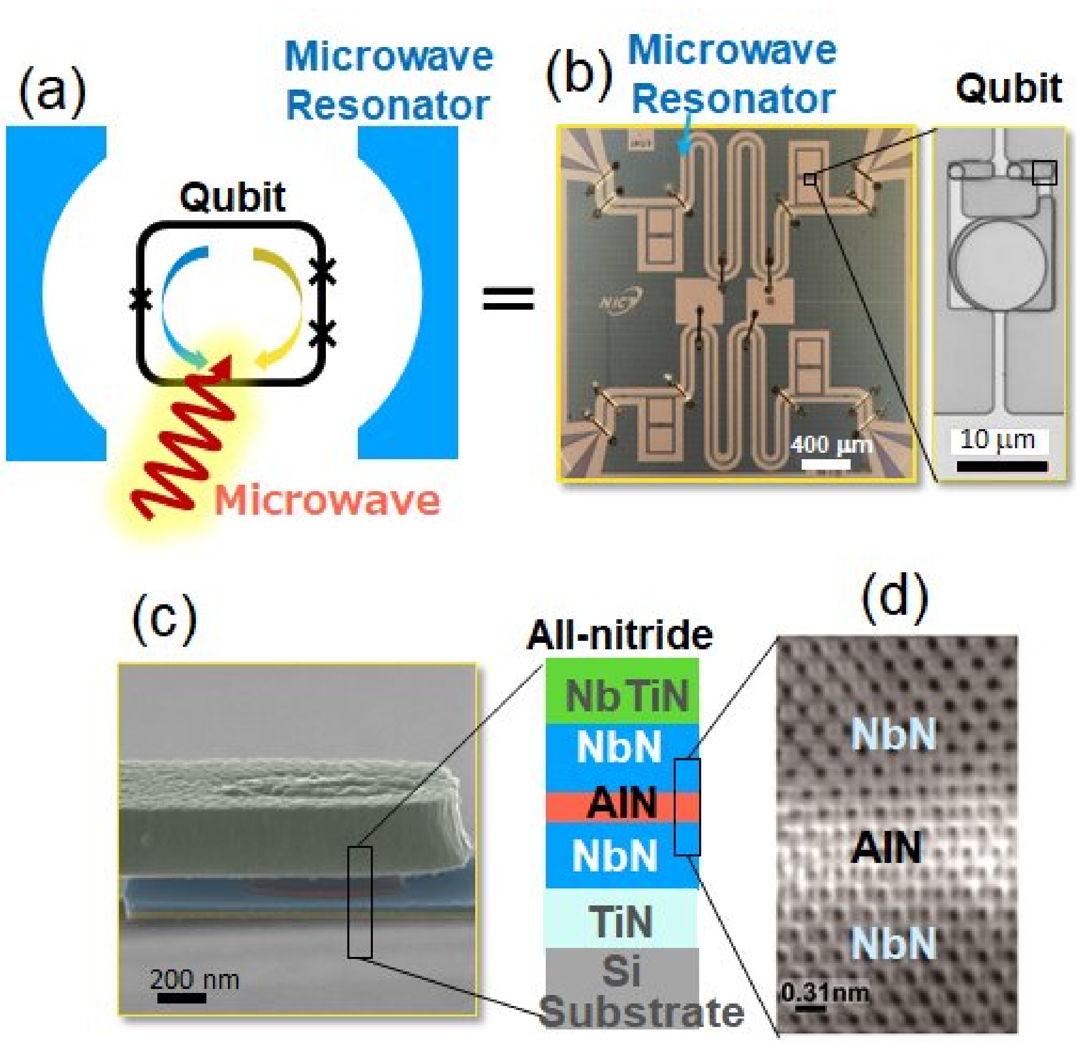
All-nitride superconducting qubit made on a silicon substrate

September 20 2021



(a) Conceptual diagram of microwave cavity and qubit (b) Optical micrograph of nitride superconducting qubit circuit (c) Electron micrograph of nitride superconducting qubit (part) and cross-sectional view of the device (d) Transmission electron micrograph of epitaxially grown nitride Josephson junction. Credit: National Institute of Information and Communications Technology, National Institute of Advanced Industrial Science and Technology, and Nagoya University

Researchers at the National Institute of Information and Communications Technology (NICT, President: Tokuda Hideyuki, Ph.D.), in collaboration with researchers at the National Institute of Advanced Industrial Science and Technology (AIST, President: Dr. Ishimura Kazuhiko) and the Tokai National Higher Education and Research System Nagoya University (President: Dr. Matsuo Seiichi) have succeeded in developing an all-nitride superconducting qubit using epitaxial growth on a silicon substrate that does not use aluminum as the conductive material.

