Character and fabrication of Al/Al$_2$O$_3$/Al tunnel junctions for qubit application

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The superconductive Josephson junction is the key device for superconducting quantum computation. We have fabricated Al/Al$_2$O$_3$/Al tunnel junctions using a double angle evaporation method based on a suspended shadow mask. The Al$_2$O$_3$ junction barrier has been formed by introducing pure oxygen into the chamber during the fabrication process. We have adjusted exposure conditions by changing either the oxygen pressure or the oxidizing time during the formation of tunnel barriers to control the critical current density $J_c$ and the junction specific resistance $R_c$. Measurements of the leakage in Al/Al$_2$O$_3$/Al tunnel junctions show that the devices are suitable for qubit applications.

Al/Al$_2$O$_3$/Al junctions, electron beam evaporation, superconducting qubit

In recent years, superconducting devices, such as superconducting Josephson junctions [1], filters [2–5], single photon detector [6] and hot electron bolometer (HEB) mixer [7] have attracted a great deal of interest in China. Important aspects to qubit applications are Josephson junctions and Superconducting Quantum Interference Device (SQUID) [8–12]. Quantum computation entails a new computation system that exceeds its classical counterpart. It is anticipated there will be an exponential speed up in solving problems which are difficult for classical computers, such as prime factorization. This prospect has fuelled much research into various experimental realizations of a quantum computer. Superconducting quantum computation is a viable and scalable approach to achieving a quantum computation scheme. Because of their solid state nature, their macroscopic phase coherence and their similarity to conventional semiconductor circuits, Josephson junction circuits are a promising technology within superconducting quantum computation schemes [13–16]. A typical flux qubit [16–19] consists of an isolated superconductive junction and a SQUID. In a SQUID the tunnel junctions are arranged in parallel to form a superconducting loop. The superconductive Josephson junction is the key device for superconducting quantum computation. The most commonly used materials for Josephson junction qubits are Aluminum (Al) and Niobium (Nb), because of the purity of their superconducting state as well as their relatively low transition temperatures ($T_c = 1.2$ K and 9.3 K, respectively) [20]. We have chosen to work with aluminum for several reasons. Firstly, high quality aluminum oxide has been shown to be less detrimental to Josephson junction qubits than other materials [21], with longer coherence times seen in aluminum-based devices [22]. Also, the fabrication of Al is flexible because of the fact that its melting point (660°C) is significantly lower than that of other popular superconducting materials, such as Nb (2477°C).

For qubit applications, we have explored the electronic properties of the Al/Al$_2$O$_3$/Al tunnel junction, including the critical current density $J_c$ and the junction specific resistance $R_c$, which depend on the oxygen pressure and the oxidation...
time during the formation of the tunneling barrier. We have used the double angle evaporation technique [23] to fabricate the Al/Al₂O₃/Al tunnel junctions. This technique has the advantage of allowing for the creation of small junction overlaps with sizes down to the submicron level. Likewise, this technique relies on a relatively simple process that does not involve breaking the vacuum. To create the small junction overlaps, we have evaporated aluminum at an angle with respect to the substrate. Factors that may limit the coherence time in flux qubit systems are the dissipation and the Johnson noise, because of sub-gap leakage in the junction. In this work, we report measurements of the sub-gap leakage in Al/Al₂O₃/Al tunnel junctions and DC-SQUIDs. We have found that the devices have a low level of dissipation (less than 1%), which is suitable for qubit applications.

1 Fabrication of the Al/Al₂O₃/Al tunnel junctions with controllable junction overlaps

Firstly, we fabricated a suspended shadow mask using a bilayer of photolithographic resist. We used a bottom layer of presensitized resist (LOR10B) and a top layer of high resolution EBL resist (495PMMAC8). Then, we deposited two layers of aluminum (purity = 99.999%) using e-gun evaporation at different angles with respect to the substrate. Finally, we introduced high purity oxygen (purity = 99.99%) to the chamber where a sample stage was situated to form the tunneling barrier between the evaporation steps. The sample stage was attached to a rotational motor, allowing for tilting of the sample from 0 to 90 degrees. For better orientation, the vacuum pressure was kept lower than 10⁻⁵ Pa. The substrate was placed roughly 80 cm from the evaporation source to ensure the aluminum was evaporated straight to the substrate. The area of junction overlaps can be calculated from the height of the bottom layer and the evaporation angles. In our experiments, junction overlaps ranging from 1 to 8 µm² were successfully fabricated (as shown in Figure 1).

It is critical to attain uniform and electrically continuous films for high quality barriers. Atomic force microscopy (AFM) was used for nanoscale imaging of the Al films. We have measured the Root Mean Square (RMS) value of the surface roughness for different thickness Al films deposited at different rates (as shown in Tables 1 and 2). The results show that the thinner Al films have smoother surfaces, whereas the depositing rate does not significantly affect the surface roughness. Each of the layers of aluminum film in our fabrication process were 100 nm thick and deposited at a rate of 0.2 nm/s with a critical current density of \( J_c \approx 1\times10^5 \text{ A/cm}^2 \).

2 Controllable electronic-properties of Al/Al₂O₃/Al tunnel junctions

Important requirements for achieving superconducting qubits include attaining suitable electronic properties, such as the critical current density \( J_c \), the energy gap \( V_g \) and the sub-gap current \( I_c \), which depend on the junction barrier quality. Oxygen-doped aluminum has long been used to significantly alter the superconducting energy gap from the bulk value. To discover the best conditions for junction barrier formation, we have adjusted the exposure conditions by changing either the oxygen pressure or the oxidizing time to obtain different barrier thicknesses. Since the tunnel junction resistance \( R_J \) is inversely proportional to the area of the junction, then the junction specific resistance \( R_c \) (the product of the tunnel junction resistance \( R_N \) and the junction area) is used as a characteristic figure [24].

