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Experimental Investigations on Barrier Oxidation in NB/ALOX/NB Josephson Junctions

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Abstract**-- Josephson junctions were fabricated for several oxidation conditions and several junction sizes. Considering self-field effect suppressing the observed critical current (Ic) at large junctions, the observed Ic values were in good agreement with theoretical prediction. The predicted junction critical current for small junction limit was also confirmed by experiment. The dependence of the estimated Jc as a function of oxidation exposure showed that our junctions have lower Jc than other authors' at the same oxidation exposure. This is thought to be one of equipment-specific phenomena. Details of experimentals will be reported with brief discussion.**

1. INTRODUCTION

RSFQ (Rapid Single Flux Quantum) technology [1] is boosting the recent interests on developments in superconductor digital electronic technology. The main advantage of RSFQ circuits is ultra low power consumption and very high operation speed. In order to facilitate these positive features fabrication technology of small size, high critical current Josephson junction is an essential basis, and so far the proven material for the Josephson junction is Nb/AlOx/Nb. However, the microscopic process of barrier oxidation of Nb/AlOx/Nb Josephson junction is not well understood, and it is often found that the oxidation is sensitive to unknown fabrication conditions. In this paper, we will describe our oxidation result in terms of junction critical current, and compare it with other authors' results. In the second section we will report on the fabrication and critical current measurement, and in the third section we will analyze the experimental results and deduce the critical current density value as a function of oxidation exposure. In the last section, we will discuss on our result.

2. FABRICATION AND MEASUREMENT

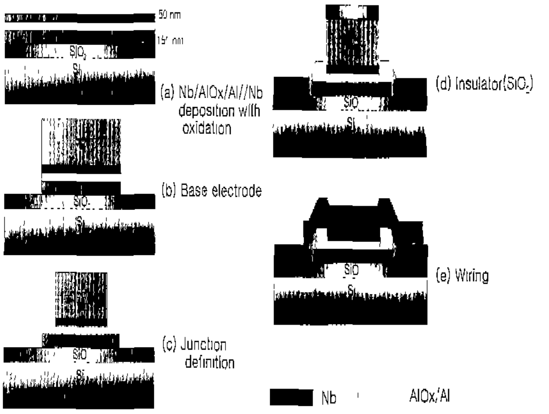


Fig. 1. Fabrication process with self-aligned techniques: (a) Tri-layer deposition, (b) base electrode etching, (c) top electrode etching, (d) insulator deposition with self aligned mask, (e) wiring

The fabrication process of Nb/AlOx/Nb Josephson junctions is shown in Fig. 1. The Nb/AlOx/Nb tri-layer is deposited by dc magnetron sputtering without breaking vacuum. The SiO2 layer was deposited by PECVD(Plasma Enhanced Chemical Vapor Deposition). The junction top Nb layer was etched by RIE (Reactive Ion Etching). The barrier oxidation was controlled at room temperature by both oxygen pressure and time. The key feature of our fabrication process is the use of the self-aligned technique for definitions of both junction area and insulating window area [2].

It simplifies the one lithography step saving one photomask, and as a result helps to improve the fabrication yield. In our experiment four different size square junctions were designed, i.e.: 3 μm x 3 μm, 5 μm x 5 μm, 10 μm x 10 μm, and 50 μm x 50 μm. The 50 μm x 50 μm junction was cross type where bias current flows crossing between the two adjacent sides of the square and the others were in line type where the current flows straight between the two facing sides of the square.

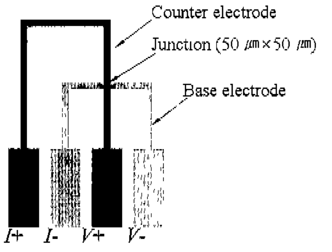
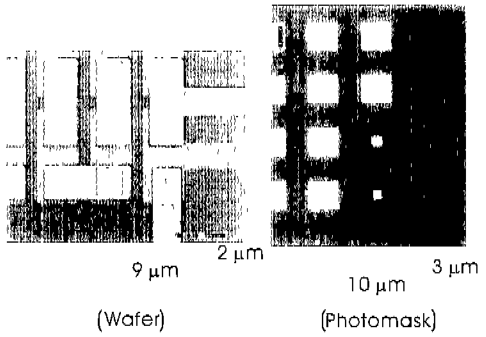


Fig. 2. Layout of the cross type square junction with 50 μm width.



