Fabrication of Al/AlO$_x$/Al junctions using pre-exposure technique at 30-keV e-beam voltage*

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We fabricate high-quality Al/AlO$_x$/Al junctions using improved bridge and bridge-free techniques at 30-keV e-beam voltage, in which the length of undercut and the size of junction can be well controlled by the pre-exposure technique. The dose window is 5 times as large as that used in the usual Dolan bridge technique, making this technique much more robust. Similar results, comparable with those achieved using a 100-keV e-beam writer, are obtained, which indicate that the 30-keV e-beam writer could be an economic choice for the superconducting qubit fabrication.

Keywords: Josephson junction, pre-exposure, 30-keV E-beam voltage, superconducting qubit

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1. Introduction

As a nonlinear element, the Josephson junction is the key component of many superconducting electronic devices such as the superconducting quantum interference device (SQUID),[1] rapid single flux quantum (RSFQ),[2] single electronic transistor (SET),[3] Josephson parameter amplifier (JPA),[4] and superconducting quantum bit (qubit).[5] With the rapid development in the last twenty years, supconducting quantum computing (SQC) is regarded as a promising candidate to realize a practical quantum computer. As a foundation of SQC, the reliability and reproducibility of qubit fabrication are important, especially for its scaling. Owing to its long coherence time and simple fabrication process, the Al/AlO$_x$/Al junction is used by many SQC groups nowadays.[6–14] Among different kinds of fabrication processes of the aluminum junction, the Dolan bridge technique is widely adopted because it only needs one lithographic patterning step[15] in which a suspended bridge is formed via a different clearing dose of the bilayer resist. After two-angle aluminum film depositions and an *in-situ* oxidation in electron beam evaporator, the Al/AlO$_x$/Al junction is prepared. Although this fabrication process is simple, its robustness is not optimistic since the suspended bridge formed by the different clearing dose of bilayer resist is frail. Due to the instability of e-beam, the variation of resist thickness, and its denaturation, the size and reproducibility of the junction can be easily changed and affected.

To overcome these problems, the Martinis group[16] and Buission group[17] have proposed an improved fabrication technique (here named the pre-exposure technique). In contrast to the usual Dolan bridge fabrication, the pre-exposure technique has two lithographic steps. The first one writes the bottom layer and the second one writes the top layer to define the junction pattern. Unlike the traditional technique, the suspended bridge is not formed by self-acting, which results from the different clearing dose of bilayer resist, but by the intended pre-exposure. Using this technique, high reproducibility of aluminum junctions with well-defined size can be achieved. It should be emphasized that in both pre-exposure techniques mentioned above, 100-keV acceleration voltage of e-beam is used. Under such a high e-beam voltage, the forward scattering is mainly suppressed and the e-beam with low pre-exposure dose (for bottom layer writing) has little effect to the top layer.

Can this technique be applied using the 30-keV e-beam writer, which is widely used and often built up with a 30-keV e-beam voltage scanning electron microscope (SEM) and a pattern generator? Compared with the 100-keV e-beam writer, the 30-keV e-beam writer usually has a larger forward scattering effect on the bilayer resist, which makes the applicability of the pre-exposure technique uncertain. In this paper we present a systematic study of the pre-exposure technique using a 30-keV e-beam writer and demonstrate that similar results can be obtained as in the case using the 100-keV e-beam writer. High-quality aluminum junctions with area ranging from 0.04 μm^2 to 10 μm^2 are fabricated. The clearing dose window of this technique extends to 5 times (400 μC/cm^2–600 μC/cm^2) as large as that used in the traditional Dolan bridge technique (440 μC/cm^2–480 μC/cm^2), making it more robust for the junction fabrication.

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2. Fabrications and results

The 30-keV E-beam writer used in the present work is a field emission SEM (Inspect F50 from FEI) equipped with a pattern generator (Raith), with the beam current variable between several pico-amperes and hundreds of nano-amperes depending on the selected spot size. To define the nano-scale pattern more accurately, we choose a small spot size with beam current around 20 pico-amperes. The working distance is 5.5 mm from e-gun to sample stage. We use high resistivity silicon substrates whose thinkness is 0.5 mm. The e-beam bilayer resists are PMMA950 A3 and MMA(8.5)MAA EL13 from the MicroChem company, which will be called PMMA and MAA below, respectively, for simplicity.

