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Nb/Al-AlO$_x$/Nb junctions with controllable critical current density for qubit application*

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Nb/Al-AlO$_x$/Nb tunnel junctions with controllable critical current density J_c are fabricated using the standard selective Nb etching process. Tunnel barriers are formed in different oxygen exposure conditions (oxygen pressure P and oxidation time t), giving rise to J_c ranging from 100 A/cm^2 to above 2000 A/cm^2. J_c shows a familiar linear dependence on $P \times t$ in logarithmic scales. We calculate the energy levels of the phase- and flux-type qubits using the achievable junction parameters and show that the fabricated Nb/Al-AlO$_x$/Nb tunnel junctions can be used conveniently for quantum computation applications in the future.

Keywords: Nb junctions, fabrication, superconducting qubit, macroscopic quantum state
PACC: 7450, 7475, 7490

1. Introduction

Quantum computation based upon the quantum states of spins, photons, atoms/ions, and superconducting circuits has received much attention in the past years. Generally speaking, a quantum system having two quantum states can be used to construct a qubit. Due to their convenient device design and well-developed fabrication technique such as modern lithographic patterning and etching, superconducting Josephson junctions have become attractive candidates for solid-state qubits. The quantum behaviour of Josephson junctions has been extensively studied, both experimentally and theoretically.[1,2] Recently, many kinds of superconducting qubits using Josephson junctions, including phase-,[3] charge-,[4] and flux-type[5] qubits, have been experimentally demonstrated.

Nb/Al-AlO$_x$/Nb junctions have the advantage of being stable against thermal cycling, which is crucial for the actual applications, and have been considered in many of the recent qubit studies. In our previous work, high-quality Nb/Al-AlO$_x$/Nb junctions with sizes down to submicron level have been successfully fabricated using the standard selective Nb etching process (SNEP) and electron beam lithography.[6] In this work, we show that the junction key parameters, namely the critical current density J_c, can be adjusted by controlling the oxygen pressure P and oxidation time t during the formation of the tunnelling barrier. We calculate the energy levels of the phase- and flux-type qubits using the achievable junction parameters and show that the fabricated Nb/Al-AlO$_x$/Nb tunnel junctions can be used conveniently for quantum computation applications in the future.

2. Experiment

Our Nb/Al-AlO$_x$/Nb junctions were fabricated using the standard SNEP technique. The basic trilayer structures were prepared by magnetron sputtering on clean oxidized silicon chips in an ultrahigh vacuum system having a background pressure of 1×10^{-6} Pa. The junction wirings were defined by photolithographic patterning and junction areas were defined by electron beam lithographic patterning using PMMA or ZEP520 resist. Reactive ion etching in SF_6 and Ar ion milling were used to remove the unwanted parts. Insulation was done by sputtering SiO_2 layers with a typical thickness of 100 nm.

The junction barrier AlO$_x$ was formed in the load-lock chamber on Al in the trilayers by introducing pure

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oxygen into the chamber during the fabrication process. Different barrier thicknesses were obtained by varying the oxygen exposure. We adjusted the exposure condition either by changing the oxygen pressure P or by changing the oxidizing time t. For a given oxygen exposure, the barrier's thickness was found to have a well defined value, as reflected in the critical current density J_c of the junctions described below. In Fig.1, we show an oscilloscope image of the I–V curve of a Nb/Al-AlO$_x$/Nb junction measured at 4.2 K. The I–V curve displays a suppressed critical current because of thermal activation and environmental noise. The actual critical current can be estimated from the following formula:

$$I_c(T) = \frac{\pi \Delta(T)}{eR_N} \tanh \frac{\Delta(T)}{2kT}, \qquad (1)$$

where $\Delta(T)$ is the energy gap and R_N is the junction's normal-state resistance, which can be obtained from the gap voltage and high-bias resistance from the I–V curves. For the sample in Fig. 1, the critical current estimated from Eq.(1) is $I_c = 6.8$ μA, corresponding to J_c of 170 A/cm^2 if the junction area of 4 μm^2 is considered (we measure the area from the SEM photos of the junctions).