(Wafer) (Photomask)

Fig. 3. Microscope photo of a part of the fabricated in line type junctions.

Fig. 2 shows the layout of the cross type junction. Fig. 3 shows the microscope photo of a part of the fabricated in line type junctions, where the 3 μm x 3 μm and 10 μm x 10 μm series-junctions are shown. We expect the size of fabricated junction is reduced by a small amount from the originally designed size on the photomask during the lithography process. This is usually observed after any etching process in practical fabrication. In order to measure the junction critical current density, especially for small junctions, it is necessary to estimate the effective size of junction area after fabrication. The effective junction size could be experimentally determined from Fig. 4, where the vertical axis is square root of junction critical current and the horizontal axis is the designed junction size. Therefore the vertical axis should be proportional to the effective junction size. The experimentally obtained effective size fits well along a straight line which meets 0 at the designed junction of about 1 μm, this means the effective junction size is reduced by approximately 1 μm from the designed size after fabrication.

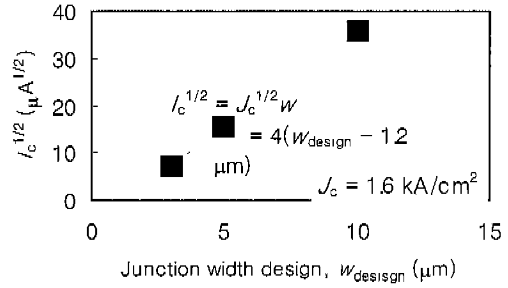


Fig. 4. Effective junction size after fabrication. The vertical axis is square root of junction critical current and the horizontal axis is the designed junction size.

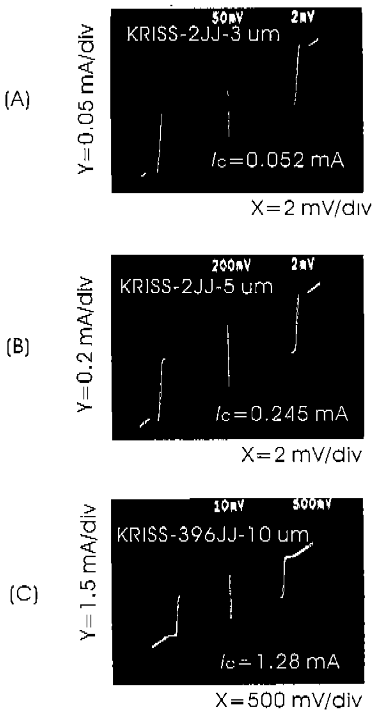


Fig. 5. Current-voltage (*I-V*) curves of the in-line type Josephson junctions fabricated on the same wafer with the same oxidation condition. (a) is for 2 junctions (2 μm) in series, (b) is for 2 junctions (4 μm) in series, (c) is for 396 junctions (9 μm) in series.

Fig. 5 shows some examples of current-voltage (I-V) measurements of the in-line type Josephson junctions fabricated on the same wafer with the same oxidation condition. The 9 μm junction photo of Fig. 5 (c) is for 396 junctions in series and the other photo of Fig. 5 (a) and Fig. 5 (b) are for 2 junctions in series. For these small junctions with widths of 2 μm, 4 μm and 9 μm, the observed critical currents agree well with the expected one from BCS theory, which says

$$I_{c(BCS)} = (\pi/2)(\hbar\Delta)/(eR) = 0.78\,V_g/R \qquad (1)$$

(V_g is observed gap voltage).

Fig. 6 shows I-V curves of the cross type single junctions fab3OOricated with different oxidation condition. For these larger junctions of width 50 μm, we observed the critical currents are more reduced from the BCS expectation as the critical current increases higher.

3. CRITICAL CURRENT DENSITY AND OXIDATION EXPOSURE

The above experimental observations on critical current reduction from the BCS theory for large junctions can be well explained with geometrical effect. As the critical current density increases, the Josephson penetration depth Λ_J given by eq. (2) decreases and the current distribution on the junction area becomes nonuniform.

$$\lambda_J = \left(\frac{\hbar}{2e\mu_0 J_c(2\lambda_{Nb}+d)}\right)^{1/2} \qquad (2)$$

