Fabrication of rhenium Josephson junctions*

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Rhenium is a superconductor with a relatively weak tendency to oxidize, which is advantageous in superconducting quantum circuit and qubit applications. In this work, Re/Al–AlO_x/Re Josephson tunnel junctions were fabricated using a selective film-etching process similar to that developed in Nb trilayer technology. The Re films had a superconducting transition temperature of 4.8 K and a transition width of 0.2 K. The junctions were found to be highly reproducible using the fabrication process and their characteristics had good quality with a low leakage current and showed a superconducting gap of 0.55 meV.

Keywords: Re Josephson junctions, trilayer process, qubit application

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1. Introduction

Superconducting quantum circuits based on Josephson junctions have the advantages of low dissipation, scalability, and flexibility in quantum-state preparation, manipulation, and readout. They are promising candidates in the realization of solid-state quantum computing and quantum information,[1] and can also serve as a useful platform in atomic physics and quantum optics studies.[2] Various kinds of superconducting qubits using Josephson junctions, including phase-type, charge-type, and flux-type qubits, have been developed, and the quantum behavior of these devices has been extensively studied.[1,2]

A key obstacle so far in the related studies is the quantum decoherence process, arising either from device coupling to the environment or from material defects that produce charge or spin fluctuations. For example, it has been shown that defects in amorphous AlO_x tunnel barriers in Al junctions act as microscopic two-level fluctuators (TLFs) which cause significant decoherence[3] while epitaxially grown Al_2O_3 tunnel barriers display significantly longer coherence times on account of the lower density of TLFs.[4,5] In the works reported in Refs. [4] and [5], superconducting epitaxial rhenium films were used in place of Al films as bottom layers. Rhenium films were also used for superconducting coplanar waveguide resonators which show a considerable decrease of loss and improvement of the resonator performance, primarily due to the hardly oxidizable nature of the material that results in much reduced device surface defects.[6]

Presently, Al and Nb materials have been widely used in many experiments. The Al-based qubits show considerable long decoherence time than that in Nb devices.[7] It is believed that various complex oxides formed on the Nb film surface will produce defects that cause decoherence. On the other hand, Nb junctions are known to have the advantage of being stable against thermal cycling, which is important for the practical applications. Since Re has been demonstrated to be more resistant to surface oxidation[4–6] and is also a hard metal similar to Nb in many ways, it is desirable to develop a successful Re Josephson junction fabrication process for superconducting qubit applications.

In our previous work, high-quality Nb/Al–AlO_x/Nb junctions with sizes down to submicron level have been successfully fabricated[8,9] using the standard selective Nb etching process (SNEP).[10–12] In this work, we use the same technique to fabricate Re/Al–AlO_x/Re Josephson junctions. We show that the Re material has similar properties in parallel to Nb during sample preparations and high-quality Re/Al–AlO_x/Re tunnel junctions can be fabricated conveniently for future applications.

2. Fabrication

Re/Al–AlO_x/Re junctions were fabricated using a process similar to the standard SNEP technique.[10–12] The Re/Al–AlO_x/Re trilayer structures were first deposited by dc magnetron sputtering on clean oxidized silicon chips in an ultra-high vacuum system having a background pressure of 1×10^{-6} Pa. The Ar pressures during sputtering was set to be 2.5 Pa and 1.5 Pa for the Re and Al films, and the deposition rates were 150 nm/min and 10 nm/min, respectively. These preparation conditions, with substrate placed at room temperature, resulted

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in polycrystalline thin films for both Re and Al. The film thicknesses in the trilayers from bottom to top were 150 nm (Re), 4 nm (Al), and 50 nm (Re). The junction AlO_x barrier was formed in the load-lock chamber on the sputtered Al film in the trilayers by introducing pure oxygen into the chamber. The junction barrier thickness was controlled by varying the oxygen pressure and the oxidation time.

The junction areas and top wirings (200-nm thick Re) were defined by photolithographic patterning. Reactive ion etching (RIE) in SF_6 for Re as well as Ar ion milling for Al was used alternatively to remove the unwanted parts. Insulation layers were prepared by rf sputtering SiO_2 films with a typical thickness of 100 nm and at a rate of 3 nm/min. In the RIE process, the SF_6 pressure was 4.5 Pa, which was controlled by throttling the turbo pump and adjusting the mass-flow controller [typically with a flow of 22 sccm (standard-state cubic centimeter per minute)], and the etching rate for Re was about 80 nm/nim, about half the value for Nb under the same etching condition. A side view of the final junction geometry is shown schematically in Fig. 1.

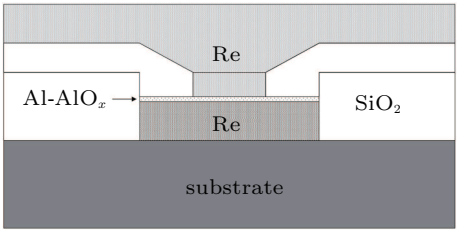


Fig. 1. Schematic side view of the Re/Al–AlO_x/Re junction fabricated using the selective film-etching process.

