Fabrication of Al/AlO$_x$/Al Josephson junctions and superconducting quantum circuits by shadow evaporation and a dynamic oxidation process*

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Besides serving as promising candidates for realizing quantum computing, superconducting quantum circuits are one of a few macroscopic physical systems in which fundamental quantum phenomena can be directly demonstrated and tested, giving rise to a vast field of intensive research work both theoretically and experimentally. In this paper we report our work on the fabrication of superconducting quantum circuits, starting from its building blocks: Al/AlO$_x$/Al Josephson junctions. By using electron beam lithography patterning and shadow evaporation, we have fabricated aluminum Josephson junctions with a controllable critical current density (j_c) and wide range of junction sizes from 0.01 μm^2 up to 1 μm^2. We have carried out systematical studies on the oxidation process in fabricating Al/AlO$_x$/Al Josephson junctions suitable for superconducting flux qubits. Furthermore, we have also fabricated superconducting quantum circuits such as superconducting flux qubits and charge-flux qubits.

Keywords: Josephson junction, Al/AlO$_x$/Al, superconducting qubit

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1. Introduction

Josephson junctions, which are nonlinear elements based on the Josephson effect[1] are building blocks of various nanodevices and circuits such as superconducting quantum circuits,[2] nano fridges,[3] and voltage standard circuits.[4] In the last two decades, superconducting quantum circuits have attracted much attention due to their abilities to demonstrate and test fundamental quantum phenomena on a macroscopic scale and serving as promising candidates for realizing quantum computing. The behavior of a superconducting circuit is similar to that of a natural atom despite its huge dimension, which typically ranges from a few hundred nanometers to a few hundred micrometers, much larger than the dimension of a natural atom. In the simplest way, a superconducting circuit can be taken as a quantum two-level system, referred to as superconducting qubit. Superconducting qubits are one of a few promising candidates for realizing quantum computing. A major advantage of the superconducting qubit is that its fabrication is compatible with the existing semiconductor fabrication techniques, which offers more design flexibilities and scalabilities. Metallic Josephson junctions are generally used for superconducting quantum circuits due to their high quality and easy fabrication. Among Josephson junctions fabricated with different metals, Al/AlO$_x$/Al junctions are the most widely used in superconducting qubits due to the longer coherence times of the qubits they form.

There are two commonly used approaches to fabricating Al/AlO$_x$/Al Josephson junctions, one is the tri-layer technique feasible for complicated circuitry structures[5] and the other is the shadow evaporation technique using a micro-fabricated Dolan bridge.[6] While the first approach is much more versatile, especially for realizing complicated circuitry, the second approach has been recognized as producing Josephson junctions with much higher quality as well as having a simpler fabrication process, and besides, recent studies have shown that these two approaches can be combined together[7] to utilize their advantages.

In this paper we report our work on the fabrication of Al/AlO$_x$/Al Josephson junctions and superconducting qubits. In the fabrication of Al/AlO$_x$/Al Josephson junctions, the fabrication approach we adopt is the Dolan bridge shadow evaporation technique. By patterning a doublelay resistor on silicon substrate using electron beam lithography and evaporating aluminum from slanted angles, with precisely controlled *in situ* oxidation, we fabricate high-quality Al/AlO$_x$/Al junctions. The crucial issue is to obtain high junction quality and high controllability over junction parameters. Having successively fabricated Al/AlO$_x$/Al junctions, we further fabricated

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flux qubits, flux-charge qubits, direct-current superconducting quantum interference devices (DC-SQUIDs), and other on-chip components such as coplanar waveguides, shunting capacitors, and on-chip resistors.

