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

Shin'ichi Morohashi, Ryotaro Imura, Shuichi Fukuda, Norihisa Yamashita, and Michiaki Ikuta
Faculty of Engineering Yamaguchi University, 2-16-1, Tokiwadai, Ube, 755-8611, Japan
Fax:81-836-85-9601, e-mail: smoro@yamaguchi-u.ac.jp

We have fabricated a Nb/AlOx-Al/Nb Josephson junction using facing target sputtering technique. Nb, Al and SiO_2 layers can be deposited under the high-density plasma in the condition that it is not directly exposed to the plasma region generated between a pair of targets. The transition temperature of the Nb layer and the residual resistance ratio have indicated 9.3 K and more than 3. Fabricated Nb/AlOx-Al/Nb Josephson junction has exhibited current-voltage characteristics with a low sub-gap leakage current (Rsg/Rnn = 42 measured at 4.2 K).

Key words: Facing Target Sputtering, Josephson Junction, Nb/AlOx-Al/Nb Junction, Detector.

1. INTRODUCTION

A Nb/AlOx-Al/Nb Josephson junction is widely used as a highly sensitive detector for X-rays and particles [1]. This junction was originally developed for digital applications, and fabricated using a conventional magnetron sputtering with the substrate placed opposite to the target [2], [3]. For a highly sensitive detector, it is desirable to reduce the sub-gap leakage current to the limit indicated in the BCS theory. We think that it needs to fabricate the junction so as to minimize the thermal and physical damage to the junction interface for obtaining the junction with small sub-gap leakage current [4].

The purpose of this study is to fabricate the Nb/AlOx-Al/Nb junction with small sub-gap leakage current. First of all, we focus on the reduction of the thermal and physical damage to the junction interface due to both ion bombardment and γ electron generated in the plasma during the deposition. In the conventional magnetron sputtering, the junction structure fabricated on the substrate may be influenced by both ion bombardment and γ electrons generated in the plasma.

We take a different approach, a facing target sputtering (FTS) technique, for the fabrication of the junction. First, we compare the damage to the substrate between the conventional magnetron sputtering and FTS system taking the deposition of an SiO_2 layer used as the insulation layer as an instance. Second, we study the characteristics of Nb and Al layers deposited using this FTS technique. Third, we show the current-voltage (I-V) characteristics of Nb/AlOx-Al/Nb junctions fabricated using this FTS technique.

2. FABRICATION OF NB/ALOX-AL/NB JUNCTION

2.1 Damage to Substrate during 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 is generated during the sputtering because the γ electrons generated in the plasma are retained and reciprocated between both targets by means of the magnetic field produced by a permanent magnet. Since the high-density plasma is continued by the magnetic field, the thin film can be deposited under the high-density plasma in the condition that the layer is not directly exposed to the plasma. We think that this technique does not to damage the junction interface during the fabrication of the junction.

We compared the damage to the substrate during the deposition of the SiO_2 insulation layer between the conventional magnetron sputtering and the FTS system. We judged the degree of the damage from whether a Teflon tape bound on the Si wafer changes its shape during the SiO_2 deposition. Fig. 2(a) shows the result deposited using the conventional RF magnetron sputtering. The main pump of our conventional RF magnetron sputtering system is turbo-pump and its background pressure was 1.3×10^{-4} Pa. The SiO_2 target size was 100 mm in diameter. 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.

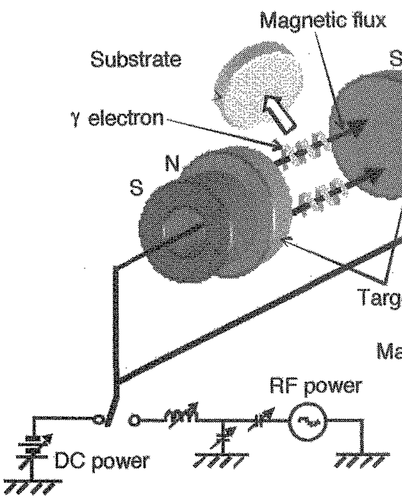

Fig. 1. Schematic diagram of Facing target sputtering system.