3. Results and discussion

Superconducting properties of Re have been studied previously for films prepared by electron-beam evaporation and by sputtering.[13–15] It is known that the film superconducting transition temperature T_c depends critically on the crystallinity of the sample. It will get close to the bulk value below 2 K when the Re films have the hexagonal close packed structure. Usually, the film T_c will be higher (up to 6 K) due to the presence of other phases such as the face-centered cubic structure.

Figure 2 shows the temperature dependence of the resistance across a Re/Al–AlO_x/Re junction with an area of 2 μm × 2 μm fabricated using the process described above. The oxygen pressure and the oxidation time for the tunnel barrier formation of this junction were 400 Pa and 6 minutes, respectively. The measurement was performed using a bias current of 1 μA. The result shows a superconducting transition temperature T_c = 4.8 K and a transition width of 0.2 K. The ratio of the resistance at 300 K and that at 10 K is R(300 K)/R(10 K) = 1.5, indicating relatively large residual resistance which may result either from the mixed phases or from the poor film crystallization due to the sputter deposition at room temperature.

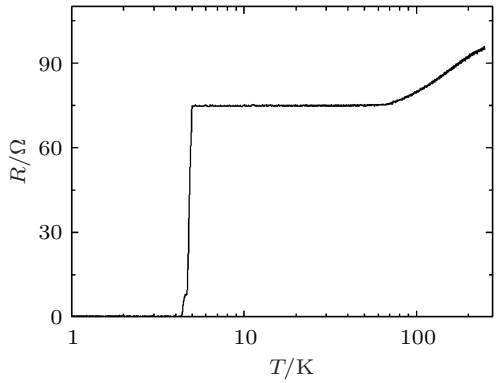


Fig. 2. Temperature dependence of the resistance across a Re/Al–AlO_x/Re junction and its leads plotted in semi-logarithmic scale.

Figure 3 shows an oscilloscope image of the I–V curve of this junction measured at 0.3 K. The I–V curve displays a very low leakage current as well as a sharp current rise at the gap voltage of $2\Delta/e \sim 1.1$ mV, where Δ is the energy gap. Since the junction has a normal-state resistance of R_N = 22.5 Ω, the Josephson critical current can be estimated from the following formula

$$I_c(T) = \frac{\pi\Delta(T)}{2eR_N}\tanh\frac{\Delta(T)}{2kT} \tag{1}$$

to be 38 μA, which corresponds to a critical current density of J_c of 750 A/cm^2 at $T = 0.3$ K if the junction area of 4 μm^2 is considered.

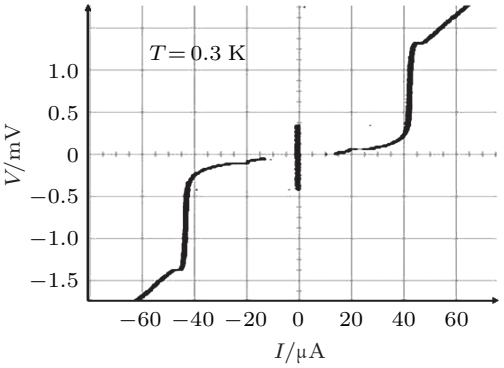


Fig. 3. The I–V characteristic of the Re/Al–AlO_x/Re junction with its R–T curve shown in Fig. 2.

An interesting feature of the I–V curve shown in Fig. 3 is a small but clear step near the voltage of $\Delta/e = 0.55$ mV in the subgap region. There are several mechanisms responsible for this: multiple-particle tunneling, multiple Andreev-reflection process, and self-coupling,[16,17] among which the multiple-particle tunneling process seems more likely.[17] In any case, the appearance of the subgap step indicates a very thin tunnel barrier, which is consistent with the above relatively high critical current density J_c. We notice that the result

in Fig. 3 shows that the resistance ratio R_D/R_N well exceeding 100 when the subgap resistance R_D is taken at voltages below the subgap current step, which indicates a high quality of the junction sufficient for qubit performance. Since lower critical current density can be easily achieved by increasing the oxygen exposure during AlO_x tunnel barrier formation, these results demonstrate that the present trilayer process for the fabrication of Re/Al–AlO_x/Re Josephson junctions is flexible for their possible applications in superconducting quantum computing and quantum information.

4. Conclusion

Superconducting Re/Al–AlO_x/Re tunnel junctions with high quality, high critical current density, and high reproducibility were successfully fabricated using an SNEP-like process. Our results demonstrated that the Re junctions can be useful for their possible superconducting quantum circuit applications. Further works in this area will involve the epitaxial growth of the Re films with a lower sputtering deposition rate in ultra-high vacuum environment on substrates at elevated temperatures.[4,5] Recently, the epitaxial Re film surface structure and surface chemical reactive processes when exposed in the different oxygen environment have been theoretically investigated.[18] It will be interesting to compare the qubit flux noises and decoherence process in the devices fabricated using Re and Al (or Nb) materials in the future studies.

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