Characteristics of Nb/Al-AlOx-Al/Nb Josephson junction Fabricated using Facing Target Sputtering

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Abstract. Nb and Al films in the Nb/Al-AlOx-Al/Nb junction structure have been deposited using facing target sputtering applied with DC power. In this sputtering system, the \(\gamma\) electrons generated in the plasma are retained and reciprocated between a pair of targets and those hardly do damage to the junction interface during the deposition. An SiO\(_2\) film has been also deposited using the same sputtering applied with RF power. An anodization process is used for the fabrication process. Fabricated junctions have indicated the I-V characteristics with small sub-gap leakage current (0.11 pA/\(\mu\)m\(^2\) at 0.49 K). We think it is effective for both the facing target sputtering technique and the anodization process to obtain the junction with small sub-gap leakage current.

1. Introduction

Josephson junction is a promising device for energy-resolving X-ray and particle detection\[1\]. A Nb/Al-AlOx-Al/Nb junction is widely used as the de-fact standard junction for those usage. This junction is originally developed at the aim of the digital application and fabricated using the conventional DC magnetron sputtering technique\[2,3\]. In the conventional magnetron sputtering, the substrate is opposite to the target. The Nb and Al films composing the Nb/Al-AlOx-Al/Nb junction structure are deposited on the substrate in the condition exposed to the plasma region generated between the substrate and the target. Both ion bombardment and \(\gamma\) electron generated in the plasma may cause the thermal and physical damage to the junction interface. In the use of a highly sensitive X-ray and particle detector, it is necessary to reduce the sub-gap leakage current to the limit indicated in the BCS theory. For obtaining the junction with small sub-gap leakage current, it is pointed out that it needs to fabricate the junction so as to minimize the thermal and physical damage to the junction interface. In the experiment of the Nb/AlOx-Al/Nb junction fabricated using the conventional magnetron sputtering \[4\]. We focus on the reduction of the thermal and physical damage to the junction interface due to both ion bombardment and \(\gamma\) electron generated in the plasma. We take a different approach, that is, a facing target sputtering technique, for fabricating the junction consisted of Nb, Al and SiO\(_2\) films.
2. Damage under Deposition

Fig. 1 shows the schematic diagram of the FTS system, with a pair of targets with the same size arranged oppositely. A substrate is placed on the outside of the pair of targets. The ionization of the inert gas is accelerated, and the high-density plasma generated during the sputtering, because γ electrons generated in the plasma, are retained and reciprocated between both targets by the magnetic field produced by a permanent magnet. Since the high-density plasma is confined by the magnetic field, the thin film can be deposited under the high-density plasma without the layer directly exposed to the plasma. This technique does not damage the junction interface during the fabrication of the junction. Our FTS system has two pairs of targets, and both DC and RF power sources for sputtering.

![Figure 1. Schematic diagram of Facing Target Sputtering System](image)

We compared the damage during the deposition of the SiO_2 film, which is used as an film in the junction, between the conventional magnetron sputtering technique and the FTS technique. We determined the degree of the damage by observing a Teflon tape set on the Si wafer and considering changes in its shape during the SiO_2 deposition. Fig. 2(a) shows the tape deposited using the conventional RF magnetron sputtering. The target to substrate (T–S) length was 80 mm. The SiO_2 deposition rate was 13.1 nm/min at the applied RF power density of 2.55 W/cm^2 and the Ar pressure of 0.13 Pa. The Teflon tape was partially damaged when the SiO_2 layer with a thickness of 100 nm was deposited even with cooling the substrate with water. We found no damage on the Teflon tape when the SiO_2 layer with a thickness of 300 nm was deposited using the FTS system even at the high power conditions and with no substrate cooling (Fig. 2(b)). The SiO_2 deposition rate was 12.9 nm/min at the applied RF power density of 15.7 W/cm^2 and the Ar pressure of 0.13 Pa. The distance between the target and the substrate (T – S length) was 90 mm. We have defined the T-S length to be the length from the center of the target to the substrate. The deposition of the SiO_2 film has been published in detail [5]. Because of the arrangement of the target and the substrate in the conventional magnetron sputtering, both ion bombardment and γ electrons generated in the plasma contribute to the damage to the Teflon tape during the deposition. In the FTS system, such macroscopic damage is significantly reduced because the γ electrons are retained and reciprocated between both targets. We think it is desirable to fabricate the junction structure with less the thermal and physical damage to the junction interface. The Nb/Al-AlO_x-Al/Nb junction structure can be fabricated in-situ using Nb and Al targets, and the SiO_2 and Al_2O_3 films can be deposited after changing targets, without damage due to both ion bombardment and γ electrons using this FTS system.
3. I-V Characteristics of Nb/Al-AlO\textsubscript{x}-Al/Nb Junctions with Selective Anodization Process