2.1. Bridge technique

The bottom layer (MMA) is spun at 3000 rpm for 1 minute (thickness is around 600 nm) and baked at 170 °C for 3 minutes. The top layer (PMMA 950 A3) is spun at the same speed and time (thickness is around 200 nm), also baked at 170 °C for half an hour. In the traditional technique, during the exposure of e-beam at PMMA dose, high energy electrons break the bonds of PMMA and increase its solubility in the developer. The MAA polymer is much more sensitive to electrons, thus it dissolves much faster in the developer, resulting in the undercut underneath the top polymer layer. If two exposed areas are close together, the bottom layer under them will be fully developed to form a hanging bridge of the top layer, namely the Dolan bridge.

It is worth noting that the length of undercut of the Dolan bridge is formed by the different sensitivity of bilayer to e-beam which is hard to be controlled arbitrarily. For example, we need a higher e-beam dose to achieve a longer undercut. At such high dose, there is a risk of the bridge collapse which will result in the junction short. In contrast, the length of undercut can be well controlled using the pre-exposure technique as shown in Figs. 1(a) and 1(b). In the first lithography with MAA dose exposure, the writing of the bottom layer will not break down the bond of the top layer polymer due to the different sensitivity of the clearing dose of bilayer to e-beam. The top layer does not dissolve in the developer for this MAA dose. In the second lithography with sufficient PMMA dose exposure, the writing of the top layer produces a window in the developer and the exposed bottom layer is also dissolved in the developing process, which makes undercut well controlled by the first exposure.

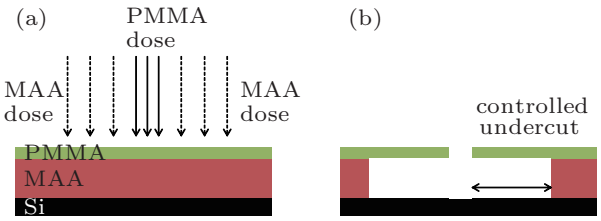


Fig. 1. (color online) Cross-section schematics of pre-exposure technique. (a) The first e-beam lithography, with MAA dose which has no effect on the top PMMA layer, writes the bottom MAA layer. The second one with PMMA dose writes the top layer. (b) After development in the developer (MIBK:IPA = 1:3), the controlled undercuts are formed.

In the present experiment, we have the clearing doses of 80 μC/cm^2–160 μC/cm^2 and 400 μC/cm^2–600 μC/cm^2 for MAA and PMMA, respectively. Any combination of MAA and PMMA doses in the dose window can make a clear and controllable undercut. We note that although the dose range mentioned above leads to a controllable undercut, different dose selection can still make a different proximity effect especially for the top layer. This is the disadvantage of the 30-keV e-beam writer compared with a 100-keV one since the latter has little forward scattering. In order to use pre-exposure at 30 keV, one should select the dose as low as possible in the clearing dose window to ensure the actual size is close to the defined size. In the application of SQC, Al/AlO$_x$/Al junctions with small size (∼ 0.2 μm) are often used by many groups[6–14] to minimize two-level system[18] which may induce decoherence. Figures 2(a) and 2(b) show the lithographic pattern and SEM picture of Al/AlO$_x$/Al junctions fabricated using the pre-exposure technique at 30 keV. To minimize alignment error, two crossed perpendicular lines are used to form the junction. The T-shape pattern can elongate the bridge and remove a stress concentrator, making the bridge more reliable.[16] Figure 2(c) is the I–V curve measured at 20 mK of the junction with an area of approximately 200 nm×200 nm. The I_cR_n product is ∼ 280 μV in accordance with the Ambegaokar–Baratoff formula at zero Kelvin.[19]

