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研究課題名（和文） 全窒化物誘電体材料と基板を用いたエピタキシャル超伝導量子ビットの作製

研究課題名（英文） Development of the epitaxial superconducting qubits using nitride dielectric material and the substrate

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研究成果の概要（和文）：本研究は、超伝導量子回路における誘電損失の原因となる２準位系について調べました。水素終端したシリコン基板上に、TiNをバッファ層として超伝導NbNエピタキシャル成長膜を作製しました。このTiN/NbN２層構造からなる超伝導共振器の誘電損失は2.25 x 10-6で、TiN薄膜単体からほぼ同じレベルであり、MgO単結晶基板上に作製したNbN薄膜の1 x 10-4に比べて劇的な改善が見られました。TiN/NbN２層構造の表面平坦性は0.5nm以下であり、TiN単層膜の0.5nm以上という表面平坦性に比べて改善しており、超伝導量子ビット回路におけるジョセフソン接合の作製により適していると考えられる。

研究成果の概要（英文）：This funded research project studies the intrinsic two level systems (TLSs) due to the dielectric loss of superconducting quantum circuit. Full epitaxially grown superconducting NbN resonator fabricates on a hydrogen terminated single crystal Si(100) substrate with a thin TiN film served as a buffer layer. The dielectric loss of this TiN/NbN resonator device is 2.25x10e-6, comparable to the same level of epitaxiall grown TiN resonator, and a significant improvement from the loss of 1x10e-4 level in epitaxial NbN resonator in single crystal MgO substrate. The TiN/NbN structure results in a more smooth surface roughness (< 0.5 nm), improved from a relatively high surface roughness (> 0.5 nm) in epitaxial TiN thin film, which is more suitable for novel Josephson device in superconducting quantum bit circuit.

研究分野：工学

キーワード：超伝導　TiN　NbN　超伝導共振器　誘電損失　エピタキシャル　ジョセフソン接合　超伝導量子回路

１．研究開始当初の背景

In quantum computer, the fundamental unit is called quantum bit (qubit). A qubit is a quantum two-state system. The qubit can be in superposition of these two quantum states. For instance, a quantum computer has n qubit could use its 2^n states to factor a very large composite number into its primes easily, which is impossible for a classical computer. Therefore, quantum computing using quantum computer has attracted extensive attentions in recent years. In quantum computing, information is stored on quantum systems such as spins, photons, and atoms. The basic element of a quantum computer is the qubit. In principle, a physical qubit can be any quantum system that has at least two quantum states. A variety of physical systems, including trapped ions, nuclear spins, photons, atoms quantum dots, and superconducting Josephson devices, including Josephson junctions and SQUIDs have been proposed and demonstrated as real physical qubits. With the flexibility in engineering, superconducting qubits have the potential to be scaled up easily. Superconducting qubit can be categorized into three types depending on their control parameters: flux, phase, and charge. Experiments have shown coherent oscillations between two fluxoid states in a superconducting flux qubit, which makes this type of qubit a good candidate in realizing quantum computer [3-6]. However, coherence times obtained in superconducting qubits are quite different across various materials. For example, coherence time in niobium (Nb) based Josephson junction (JJ) is approximately few hundreds of nanosecond [7-8]. In contrast, the coherence time in current developed qubits has a scale of approximately few micro-seconds using niobium nitride (NbN) based (~5 μs in phase qubit [9-10], 0.5 μs in a cavity coupled SQUID qubit [11]) or aluminum (Al) based (~10 μs in flux qubit [12]) JJs. Recent progress of coherence time of above 50 μs can be achieved is due to the unique cavity structure that was strongly coupled to the qubit junction [13-14]. Such a short coherence time prohibits a large scale of superconducting qubits to be implemented in QIC.