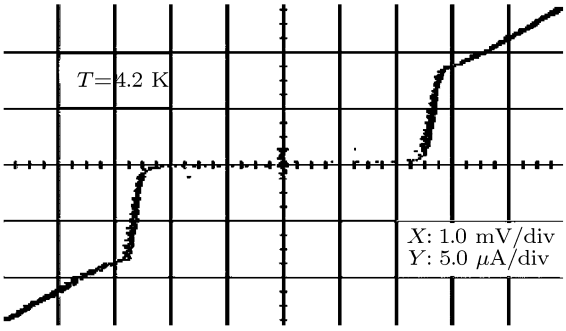


Fig.1. I–V curve of a Nb/Al-AlO$_x$/Nb junction with an area of 4 μm^2. The critical current estimated from Eq.(1) is 6.8 μA, corresponding to J_c of 170 A/cm^2.

In Fig.2, we show J_c versus oxygen exposure $P \times t$ for four samples. The four samples were fabricated for $t = 20$ min under different oxygen pressures P at room temperature. From the logarithmic presentation, we see that the relationship between J_c and oxygen exposure is almost linear, which is a result of the self-limited logarithmic dependence on the thermal oxidation. The self-limited effect is caused by coverage of the oxidized Al which prevents further oxygen contact with the Al.[7] From this result, samples with different J_c can be easily prepared using different oxygen exposure, which is useful for their qubit applications.

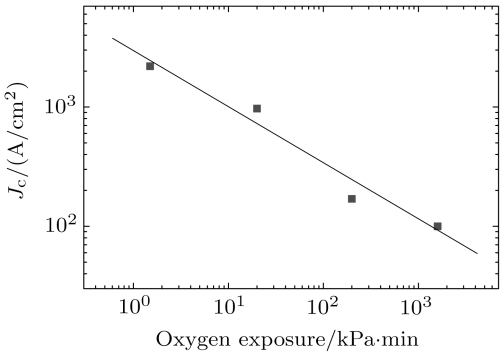


Fig.2. J_c of four Nb/Al-AlO$_x$/Nb junctions as a function of oxygen exposure condition $P \times t$. The four samples were oxidized for $t = 20$ min under different oxygen pressures P at room temperature.

3. Phase and flux qubits using Nb/Al-AlO$_x$/Nb junctions

Below we discuss the rf-SQUID type phase and flux qubits which are composed of a superconducting loop interrupted by a Nb/Al-AlO$_x$/Nb junction. Through numerical calculation we can know the quantum states of this structure.[8] If we consider a 40 μm×40 μm superconducting loop with film width and thickness of 2 μm and 200 nm respectively, its inductance L will be about 118 pH. For the qubit to have a double well potential, the β_L=$2\pi I_c L/\Phi_0$ parameter should satisfy $\beta_L > 1$. This requires the junction's critical current I_c to be larger than 2.8 μA. On the other hand, the junction's capacitance C, which is mainly determined by the junction area, plays a role in energy level spacings considering that they roughly scale with the plasma frequency $\omega_0 = (2\pi I_c/\Phi_0 C)^{1/2}$. Hence one needs to adjust the J_c value and junction size (or capacitance) simultaneously in order to build workable qubits with desirable parameters.[9]

We first consider the phase qubit. We computed the energy levels for a superconducting loop containing a Nb/Al-AlO$_x$/Nb junction with an area of 2×2 μm^2, $J_c = 100$ A/cm^2, and $C = 240$ fF. The results for a qubit bias of $\Phi_e/\Phi_0 = 0.522$ are shown in Fig.3. In Figs.3 and 4 ϕ is normalized total flux enclosed in the SQUID loop. The calculated energy level spacing E_{01} between the first and the second energy level is 19.5 GHz, which is quite convenient for the experimental measurements. In the figure, we can see the level spacing decreases for higher energy levels

in the left well.[3]

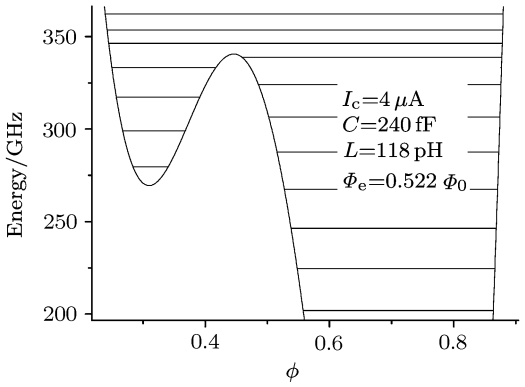


Fig.3. Calculated energy levels of rf-SQUID type phase qubit using Nb/Al-AlO_x/Nb junctions with experimentally achievable parameters.