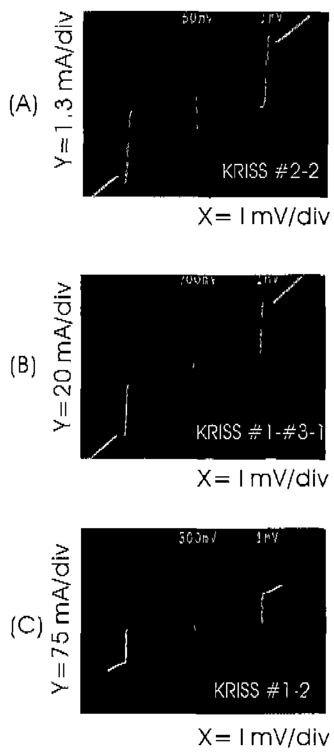


Fig. 6. *I*-*V* curves of the cross type Josephson single junctions (50 μm) fabricated with different oxidation condition.

where $\hbar$ is Planck constant divided by 2π, e is electron charge, μ_0 is permeability of vacuum, λ_{Nb} is London penetration depth of Nb, d is the junction barrier thickness, and J_c is the maximum critical current density of the Josephson junction, which can be approximately given by eq. (1) and eq. (3) for the fabricated junctions.

$$J_c = I_{c(BCS)}/w^2 \qquad (3)$$

The apparent junction critical current density obtained by $I_{c(observed)}$/(junction area) approaches J_c when junction size is much smaller compared to λ_J. The current distribution for the square junction was solved by Vaglio [3]. According to his solution, when junction width w is much larger than λ_J, the observed critical current is given by $2w\lambda_J J_c$. Table 1 shows the expected critical current from the Vaglio's theory agrees well with the observed one when $w > 4\lambda_J$ for the fabricated 50 μm junctions. Therefore the geometrical effect explains well the reduction of observed critical current for large junctions, and J_c values of the Table 1 which were estimated by eq. (3) can be regarded as a good estimate. Solid circles in Fig. 7 show the experimentally investigated relation between the junction critical current density and oxidation exposure. The oxidation exposure is defined as oxygen partial pressure P (Pa) times oxidation time t (s). In the Fig. 7, we also showed other authors' result for comparison. The open squares are from Sugiyama [4], and open triangles are from Kleinsasser [5]. Our data are quite close to, but a little bit slower than the Kleinsasser's data, and much lower and much slower than the Sugiyama's data. Overall trend is that the critical currents of our junctions are lower than the other authors' when the same oxidation exposure is used.

TABLE I COMPARISON OF THE CRITICAL CURRENT WITH THEORY FOR FABRICATED SQUARE JUNCTIONS OF SIZE 50 μm

J_c	λ_J	$4\lambda_J$	Vaglio's theory, $2w\lambda_J J_c$	I_c measured
70 A/cm^2	45 μm	180 μm	-	1.7 mA
1.5 kA/cm^2	10 μm	40 μm	15 mA	13 mA
3 kA/cm^2	7 μm	28 μm	21 mA	20 mA

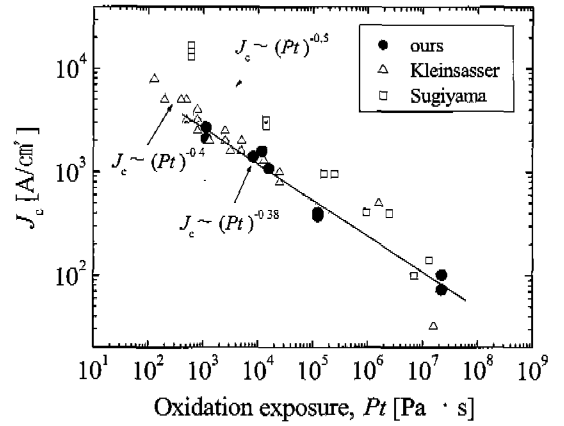


Fig. 7. Experimentally investigated relation between the junction critical current density and oxidation exposure.

4. SUMMARY AND DISCUSSION

Several different size square junctions between 3 μm and 50 μm were fabricated with different oxidation condition. For small junctions below 10 μm, the effective junction size after fabrication was found to be smaller by 1 μm than the designed size. The Ic reduction observed in 50 μm junctions were also clearly explained by the Vaglio's calculation, which is based on the geometrical deflection of current density. Taking into account these size reduction and I_c reduction effects, we could investigate the relation between junction critical current density and barrier oxidation exposure. Comparing with other authors' data, our data showed a smaller critical current at the same oxidation exposure. This implies the effective oxidation process is faster in our equipment, and some residual impurities accelerating the Al oxidation process is present in our oxidation chamber.

ACKNOWLEDGMENT

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