Theoretical models [15-18] suggested that TLSs could originate in the amorphous oxide material of junction tunnel barrier, or at the interface of superconducting thin film and oxide substrate, or arise from the local impurities at the interface of the superconductor and dielectric insulator of the Josephson junction. In typical Nb-, Al- based Josephson junction fabrication process, oxide materials have been widely used to form the tunnel barrier. However, the amorphous oxide material, for example, SiO_2 and AlO_x can contain large densities of defects that can form TLSs whose energy scale are close to that of qubit energy, therefore strongly interact with the qubits. In order to reduce the number of TLSs, fabricating full epitaxial Josephson junctions is critical. Recent evidence of lower density of TLSs has been demonstrated in phase qubit with an epitaxial Al_2O_3 barrier on a crystalline rhenium (Re) film on sapphire [19-20]. Certain superconducting nitride films also have better surface properties than oxidized film in terms of dissipation at microwave frequencies. For example, superconducting resonators with NbTiN and TiN film contain less densities of TLSs on the thin film surface than those oxidized surfaces [21-23]. Low frequency noise (LFN) measurement in epitaxially grown NbN/AlN/NbN junctions suggested that LFN is mainly due to the defects from the amorphous SiO_2 dielectric layer since the defects inside the AlN tunnel barrier have been largely reduced due to the epitaxial structure of NbN/AlN/NbN junction [24]. The existing standard fabrication process of epitaxial NbN/AlN/NbN junction in our clean room make it possible for us to eliminate TLSs originated in 1) amorphous oxidized dielectric layer by using nitride material, such as, SiN_x, for the dielectric layer for superconducting crosswire; 2) oxidized MgO substrate by removing the substrate after the formation of the epitaxial junction.

２．研究の目的

Superconducting qubit based on Josephson junction has long been considered as one of the promising candidates for implementation of quantum information and computation (QIC). However, the intrinsic two level systems (TLSs) formed from the local –OH bond defects at either the amorphous dielectric layer (SiO_2, etc) around the junction tunnel barrier or on the surface of the oxide substrate (MgO, SiO_2 or SiO on Si) in superconducting qubit circuit (SQC) can introduce noise that destroy the coherent quantum states in qubit [1-2]. The main purpose of this proposed research is to eliminate such local defects by using nitride material instead of oxide material in epitaxially grown Josephson junction dielectric layer and nitride substrate in SQC.

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３．研究の方法

(1) The proposed research focuses on characterization and optimization the deposition parameters of the dielectric materials, which include SiO_2, SiO, SiN, and AlN. NbN junction with different dielectric material will be fabricated by using the optimized gas flow rate, total pressure, source power. Extra efforts also focus on improvement of high quality JJs (low sub-gap leakage current), stable junction critical current density (J_c), as well as the uniformity control of junction size. Junction I-V characteristic will be examined in liquid Helium temperature in order to obtain the junction quality factor. The preliminary result will be evaluated together with that of SiO_2 as junction dielectric material.

(2) Microscopic TLSs in dielectric material in superconducting tunnel junction is one of the possible decoherence sources that resulted short coherence time in this type of qubit. Evidence on how and to what extend that the fluctuation of TLSs in the dielectric material affect the qubit decoherence is collected by measuring the loss of the superconducting coplanar waveguide circuit with various selection among different superconducting materials as well as substrates.

４．研究成果

Low critical current density (100 A/cm^2) and full epitaxial NbN Josephson junctions on MgO substrate (Figure 1) have been fabricated and characterized at the liquid Helium temperature. Full epitaxial NbN qubit embedded in the NbN coplanar waveguide resonator on a single crystal MgO substrate has been fabricated with SiO_2 as the insulation layer for the junction (Figure 2). The device was measured at 30 mK in the Dilution refrigerator with an internal loss level of 3.3×10^{-4} for the overall circuit. The estimated energy relaxation time T_1 of 1 μs, agrees well with the measured qubit energy relaxation T_1 time.

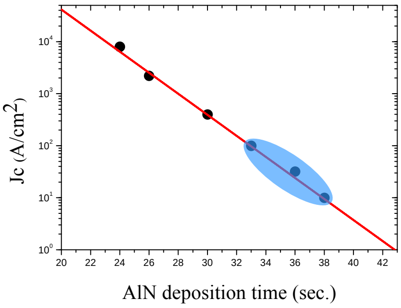

Fig. 1. Junction critical current density J_c as a function of AlN barrier deposition time.