2. Fabrication of Al/AlO$_x$/Al Josephson Junctions

For the special purpose of shadow evaporation and controlled oxidation process, we develop a dedicated electron beam evaporation system consisting of an evaporation chamber and an oxidation chamber. Each chamber is pumped by a dedicated turbo pump. The pressure can reach as low as 2×10^{-7} Pa for the evaporation chamber and 1×10^{-5} Pa for the oxidation chamber. Inside the evaporation chamber the substrate can be rotated around two perpendicular axes, enabling shadow mask evaporation at different angles. Oxidation is done by inletting a very low flow of pure oxygen into this chamber while pumping simultaneously.

We use electron beam evaporation for aluminum film deposition. The electron gun has a maximum power of 8 kW. To avoid heating, a relatively long distance of 60 cm is chosen between the evaporation source and the substrate. We can deposite different metal films with controllable deposition rates ranging from 0.01 nm/s to 15 nm/s.

Figure 1(a) shows an atomic force microscopy (AFM) image of a deposited aluminum film sample. The average grain size of the film surface is about 50 nm, showing relatively good smoothness of the surface. Figure 1(b) is the resistance–temperature (R-T) measurement result of an aluminum film strip measured on a cryogen-free ^{3}He cryostat (Oxford Instruments), the superconducting transition temperature is 9 mK in width at 1.26 K, indicating high purity of the aluminum deposited.

The Dolan bridge shadow mask evaporation technique we use for fabricating Al/AlO$_x$/Al junctions consists of two steps, the first one is to fabricate a polymer resistor mask with micro-suspending bridges, also called the Dolan bridge, the second one is to deposit aluminum film from two different angles and controll the oxidation of the aluminum film surface. These two steps are schematically illustrated in Fig. 2.

Typical small structures of a superconducting qubit are about 100 nm. To fabricate such small structures we use electron beam lithography for patterning. The electron beam lithography system we use is a Raith 150, its working voltage is 20 kV. The whole process starts with spinning two different electron beam sensitive polymer layers onto a clean silicon substrate with a thermally grown 0.5-μm thick SiO_2 layer which isolates the junction and circuits from the pure silicon, the desired structure patterns are then written onto the polymer resistor layers by electron beam lithography. During exposure to electron beams, high energy electrons break the bonds in the polymer, which increases their solubility in some solvents, the developer. The bottom layer of the polymer is much more sensitive to electrons, thus making it dissolve much faster in the developer, making hollows underneath the top polymer layer, called the undercut. If two exposed areas are close together, the bottom layer under them will be totally hollowed, forming a hanging bridge of the top layer, called the Dolan bridge. The bottom polymer layer we use is PMMA/MAA (MicroChem PMMA(8.5)MMA EL9), the top polymer layer is PMMA (MicroChem PMMA950 EL5) and spun at a higher speed (6000 r/min) to produce a thinner layer than on the bottom layer. The substrate is baked on a hot plate after spinning each resistor layer, and after spinning the top layer, the substrate is baked at 170 °C for 30 min to remove as much solvent as possible.