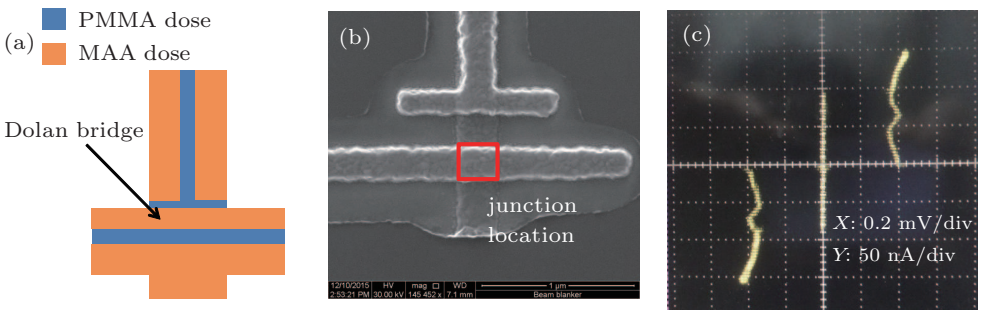


Fig. 2. (color online) (a) An e-beam lithographic pattern to fabricate the Josephson junction using the pre-exposure technique. Blue color indicates the area with PMMA dose and orange color the area with MAA dose. (b) An SEM picture of the Josephson junction after shadow evaporation and lift-off. The red square is the junction area with the size of 0.2 μm. (c) Current–voltage characteristic (I–V curve) of a Josephson junction fabricated using this technique. The junction's critical current is ∼ 100 nA.

2.2. Bridge-free technique

The bridge-free technique was first developed by Lecocq *et al.*[17] using a 100-keV e-beam writer and soon adopted by other groups for fabricating superconducting qubit.[20] This technique has some advantages such as the size of junction unlimited by the suspended bridge and the more robust mechanical strain of bilayer undercut. Moreover, strong argon plasma etching can be used to clean the substrate surface before film evaporation. Recent experimental results[21] show that the cleaning of the residual resist is a key procedure for fabricating a high-quality qubit with long coherence time. As an extension of the former work, we develop this technique at 30-keV e-beam voltage. The e-beam resist of bilayer, the substrate, the procedure of resist spin, and the dose windows of MAA/PMMA are the same as those used in the bridge technique. The two lithographic patterns are shown in Fig. 3(a). After the exposure of e-beam at 30 keV, an asymmetric undercut structure of bilayer is formed. The length of undercut can be well controlled from 0.2 μm to 1 μm. The junction is located at the open area without any suspended bridge, so strong plasma etching can be used to clean the surface of substrate. The key to this bridge-free technique is the wire of the up and down arms. The asymmetric structure of the bilayer undercut makes the first and second evaporated films remaining on the substrate while the other parts which cover the side walls are lifted off. Figure 3(b) shows the SEM picture after a ±65 °C evaporation. The junction is located at the red rectangle with the area of 2 μm×3 μm. Figure 3(c) shows the *I*–*V* curve of this junction measured at 20 mK with a critical current around 1.2 μA. This junction size and critical current are appropriate for phase qubit and JPA application and can hardly be obtained using the Dolan bridge technique.

We have also tried the two pre-exposure techniques for devices on sapphire substrates at 30 keV, and the results are similar. The only difference from the process with the silicon substrate is that a thin aluminum film (10 nm) should be evaporated on the resist bilayer before lithographic patterning and removed using aluminum etching solution before development in order to avoid the electron charging of e-beam. In addition, the e-beam resist of PMMA A5 and MAA EL11 are also tried at 30 keV. With the proper adjustment of clearing dose based on the considerations mentioned above, the same results have been obtained.

By using the bridge technique of pre-exposure, we fabricated the 3D transmon qubit[22] based on a sapphire substrate. Its Rabi oscillation and relaxation time ($T_1 \sim 20$ μs) (Fig. 4) show a good coherence behavior. The quality of Josephson junction definitely meets the demand for superconducting quantum computing. Although, it cannot behave as well as other groups have achieved,[22] we believe this is mainly caused by the insufficient shielding and filtering of noise.