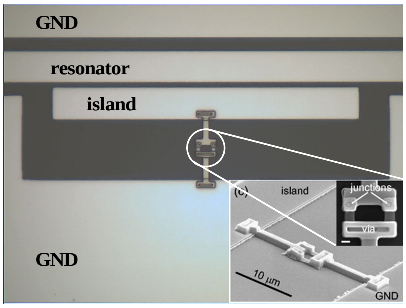

Fig. 2. SEM image of an eptaxially grown NbN resonator coupled with an epitaxially grown SQUID qubit via. an island.

To investigate which mechanisms contribute to the high loss in NbN qubit on MgO, systematical characterization of the internal loss using epitaxially grown NbN thin film coplanar waveguide resonator on MgO substrate has been carried out at 300 mK in a He^3 cryostat. It showed that both SiO_2 and SiNx amorphous films deposited by sputtering contribute the same level of loss in the NbN superconducting qubit circuit. The loss of a NbN resonator without SiO_2 or SiNx is ~ $1.0x10^{-4}$. Superconducting material related loss has been also studied. Aluminum CPW resonators have been developed by both dc sputtering and thermal evaporation methods and only show limited improvement of loss compare to Nb (100) resonator. TiN (200) resonator developed on hydrogen-terminated Si (100) substrate shows a significant loss improvement at the level of $2x10^{-6}$ at the temperature of 300 mK (Figure 3). Clearly, the MgO substrate dominates the internal loss of the NbN-qubit circuit developed on MgO substrate.

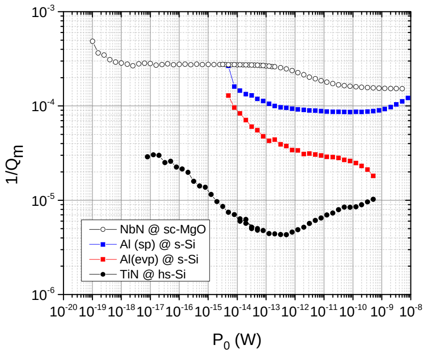

Fig. 3. Comparison of dielectric losses in CPW resonator circuits from: 1) NbN (100) by sputtering on MgO (black circle); 2) Aluminum by sputtering on Si (Blue square); 3) Aluminum by thermal evaporation on Si (Red square); 4) TiN (200) by sputtering on hydrogen-terminated Si (Black squre).

To further study the TiN thin film deposition procedure, we found that the surface roughness of TiN thin film is quite large (> 0.5 nm) compare to the surface roughness of NbN thin deposited on MgO. Thus, the quality of the TiN/AlN/TiN tunnel junctions is not comparable to the high quality tunnel junctions epitaxially grown on MgO substrate. To further solve this problem, a new multi-layer structure process has been developed where a thin TiN (200) layer served as the buffer layer before NbN (100) is deposited. Overall, one can get a promising TiN/NbN/AlN/NbN multi-layer structure for future high quality tunnel junction device fabrication due to the high quality NbN layer. To examine the loss in CPW resonator developed from this new process, we measured the loss by using a multiplexed TiN/AlN superconducting quarter-wavelength (λ/4) circuit (Figure 4). The results show a further improvement in dielectric loss of $1.82x10^{-6}$ and more uniformed photon power dependency compare to epitaxial TiN resonator.

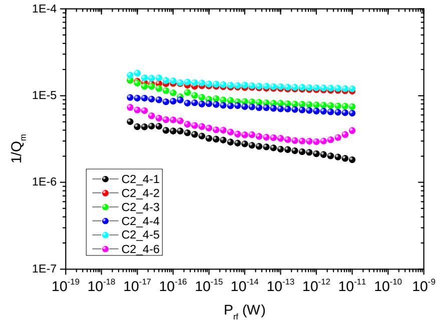

Fig. 4. Measured electric losses in multiplexed (six quarter-wave, λ/4 meandered) superconducting TiN/NbN resonator on hydrogen-terminated Si.

5．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

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