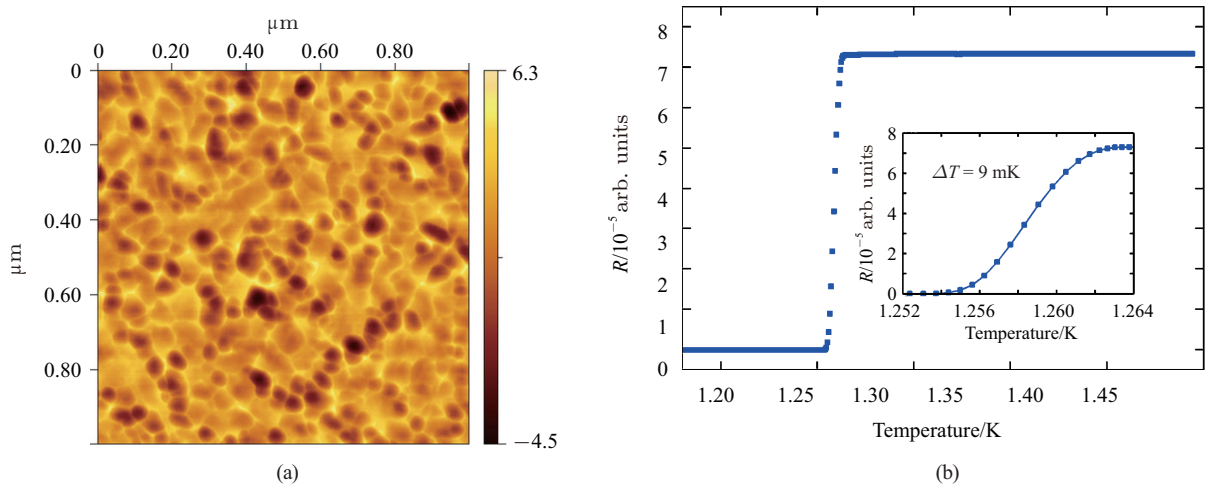


Fig. 1. (color online) (a) AFM image of an aluminum film sample, with average grain size being about 50 nm. (b) R-T measurement result of an aluminum film strip, where the superconducting transition temperature is 9 mK in width at 1.26 K.

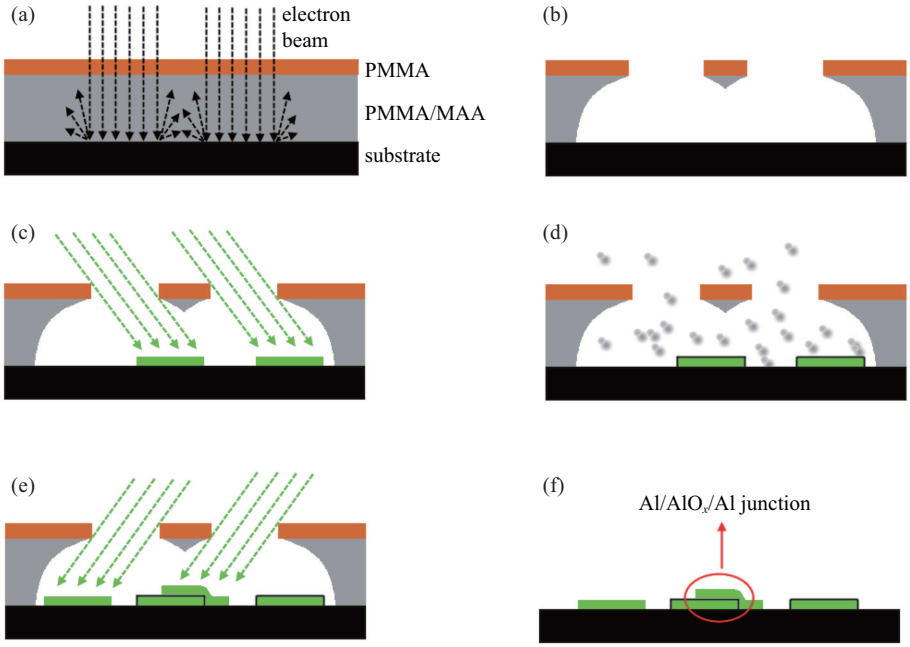


Fig. 2. (color online) Schematics of Al/AlO$_x$/Al junction Dolan bridge shadow evaporation fabrication process. (a) Electron beam writing, (b) development, (c) first aluminum layer evaporation, (d) oxidation, (e) second aluminum layer evaporation, (f) liftoff.

After the lithography process, the substrate is then loaded into an evaporator. A first layer of aluminum thin film is deposited onto the substrate. The existence of the Dolan bridge interrupts the deposition underneath the bridge from an angle. This first aluminum thin film layer is then subjected to an oxidation process under a low pressure of oxygen for some time without breaking the vacuum, forming a very thin layer of AlO_x on the surface. A second layer of aluminum thin film is deposited right after the oxidation process from a different angle. These two aluminum layers, deposited from two different angles and interrupted by the Dolan bridge, have a small overlap under the Dolan bridge which is only separated by the thin AlO_x layer on the surface of the first layer, forming an Al/AlO$_x$/Al junction. Resistors and unwanted aluminum films are removed by lift-off with acetone.