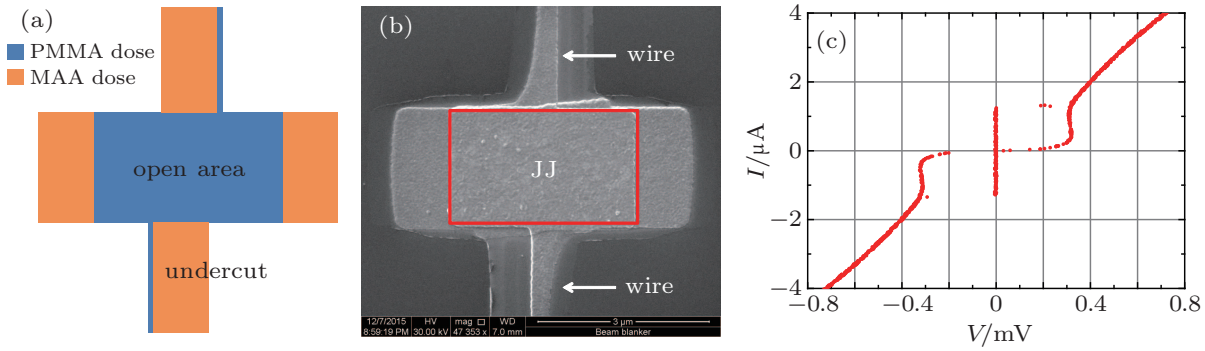


Fig. 3. (color online) (a) An e-beam lithographic pattern to fabricate large-area Josephson junction using the bridge-free technique. Blue color indicates an open area of junction location exposed with PMMA dose while orange color the area exposed with MAA dose. (b) The SEM picture of the Josephson junction after shadow evaporation and lift-off. The red rectangle is the junction with an area of 2 μm×3 μm. (c) *I*–*V* curve of a Josephson junction prepared using this technique with critical current of 1.2 μA and I_cR_n product of ∼ 280 μV.

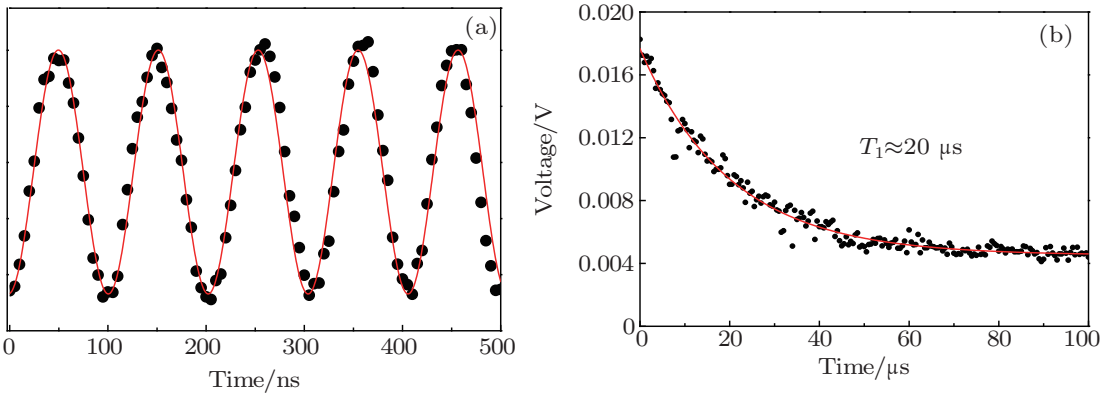


Fig. 4. (color online) (a) Rabi oscillation and (b) relaxation time T_1 of a three-dimensional transmon sample which is made by using pre-exposure technique.

3. Conclusion and perspectives

We have investigated the pre-exposure technique using a 30-keV e-beam writer to fabricate Al/AlO_x/Al Josephson junctions. Both bridge and bridge-free techniques are studied. Similar results, comparable with those achieved using the 100-keV e-beam writer, are obtained. The undercut of the bilayer resist can be well controlled. High-quality junctions with the area ranging from 0.04 μm^2 to 10 μm^2 are fabricated. Our results indicate that the 30 keV e-beam writer can be an economic choice for the pre-exposure technique in the superconducting qubit fabrication.

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