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Resistively shunted NbN/AlN/NbN tunnel junctions for single flux quantum circuits

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Abstract

We have developed resistively shunted NbN junctions to realize superconducting single flux quantum circuits operating at 10 K and/or high speed. The junctions consist of epitaxial NbN/AlN/NbN tunnel junctions and molybdenum (Mo) resistors fabricated on single-crystal MgO substrates. The junction qualities are systematically investigated in a wide range of critical current density (J_c). The gap voltage and the ratio of R_{sg}/R_N were about 5.6 mV and 11 for the junctions with the J_c of 10 kA/cm^2, respectively. The overdamped Josephson junctions with parallel Mo resistors having a nominal sheet resistance showed non-hysteretic current-voltage characteristics for the junctions with J_c of 10 kA/cm^2.

Keywords: NbN;Tunnel junction;Josephson junction; Single flux quantum;overdamped *I-V*

1. Introduction

Ordinary superconducting digital circuits basically consist of superconductor-insulator-superconductor (SIS) of tunnel junctions. Today, Nb/AlO$_x$/Nb Josephson junctions are used in most superconducting digital circuits. Recently, there have been proposed of single flux quantum (SFQ) integrated circuit using NbN based SIS junctions. NbN SIS junctions are a candidate because of their high superconducting energy gap. In addtion, NbN tunnel junctions have been operated at 9 K [1,2]. While, SFQ circuits always require accurate control of several circuits parameter, such as critical parameter, before design of SFQ circuits. SFQ circuits are composed overdamped tunnel junctions with non-hysteretic current-voltage (*I*-

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V) curves [3]. Therefore, optimization of the performance of NbN-based overdamped tunnel junctions for SFQ is an important issue. However, SIS tunnel junctions are essentially underdamped and hysteretic *I*-*V* character. For the present, several processes for the fabrication of overdamped NbN Josephson junctions have been developed [4,5]. In this paper, we have introduced an NbN/AlN/NbN tunnel junction as externally shunted junctions. We report the observation of the *I*-*V* characteristics of NbN/AlN/NbN tunnel junctions with parallel Mo resistors.

2. Experimental detail

Cross section for the typical layout of shunted tunnel junctions are shown in Figs 1. To begin with, the tunnel junctions were fabricated from NbN(300 nm)/AlN/NbN(200 nm) trilayer samples deposited on a single-crystal (100) MgO substrates(Fig. 1 (a)). NbN and AlN films were prepared by DC magnetron sputtering in a load-lock sputtering system at ambient substrate temperatures. During the deposition of NbN and AlN films, the total pressure were kept at 0.27 Pa. X-ray and TEM analysis showed that all NbN and AlN layers that formed the tunnel junctions were epitaxially grown. Supercondcuting transition temperature T_C and resistivity at 20 K of the NbN layer had ~ 16 K and ~ 60 μΩcm, respectively [6]. Next,the counter and base electrodes were patterned using AZ5214 (Clariant Co.). The NbN films were etched by reactive ion etching (RIE) with CF_4(Fig. 1 (b)). A150 nm-thick SiO_2 film was deposited by RF sputtering to isolate between the NbN electrodes forms a Mo film (Fig. 1 (c)). After the deposition and pattern of 100-nm-thick Mo layer, a 200nm-thick SiO_2 film was deposited to isolate the electrode and resistor from the wiring layer. Furthermore, the contact via to electrode was formed in the SiO_2 film by RIE with CHF_3(Fig. 1 (d) and (e)) . Finally, a wiring NbN layer was deposited and patterned to form to the upper electrodes (Fig. 1 (f)). An optical micrograph of shunted junction is shown in Fig. 1(b). The *I* – *V* characteristics of the junctions were investigated in the standard four-point-probe method, sweeping a low frequency alternating bias voltage. All *I* –*V* measurements were carried out in a liquid helium dip stick probe with μ-metal shielded sample space.