Figure 3(a) is a scanning electron microscope (SEM) image of a typical Al/AlO$_x$/Al Josephson junction we fabricated, which shows a well-defined junction area. We can fabricate Al/AlO$_x$/Al junctions with sizes from as small as 0.01 μm^2 up to 1 μm^2, for different types of superconducting qubits. Figure 3(b) shows the current–voltage characteristic (IVC) of an Al/AlO$_x$/Al Josephson junction sample, measured on a cryogen-free dilution refrigerator (Oxford Instruments DR 200).[8] Note that IVCs are obtained by applying currents supplied by a current source whose internal resistance is much bigger than the normal resistance of the Josephson junction or SQUID to be measured. In some cases, like flux qubit measurement, the bias of the SQUID is applied through coaxial cable equipped with attenuators and a bias resistor at the end. This bias resistor is an effective internal resistance of the current source

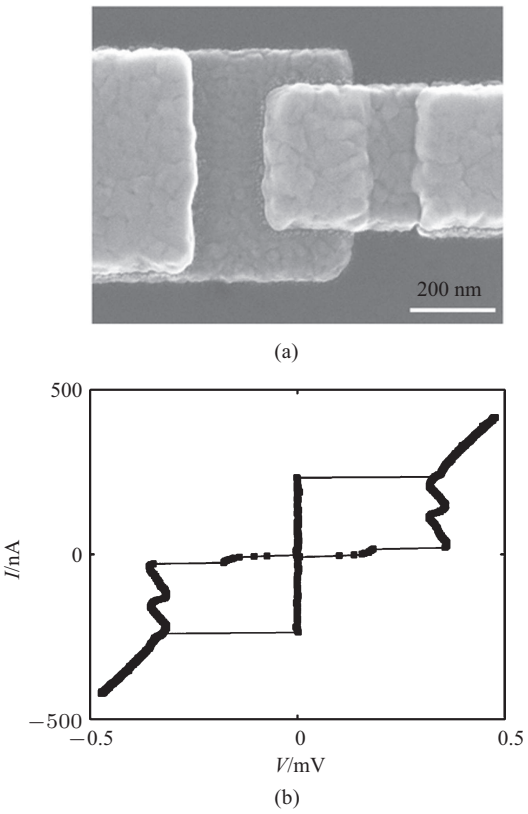


Fig. 3. (a) The scanning electron microscope (SEM) image of an Al/AlO$_x$/Al Josephson junction. (b) Current–voltage characteristic (IVC) of an Al/AlO$_x$/Al Josephson junction sample.

and it has to be much bigger than the normal resistance of the SQUID. From the IVC we can see that the product I_cR_n well satisfies the Ambegaokar–Baratoff formula:

$$I_cR_n = \pi\Delta/2e = \pi V_g/4 \quad (T = 0), \tag{1}$$

and the gap voltage $V_g \approx 360$ μV is in accordance with the gap voltage value calculated from the superconducting transition

temperature of the aluminum film, $T_c = 1.26$ K. Furthermore, the IVC shows very low subgap current, indicating the high quality of the junction. The junction capacitance is estimated to be about 110 fF/μm^2.

The most important parameter of a Josephson junction in qubit applications is its critical current density (j_c), which is determined by the thickness of the AlO_x insulating barrier formed in the oxidation process. For superconducting flux qubit samples, we need high j_c values (~200 A/cm^2–2000 A/cm^2). The superconducting energy gap Δ of aluminum is low compared with those of other commonly used superconducting metals (such as Nb and Pb), according to Eq. (1), in order to obtain high j_c Al/AlO_x/Al Josephson junctions we need to fabricate junctions with very thin AlO_x barrier layers.