This qubit uses niobium nitride (NbN) with a superconducting transition temperature of 16 K (-257 °C) as the electrode material, and aluminum nitride (AlN) for the insulating layer of the Josephson junction. It is a new type of qubit made of all-nitride materials grown epitaxially on a silicon substrate and free of any amorphous oxides, which are a major noise source. By realizing this new material qubit on a silicon substrate, long coherence times have been obtained: an energy relaxation time (T_1) of 16 microseconds and a phase relaxation time (T_2) of 22 microseconds as the mean values. This is about 32 times T_1 and about 44 times T_2 of nitride superconducting qubits grown on a conventional magnesium oxide substrate.

By using niobium nitride as a superconductor, it is possible to construct a superconducting quantum circuit that operates more stably, and it is expected to contribute to the development of quantum computers and quantum nodes as basic elements of quantum computation. We will continue to work on optimizing the circuit structure and fabrication process, and we will proceed with research and development to further extend the coherence time and realize large-scale integration.

These results were published in the British scientific journal *Communications Materials* on September 20 2021 at 18:00 (Japan standard time).

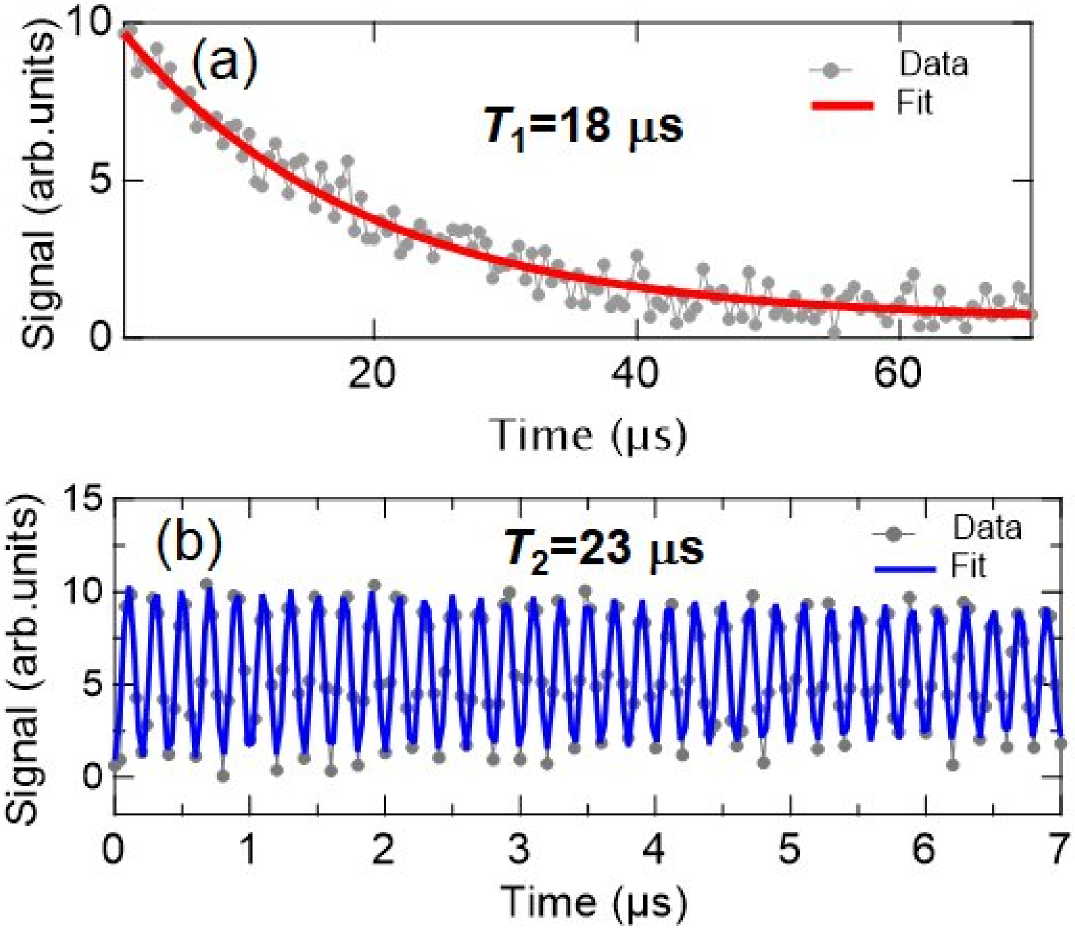
Background and challenges

Toward the coming future Society 5.0, there are limits to the performance improvement of semiconductor circuits that have supported the information society so far, and expectations for quantum computers are rising as a new information processing paradigm that breaks through such limits. However, the quantum superposition state, which is indispensable for the operation of a quantum computer, is easily destroyed by various disturbances (noise), and it is necessary to properly eliminate these effects.

