for qubit improvement.

An alternative approach using CMOS-compatible fabrication techniques

Jeroen Verjauw, Ph.D. researcher at IMEC, says, "Our team at IMEC has explored alternative ways of fabricating the superconducting circuits. Our focus was on creating so-called overlap Josephson junctions using only CMOS-compatible materials and techniques, as this enables leveraging the reliability and reproducibility offered by state-of-the-art CMOS processing steps to control variability and facilitate upscaling."

Overlap junctions have two electrodes (bottom (BE) and top (TE)) separated by a thin insulator layer. The electrodes are defined in two patterning cycles, with a vacuum break in between. The break introduces uncontrolled growth of native metal oxide, which must be removed during a so-called Ar-milling step. "This Ar-milling step is however known to be very critical and has previously been reported to introduce unwanted energy losses," adds Jeroen Verjauw.



(Left) Qubit energy relaxation measurement and (right) average gate fidelity and average error per gate. Credit: imec

Coherence times up to 100 µs, gate fidelity of 99.94%

Tsvetan Ivanov, researcher at IMEC, says, "We have demonstrated in our lab superconducting qubits with coherence times exceeding 100 µs and an average single-qubit gate fidelity of 99.94%. These results are comparable with state-of-the-art devices, but, for the first time, have been obtained using CMOS-compatible fabrication techniques—such as state-of-the-art sputtering deposition and subtractive etch. These breakthrough results could be achieved by improving the known process for making the overlap junctions. The improvements include process optimization to reduce the number of process steps and interfaces (and hence, the risk for energy losses), an improved Ar-milling step, and the exclusive use of aluminum (Al) for making the electrodes."

The next steps: 300 mm fabrication, reducing the losses and addressing reproducibility

Our experiments described in NPJ Quantum Information have so far only been achieved in a lab environment, on substrate coupons. Tsvetan Ivanov: "Yet, the presented fabrication method heralds an important milestone towards a manufacturable 300mm CMOS process for high-quality superconducting qubits. Soon, we will transfer the fabrication of these superconducting circuits into IMEC's 300mm fab. We are eager to verify whether the high coherence times can be reproduced on larger wafer substrates."

Jeroen Verjauw: "In addition, we designed our test vehicles such that we can study where the energy losses come from. First results have indicated that the losses mainly occur at the outer surface of the structure, and not, at the critical junction level. This is encouraging, as it leaves room for optimization by applying more dedicated surface treatment steps. And, finally, our fabrication method provides a path towards fabricating reproducible qubits over a large wafer area, with low variation in for example qubit frequency."

Yet, there are other obstacles on the road towards practical superconducting-based quantum computers. Anton Potočnik concludes: "Superconducting qubits are still relatively large (mm-sized) compared to for example semiconducting spin qubits (nm-sized). We investigate how we can further shrink the devices. Many efforts are also ongoing on the algorithmic side. The qubits that we make today are not ideal, so there is a huge effort from the theoretical side to develop algorithms that are more resilient to losses and errors, and to develop quantum error correction protocols. On top of that, our community will need scalable, very well calibrated instrumentation to interface with the growing number of superconducting qubits, to control them and readout meaningful results."

Conclusion and outlook

Kristiaan De Greve, program director quantum computing at IMEC, sees this work by Anton, Tsvetan, Jeroen and their coworkers as a crucial milestone towards being able to overcome fundamental barriers to upscaling of superconducting qubits by virtue of the control and accuracy benefits of industry-standard processing methods: "As many thousands to millions of physical qubits will likely be required for the quantum processors of the future, overcoming limitations due to variability and low yield will be crucial. IMEC therefore invests significantly in understanding and benchmarking these limitations and introducing novel solutions that leverage our experience in advanced process control."

Danny Wan, program manager quantum computing at IMEC, adds: "Within IMEC's program on quantum computing, our scientists have set themselves the challenge to bring quantum computing (both semiconducting and superconducting based) from the lab to the world. Results as described in NPJ Quantum Information are extremely encouraging and confirm that we are on the right track in pursuing our mission."

The study is published in *npj Quantum Information*.

More information: J. Verjauw et al, Path toward manufacturable superconducting qubits with relaxation times exceeding 0.1 ms, *npj Quantum Information* (2022). DOI: 10.1038/s41534-022-00600-9

Provided by IMEC

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