We have tried different oxidation methods. First we tried oxidation with pure oxygen in a pre-pumped oxidation chamber, only to find that the oxidation is too fast to be controllable. We then used an O_2 (0.5%)/Ar(0.95) mixture instead of pure oxygen to reduce the oxygen partial pressure. The oxidation rate is slow enough with this method but the j_c of the Josephson junctions fabricated are quite unpredictable, we attribute this to the leaking of oxygen from the atmosphere into the oxidation chamber in the oxidation process. As the oxygen partial pressure is low and the oxidation process took more than ten min, this unpredictable leaking process could greatly affect the oxidation process. To handle this, we have adopted an oxidation method which we call the dynamical oxidation. In this method, oxygen flows into the oxidation chamber continuously at a low rate while the turbo pump keeps pumping, keeping the oxidation chamber at a pressure of about 1×10^{-1} Pa. With this method, we have been able to obtain high controllability of critical current density by varying the oxidation time to fabricate Josephson junctions with different critical current densities.

Though the process is simple enough, to obtain controllable critical current density is still quite a tricky task, the whole oxidation system involved is under test. As the oxygen pressure is so low that high vacuum condition is indispensable because residual gases like water remaining in the oxidation chamber might affect the oxidation process greatly. Other facts like the inaccuracy of the vacuum gauge, position of the sample in the oxidation chamber in the oxidation process or even changes of the weather might induce unexpected variation of the critical current density of the sample fabricated. Figure 4 shows the critical current density versus oxidation time of several Al/AlO_x/Al Josephson junction samples we fabricated. These samples are fabricated in a short time span, for samples fabricated a long time apart, this strict linear relation is never strictly observed. The critical current density oxidation time relation has always to be adjusted with time going by on our system. We have observed that the critical current densities of our Josephson junction samples tend to go down with time going by, some even drop off to a value of half its initial value when measured half year later. We attribute this to a slow oxidation process of the junction by oxygen since our samples are stored in atmosphere. This may well be prevented if the samples are stored in vacuum or an oxygen free environment.

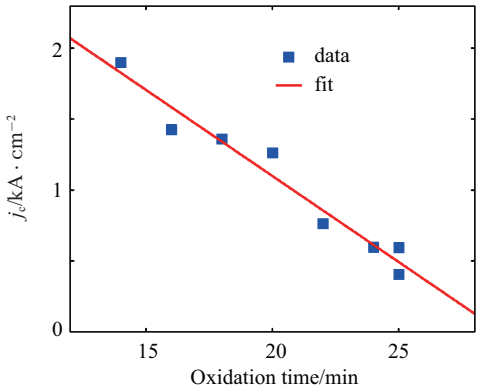


Fig. 4. (color online) Critical current j_c versus oxidation time. Oxygen pressure $P = 9.6 \times 10^{-2}$ Pa.

3. Fabrication of superconducting qubits

After successfully fabricating Al/AlO_x/Al Josephson junctions we further fabricate superconducting qubits such as flux qubits[9,10] and charge-flux qubits (Quantronium[11]). The core elements of all superconducting qubits are just Josephson junctions, but to control, readout and isolate the qubit from external environments, more circuit elements such as capacitors, resistors, inductors, microwave guides, and wiring need to be fabricated on chips. These on-chip elements are also fabricated using electron beam evaporation and liftoff, but we use photolithography to do the patterning due to their relatively large sizes. We use a Karl SUSS MA6 mask aligner to do the patterning. Two photolithography and evaporation processes are required. The first process is to fabricate the ground aluminum plates of the capacitors, the second process is to fabricate on chip resistors, microwave guides, and wiring. The patterns of the second photolithography process are aligned together with the existing structures fabricated in the first photolithography process by align marks.