In the case of a flux type qubit, we consider a loop containing a Nb/Al-AlO_x/Nb junction with an area of 1.4×1.4 μm^2, $J_c = 170$ A/cm^2, and $C = 110$ fF. The calculated energy levels at a qubit bias of $\Phi_e/\Phi_0 = 0.5$ are shown in Fig.4. Due to the smaller I_c compared to the case in Fig.3, we obtain a smaller $\beta_L = 1.075$, which leads to a smaller barrier size between the two potential wells. For the given parameters, we can see that there are only two splitting levels in the wells.

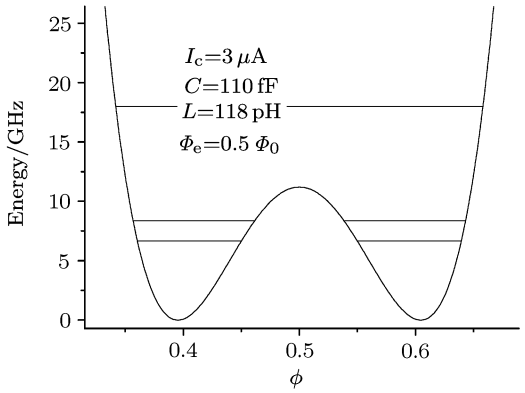


Fig.4. Calculated energy levels of rf-SQUID type flux qubit using Nb/Al-AlO_x/Nb junctions with experimentally achievable parameters.

The level spacing between the first and second energy states is $E_{01} = 1.68$ GHz and their separation to the third level is 9.63 GHz. The two splitting levels are well isolated from the higher energy levels, which is advantageous for the flux qubit operations.

From the above discussion, we see that the phase qubit needs a smaller J_c in order to have a large junction area, which can lead to a larger junction capacitance. In this case, the energy level spacing of the qubit will have an appropriate size for the effective microwave transmission in the experiment. On the other hand, the flux qubit needs a larger J_c compared with the phase qubit. In this way, the junction's capacitance can be smaller and a larger energy level spacing between the third and second quantum states will result, which prevents the undesired activation. Although there is a large spacing between the third and the second energy levels, the value between the first and second levels is small and is convenient for the experimental measurements. These results are useful for future studies of the rf-SQUID type phase and flux qubits.

4. Conclusion

Nb/Al-AlO_x/Nb tunnel junctions with controllable critical current densities were successfully fabricated using the SNEP technique. Possible applications of these junctions as rf-SQUID type phase and flux qubits were discussed by theoretical calculations of the system's energy level spacings.

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References

[1] Martinis J, Nam S, Aumentado J and Urbina C 2002 *Phys. Rev. Lett.* **89** 117901
[2] Yu Y, Han S, Chu X, Chu S I and Wang Z 2002 *Science* **296** 889
[3] Friedman J R, Patel V, Chen W, Tolpygo S K and Lukens J E 2000 *Nature* **406** 43
[4] Vion D, Aassime A, Cottet A, Joyez P, Pothier H, Urbina C, Esteve D and Devoret M H 2002 *Science* **296** 886
[5] Chiorescu I, Nakamura Y, Harmans C J P M and Mooij J E 2003 *Science* **299** 1869
[6] Yu H F, Cao W H, Zhu X B, Yang H F, Yu H W, Ren Y F, Gu C Z, Chen G H and Zhao S P 2008 *Chin. Phys.* B **17** 3083
[7] Tolpygo S K, Cimpoiasu E, Liu X, Simonian N, Polyakov Yu A, Lukens J E and Likharev K K 2003 *IEEE Trans. Appl. Supercond.* **13** 99
[8] Tian Y, Zhu X M, Liu D T, Zhao S P and Chen G H 2008 *Chin. Phys. Lett.* **25** 3757
[9] Cui D J, Yu H F, Peng Z H, Cao W H, Zhu X B, Tian Y, Chen G H, Lin D H, Gu C Z, Zheng D N, Jing X N, Lu L and Zhao S P 2008 *Supercond. Sci. Technol.* **21** 125019