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 (Fig. 2(b)). The target size is 90 mm in diameter. The main pump is cryo-pump and its background pressure is 5.3 x 10^{-5} Pa. 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 length between the target and the substrate (T – S length) is 90 mm. We have defined that the T-S length is the length from the center of the target to the substrate. We also studied the Ar pressure dependence of the SiO_2 deposition rate. The SiO_2 deposition rate was moderately increased with decreasing the Ar pressure within the range of 0.04 – 1.35 Pa. The maximum SiO_2 deposition rate of 19.6 nm/min was obtained at the Ar pressure of 0.04 Pa under the same conditions of the RF source power and the T-S length. However, we also found no damage on the Teflon tape during the deposition of the SiO_2 layer with a thickness of 300 nm even at those conditions. The 300 nm thickness is the SiO_2 insulation layer thickness in the Nb/AlOx-Al/Nb junction. A surface roughness of the Si (100) substrate was 0.3 nm. We estimated the surface roughness of the SiO_2 insulation layer as rms-roughness using the atomic force microscope (AFM). The typical surface roughness of the SiO_2 insulation layers fabricated using the FTS system were ~ 2 nm, and did not almost depend on the fabrication conditions such as the Ar pressure and the deposition rate [5].

Because of the arrangement of the target and the substrate in the conventional magnetron sputtering, we think that both ion bombardment and γ electrons generated in the plasma tend to be contributed to the damage to the Teflon tape during the deposition. We think that γ electrons generated in the plasma have little effect on the damage to the substrate because the γ electrons are retained and reciprocated between both targets in the FTS system.

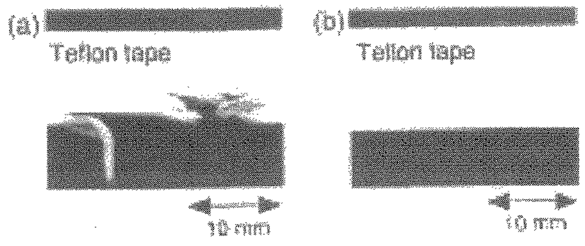

Fig. 2. Damage to the Teflon tape on the Si substrate during the deposition of the SiO_2 insulation layers by which a) is deposited using the conventional magnetron sputtering; b) deposited using the facing target sputtering, respectively.

The purpose of this study is to fabricate the Nb/AlOx-Al/Nb junction with small sub-gap leakage current. First of all, we think that it is important to reduce the thermal and physical damage to the junction interface due to both ion bombardment and γ electron generated in the plasma during the deposition, although it is known that the stress in the junctions and the insulation properties in the AlOx barrier and/or of the junction edge may influence the I-V characteristic of the junction. Here, we think the thermal and physical damages to the junction interface to create pinhole shorts in the AlOx barrier with a 1 nm thickness and increase the grain-boundary diffusion at the interface between the Al overlayer and the Nb base electrode. The I-V characteristic of the junction is very sensitive to these microscopic damages such as pinhole shorts and grain-boundary diffusion.

Conventional sputtering often shows macroscopic damage to Teflon tape in the substrate plane due to possible both ion bombardments and γ electrons generated in the plasma. However, such macroscopic damage is found to be significantly reduced using the FTS system. Although we have no direct evidence between the microscopic damage and the macroscopic damage, we think that microscopic damage to the junction barrier and/or the Al/Nb junction interface might also be correspondingly reduced using the FTS system. Our FTS system has two pairs of targets, and both DC and RF power sources for sputtering. We think that the Nb/AlOx-Al/Nb junction structure can be fabricated in-situ using Nb and Al targets, and the SiO_2 insulation layer can be deposited after changing targets, without damage due to both ion bombardment and γ electrons using this FTS system.

2.2 Characteristics of Nb and Al Layers

It is necessary to study the characteristics of the Nb and Al layers fabricated using the FTS system because of its unique layout before the fabrication of Nb/AlOx-Al/Nb junctions. The target-substrate (T-S) length was 90 mm in both Nb and Al targets because of the rotation of the substrate.