A junction structure was fabricated over the entire surface of the Si wafer, composed of a Nb base electrode (B-Nb), an Al base layer (B-Al), an Al oxide layer (AlO\textsubscript{x}), an Al counter layer (C-Al), and a Nb counter electrode (C-Nb). We studied the Al layer thickness dependence of Nb/Al-AlO\textsubscript{x}-Al/Nb junctions fabricated using the FTS system. We decided both B-Al and C-Al layers to be 18 nm thick for obtaining small leakage current [6].

The anodization process were originally developed as a Selective Niobium Anodization process (SNAP) for Nb/a-Si/Nb junction fabrication [7] and a Selective Niobium Etch Process (SNEP) for Nb/(Al)-AlO\textsubscript{x}-Al/Nb junction fabrication [2]. Although the methods of junction area definition and the thickness of the anodized Nb\textsubscript{2}O\textsubscript{5} layer differ by two methods, the role of insulating a junction from a Nb wiring layer is the same. Recently, various anodization processes for fabricating the superconducting digital circuits with micron and sub-micron junction sizes has been devised with the aim of forming the via through the dielectric layer to contact the junction without being restrained by the junction area [8]-[11]. We have fabricated Nb/Al-AlO\textsubscript{x}-Al/Nb junctions using a new selective anodization process with high reliability [6].

We studied the temperature dependence of the sub-gap leakage current density ($J_{sg}$) as indicated in Fig 3, which is defined at a bias voltage of 0.1 mV and devided by the junction area of 50 μm x 50 μm. In both junctions, the value of decreased with the temperature exponentially. The $J_{sg}$ value of the junction fabricated with Al layer deposition rate of 82 nm/min and the anodization voltage of 15 V decreased from 0.16 μA/μm\textsuperscript{2} at 4.40 K to 0.61 pA/μm\textsuperscript{2} at 0.49 K. The $J_{sg}$ value of the junction fabricated with Al layer deposition rate of 245 nm/min and the anodization voltage of 10 V decreased from 35.9 nA/μm\textsuperscript{2} at 4.29 K to 0.11 pA/μm\textsuperscript{2} at 0.49 K. In the fabrication process, at etching the Al-AlO\textsubscript{x}-Al layer by an Ar ion beam etching for the junction area definition, the re-adhesion of the etched Al and/or the damaged region formation of the AlO\textsubscript{x} layer may form the current bypass at the edge of the Al-AlO\textsubscript{x}-Al layer, may produce the sub-gap leakage current. We think the anodization process exclude these damage. We think this difference is attributed to the quality of Al layer. The residual resistivity at 10 K were 2.26 μΩ-cm at 100 nm thickness in the case of Al layer fabricated with deposition rate of 82 nm/min, 1.77 at the same thickness in the case of the deposition rate of 245 nm/min.
4. Conclusion

For fabricating the junction with a small leakage current, we have used the FTS sputtering system, which has two pairs of targets and both DC and RF power sources for sputtering, to fabricate Nb/Al-AlOx-Al/Nb junction structure. In this sputtering system, the $\gamma$ electrons generated in the plasma are retained and reciprocated between a pair of targets and those hardly do damage to the junction interface during the deposition. An anodization process is effective for removing the damage of the junction edge resulted from the junction fabrication. Fabricated junctions have indicated the I-V characteristics with small sub-gap leakage current density ($0.11 \text{ pA/}\mu\text{m}^2$ at 0.49 K). We think it is effective for both the facing target sputtering technique and the anodization process to obtain the junction with small sub-gap leakage current density.

![Figure 3. Temperature dependence of sub-gap leakage current density](image)
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