We use on-chip RC filters to isolate qubits from external environments. The typical cutoff frequency of the on-chip RC filters we use is about 500 MHz. The capacitor is an Al/AlO_x/Al structured parallel-plate on-chip capacitor. The AlO_x insulator layer is obtained by heavily oxidizing the aluminum ground plate in pure oxygen at a pressure of about $P = 1 \times 10^5$ Pa for 1 h, after liftoff, the substrate is further baked at 200 °C to ensure sufficient oxidation of the surface. The top plate of the capacitor is fabricated together with smaller structures as shown below. On-chip resistors are formed using long gold strips which each has a residual resistance at low temperatures without becoming superconducting.

Figure 5 shows an optical micrograph of a qubit sample we fabricated after the fabrication of the large on-chip elements.

After fabrication of the above mentioned large on-chip elements, small structures including Josephson junctions that form the qubit with its readout circuits like SQUID, together with microwave antennas, the top plane of capacitors, and on-chip flux bias lines are fabricated using the same method used to fabricate the Al/AlO_x/Al junctions in the previous section. These small structures are aligned to the existing structures in the electron beam lithography process, thereby completing the whole superconducting qubit devices. Figure 6 shows several of the superconducting qubit samples we fabricated.

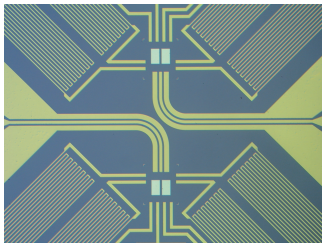


Fig. 5. (color online) Optical micrograph of a qubit sample we fabricated after the fabrication of the large on-chip elements.

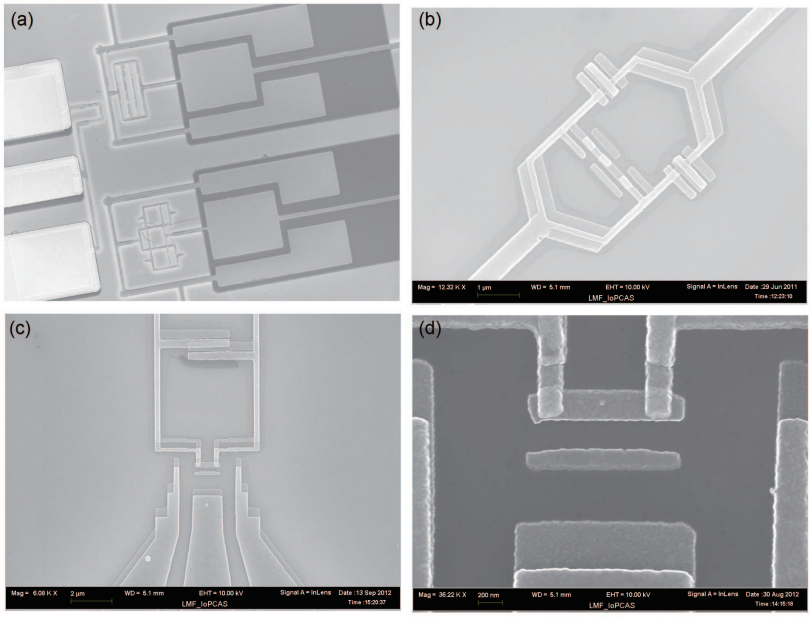


Fig. 6. (color online) Scanning electron microscope (SEM) images of several of the superconducting qubit samples we fabricated. (a) Gradiometer flux qubit and three coupling flux qubits, (b) flux qubit, (c) charge-flux qubit (Quantronium), (d) detail of a Quantronium.

4. Conclusions

We have fabricated Al/AlO_x/Al Josephson junctions using electron beam lithography and shadow evaporation, with junction sizes ranging from 0.01 μm^2 to 1 μm^2 and controllable critical current densities in a wide range. Together with on-chip circuit elements such as capacitors, resistors, inductors, microwave guides, and wiring, we have further designed and fabricated different types of superconducting flux qubits and charge-flux qubits based on Al/AlO_x/Al Josephson junctions, which are suitable for superconducting quantum measurements.

Acknowledgement

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