Samples oxidized under oxygen pressures of \( P = 25 \text{ Pa} \) for different oxidizing times have been fabricated to examine the relationship between the electronic properties of Al/Al₂O₃/Al tunnel junctions and the oxidizing time \( t \). We have found that the electronic properties are essentially independent of the oxidation time \( t \) when it is longer than 5 min, as shown in Table 3. As a consequence, attempts to find the functionality of the barrier thickness with respect to the oxidizing time will fail in certain conditions.

In Figures 2 and 3, we have plotted \( J_c \) and \( R_c \) versus the oxygen pressure for nine samples. The nine samples were Table 1 RMS of surface roughness of aluminum films deposited at the same rate (0.1 nm/s) for various thicknesses

| Thickness (nm) | RMS (nm) |
|---------------|----------|
| 50            | 2.469    |
| 100           | 4.33     |
| 200           | 8.71     |

Table 2 RMS of surface roughness of 100 nm thick aluminum films deposited at different rates

| Depositing rate (nm/s) | RMS (nm) |
|------------------------|----------|
| 0.7                    | 4.483    |
| 0.35                   | 4.487    |
| 0.08                   | 4.33     |
Table 3  $J_c$ and $R_c$ of Al/Al$_2$O$_3$/Al tunnel junctions oxidized with different oxidizing times $t$ are essentially constant. The samples were oxidized under an oxygen pressure $P=25$ Pa at room temperature.

| Sample | Oxidation time (min) | $J_c$ (A/cm$^2$) | $R_c$ (Ω μm$^2$) |
|--------|----------------------|-----------------|------------------|
| 1      | 5                    | 30              | 800              |
| 2      | 5                    | 40              | 1000             |
| 3      | 10                   | 25              | 820              |
| 4      | 10                   | 30              | 800              |
| 5      | 20                   | 25              | 1000             |
| 6      | 20                   | 30              | 800              |
| 7      | 20                   | 14              | 1500             |

Figure 2  $J_c$ and $R_c$ of nine Al/Al$_2$O$_3$/Al tunnel junctions plotted as a function of oxygen pressure $P$. The nine samples were oxidized for $t=20$ min under different oxygen pressures $P$ at room temperature.

Figure 3  $J_c$ and $R_c$ of nine Al/Al$_2$O$_3$/Al tunnel junctions plotted as a function of oxygen pressure $P$. The nine samples were oxidized for $t=20$ min under different oxygen pressures $P$ at room temperature.

3 Characters of Al/Al$_2$O$_3$/Al tunnel junctions and DC-SQUIDs

The Al/Al$_2$O$_3$/Al tunnel junctions were measured in liquid helium (at 0.3 K) using a refrigeration system produced by OXFORD INSTRUMENTS (PT403-2440301). We have implemented a DC four-probe resistance measurement technique to discover the $I$-$V$ characteristics up to a few μV and nA of bias.

In Figure 4, we show an image of the $I$-$V$ curve of an Al/Al$_2$O$_3$/Al junction measured at 0.3 K. The junction area is about 1 μm$^2$. The $I$-$V$ curve displays a suppressed critical current because of environmental noise. The actual critical current, estimated from the switching current, is $I_c ≈ 0.5$ μA. The energy gap is $V_g ≈ 0.39$ mV and the junction specific resistance is $R_c ≈ 500$ Ω. The sub-gap current is about 2.5 nA at 300 mK, approximately 0.5% of the superconducting current.

We have also made a DC-SQUID consisting of two Al/Al$_2$O$_3$/Al Josephson junctions in parallel enclosed in a small superconducting loop (as shown in Figure 5). The area of the loop is 40 × 40 μm$^2$ with a film width and thickness of 4 μm and 200 nm, respectively. The $I$-$V$ curve of the DC-SQUID measured at a temperature of 20 mK has shown that the critical current of the DC-SQUID is $I_c ≈ 2.1$ μA and the sub-gap current is about 0.007 μA, approximately 0.33% of the superconducting current.

Figure 4  The $I$-$V$ curve of an Al/Al$_2$O$_3$/Al junction at 0.3 K.
Figure 5 SEM photo of a DC-SQUID.

Figure 6 The current \( I_c \), modulated by the external flux, measured at 20 mK.

An external flux \( F \) applied to the superconducting loop induced a persistent current (as shown in Figure 6):

\[
I_s = I_c \sin \left( 2\pi \Phi / \Phi_0 \right).
\]

The DC-SQUID is a sensitive detector that can, in certain arrangements, measure the value of the flux with a resolution of a few \( \mu \Phi \) and can be applied to detect flux change in the flux qubit. As shown in Figure 6, we have measured the external magnetic field to be \( B = 2.0 \times 10^{-4} \) T.

4 Conclusion

High quality Al/Al\(_2\)O\(_3\)/Al tunnel junctions were successfully fabricated by controlling the barrier layer preparation conditions of specific parameters. The fabricated tunnel junctions that have a low level of dissipation (less than 1\%) are suitable for qubit applications. This work has provided a good foundation for the preparation of circuits of superconducting quantum bits.

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