We studied the Ar pressure dependence of the Nb deposition rate. The cathode current of the DC power source was 4.0 A in constant. The Nb deposition rate was obtained approximately 140 nm/min at the Ar pressure of 0.13 Pa. In the Ar pressure ranges between 0.13 and 1.2 Pa, the Nb deposition rate almost linearly decreased with the Ar pressure. Fig. 3 shows the Ar pressure dependence of the transition temperature (Tc) and the residual resistance ratio (RRR) of Nb layers (100 nm thickness). The Tc value of Nb layers were almost the same as that of the bulk Nb and the RRR value approximately 3 in the range of the Ar pressure of 0.1 ~ 2.0 Pa. The RRR is defined as the ratio of the resistivity measured at 273 K (ρ_{273}) to the resistivity measured at 10 K (ρ_{10}). The typical value of ρ_{10} was 5.4 μΩ-cm and its transition width at the Tc value (9.3 K) was very sharp (< 10 mK) at the Ar pressure of 0.7 Pa. We investigated the Ar pressure dependence of the stress state in Nb layers with the thickness of 100 nm (Fig. 4). For fabricating the junction with small subgap leakage current, it is also important to clarify how the stress state of the Nb layer deposited using the FTS system is in. The stress is estimated from the x-ray diffraction pattern of Nb (100). In the range of the Ar pressure of 0.1 – 1.2 Pa, the Nb layer was in the compressive state and its magnitude is ~ 10^9 N/m^2. The Nb layer was in the tensile state in the Ar pressure of 1.3 – 1.9 Pa and changed into the compressive state at the Ar pressure more than 2.0 Pa. In qualitative terms, the change of the stress from the compressive state to the tensile state was almost the same result that had previously obtained using the conventional DC magnetron sputtering [6], but the magnitude of the stress in our Nb layers was slightly small. The Nb thickness uniformity at the thickness of 100 nm was about +5% on the Si wafer of 50 mm x 50 mm at the Ar pressure of 0.7 Pa.

The Al overlayer layer acts as the proximity layer in the Nb/AlOx-Al/Nb junction structure. It is thought that an Al layer with low resistivity would weaken the proximity effect, in other words, does not reduce the gap voltage. We studied the Al deposition conditions changing the cathode current of the DC power source in constant Ar pressure of 0.4 Pa.

Table I shows the cathode current dependence of the deposition rate and the ρ_{10} value of the Al thickness of 200 nm. There was almost no difference of the ρ_{10} value of the Al thickness of 200 nm within the extent of the applied DC power in our experiment. Based on the controllability of the Al thickness in the Nb/AlOx-Al/Nb junction, we decided to deposite the Al layer at the Ar pressure of 0.4 Pa, the cathode current of 1.0 A and the deposition rate of 55 nm/min.

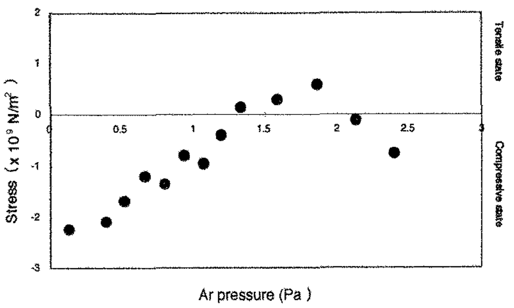

Fig. 3. Ar pressure dependence of Tc and RRR values of Nb layer with the thickness of 100 nm. Closed circle shows the Tc value and closed square shows the RRR value.

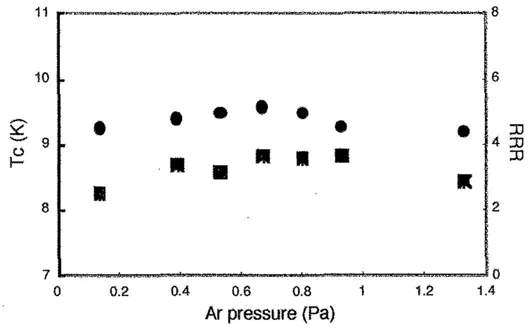

Fig. 4. Ar pressure dependence of the stress state in Nb layers with the thickness of 100 nm.