Since superconducting qubits are solid-state elements, they have excellent design flexibility, integration, and scalability, but they are easily affected by various disturbances in their surrounding environment. The challenge is how to extend the coherence time, which is the lifetime of quantum superposition states. Various efforts are being made by research institutes around the world to overcome this problem, and most of them use aluminum (Al) and aluminum oxide film (AlO_x) as superconducting qubit materials. However, amorphous aluminum oxide, which is often used as an insulating layer, is a concern as a noise source, and it was essential to study materials that could solve this problem.

As an alternative to aluminum and amorphous aluminum oxide with a superconducting transition temperature T_C of 1 K (-272 °C), epitaxially grown niobium nitride (NbN) with a T_C of 16 K (-257 °C), NICT has been developing superconducting qubits using NbN / AlN / NbN all-nitride junctions, focusing on aluminum nitride (AlN) as an insulating layer.

In order to realize a NbN / AlN / NbN Josephson junction (epitaxial junction) in which the crystal orientation is aligned up to the upper electrode, it was necessary to use a magnesium oxide (MgO) substrate whose crystal lattice constants are relatively close to those of NbN. However, MgO has a large dielectric loss, and the coherence time of the superconducting quantum bit using the NbN / AlN / NbN junction on



(a) Energy relaxation time T1=18 microseconds (b) Phase relaxation time T2=23 microseconds. Credit: National Institute of Information and Communications Technology, National Institute of Advanced Industrial Science and Technology, and Nagoya University

Achievements

NICT has succeeded in realizing NbN / AlN / NbN epitaxial Josephson junctions using titanium nitride (TiN) as a buffer layer on a silicon (Si) substrate with a smaller dielectric loss. This time, using this junction fabrication technology, we designed, fabricated, and evaluated a superconducting qubit (see Figure 1) that uses NbN as the electrode material and AlN as the insulating layer of the Josephson junction.

As schematically shown in Figure 1(a), the quantum circuit is fabricated on a silicon substrate so that the microwave cavity and the qubit can be coupled and interact with each other as shown in Figure 1(b). From the transmission measurement of the microwave characteristics of the resonator weakly coupled to the qubit under small thermal fluctuation at the extremely low temperature of 10 mK, we achieved an energy relaxation time (T_1) of 18 microseconds and a phase relaxation time (T_2) of 23 microseconds. The mean values for 100 measurements are T_1=16 microseconds and T_2= 22 microseconds. This is an improvement of about 32 times for T_1 and about 44 times for T_2 compared to the case of superconducting qubits on MgO substrates.

For this result, we did not use conventional aluminum and aluminum oxide for the Josephson junction, which is the heart of superconducting qubits. We have succeeded in developing a nitride superconducting qubit that has a high superconducting critical temperature T_C and excellent crystallinity due to epitaxial growth. These two points have great significance. In particular, it is the first time that anyone in the world has succeeded in observing coherence times in the tens of microseconds from nitride superconducting qubits by reducing dielectric loss by epitaxially growing them on a Si substrate. The superconducting qubit of this nitride is still in the early stages of development, and we believe that it is possible to further improve the coherence time by optimizing the design and fabrication process of the qubit.

Using this new material platform that may replace conventional aluminum, we will accelerate research and development of quantum information processing, which will contribute to the realization of more power-saving information processing and the realization of quantum nodes necessary for the construction of safe and secure quantum networks.

Prospects

We plan to work on optimizing the circuit structure and fabrication process with the aim of further extending the coherence time and improving the uniformity of device characteristics in anticipation of future large-scale integration. In this way, we aim to build a new platform for quantum hardware that surpasses the performance of conventional aluminum-based qubits.

More information: Sunmi Kim et al, Enhanced coherence of all-nitride superconducting qubits epitaxially grown on silicon substrate, *Communications Materials* (2021). DOI: 10.1038/s43246-021-00204-4

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