TABLE I

Cathode current dependence of Al deposition rate and ρ_{10} value of Al layers with the thickness of 200 nm.

Cathode current (A)	Deposition rate (nm/min)	ρ_{10} (μΩ-cm)
1.0	55	1.7
2.0	104	1.5
2.5	119	1.6

2.3 Characteristics of Nb/AlOx-Al/Nb Junction

A junction structure was fabricated over the entire surface of the Si wafer, composed of a Nb base electrode (B-Nb), an Al layer (Al), an Al oxide layer (AlOx) and a Nb counter electrode (C-Nb). The thicknesses of the B-Nb, Al and C-Nb layers were 100, 10 and 100 nm, at the conditions described in this section. The AlOx layer was formed at an O_2 pressure of 133 Pa and oxidation time of 30 min. The junction was fabricated using almost the same method that had previously been reported using photolithography and reactive ion etching (RIE) processes [6]. After changing targets in the FTS system, an SiO_2 insulation layer with a thickness of 300 nm was deposited using the conditions described in this section and a contact hole was patterned by RIE. After changing the target in the FTS system, a 500-nm-thick Nb wiring layer was deposited and patterned by RIE

Fig. 5 shows the I-V characteristic of a Nb/AlOx-Al/Nb junction measured at 4.2 K. The junction size is 10 μm in diameter. The Rsg/Rnn value was 42. Here, Rsg is the subgap resistance measured at 2 mV and Rnn is the normal resistance measured at 5 mV. Fig. 6 shows I-V characteristics of 100 Nb/AlOx-Al/Nb junctions connected in series measured at 4.2 K. The junction size is 14 μm in diameter. The uniformity of the critical current was ±3 %, excluding the influence of the flux trapping.

3. Conclusion

The purpose of this study is to fabricate the Nb/AlOx-Al/Nb junction with small sub-gap leakage current. First of all, we think it needs to fabricate the junction so as to minimize the thermal and physical damage to the junction interface for obtaining the junction with small sub-gap leakage current. We think it is effective for the FTS system not to damage to the junction during the fabrication of the junction because of the arrangement between the target and the substrate, although we have not added any quantitative comparisons with other junctions made by more conventional techniques. Future studies will focus on investigating whether the sub-gap leakage of our junctions current decreases with the temperature close to the BCS limit, improving not only the deposition technique, but also the fabrication processes such as the stress in the junctions and the insulation properties in the AlOx barrier and/or of the junction edge.

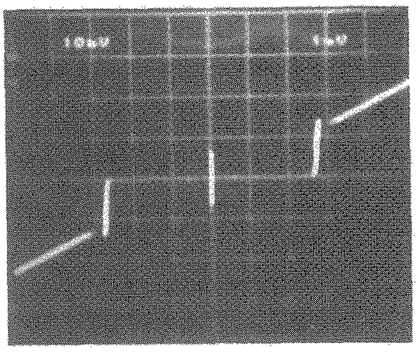

Fig. 5. I-V characteristic of a Nb/AlOx-Al/Nb junction measured at 4.2 K. The junction size is 10 μm in diameter. Vertical scale is 0.1 mA/div. Horizontal scale is 1.0 mV/div.

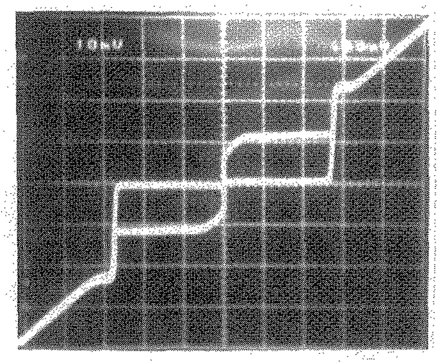

Fig. 6. I-V characteristics of 100 Nb/AlOx-Al/Nb junctions connected in series measured at 4.2 K. The junction size is 14 μm in diameter. Vertical scale is 0.1 mA/div. Horizontal scale is 100 mV/div.

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