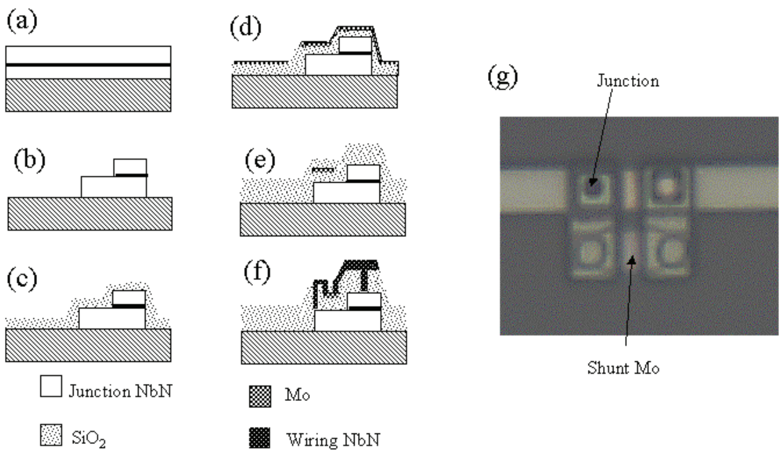

Fig. 1 (a)-(f) A cross sections for the typical layout of shunted tunnel junctions. (g) An optical microscope image of $2 \times 2\ \mu m^2$ junction on MgO substrate shunted by a molybdenum film.

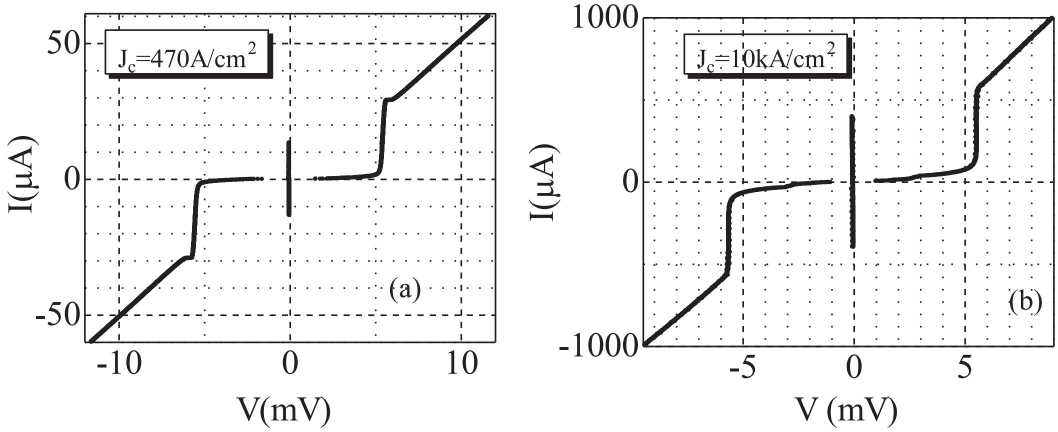

Fig. 2 Current – voltage characteristics of NbN/AlN/NbN junctions. Junction size in (a) is 2 × 2 μm^2 and critical current density J_c is 470 A/cm^2. Junction size in (b) is 2 × 2 μm^2 and critical current density J_c is 10kA/cm^2.

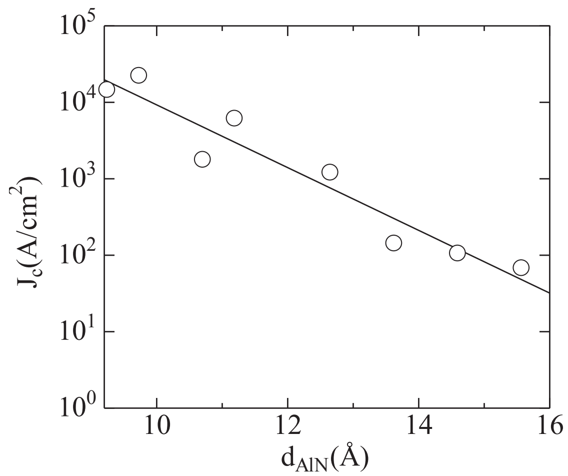

Fig. 3AlN barrier thickness d_{AlN} dependence of critical current density J_c. A solid line was calculated by the least-squares method.

3. Results and discussion

Figures 2 show I – V characteristics measured at 4.2 K for two typical NbN/AlN/NbN tunnel junctions without a parallel resistor. Both tunnel junction sizes are 2 × 2 μm^2. The I – V curves obviously shows an underdamped behavior. The critical supercurrents I_c and critical current density J_c measured from the I – V curve are 14 μA (Fig. 2(a)) and 400μA (Fig. 2(b)), J_c = 470 A/cm^2 and 10 kA/cm^2, respectively. Superconducting gap voltages V_g and the quality parameter R_{sg}/R_N, for two types of junctions have V_g, =

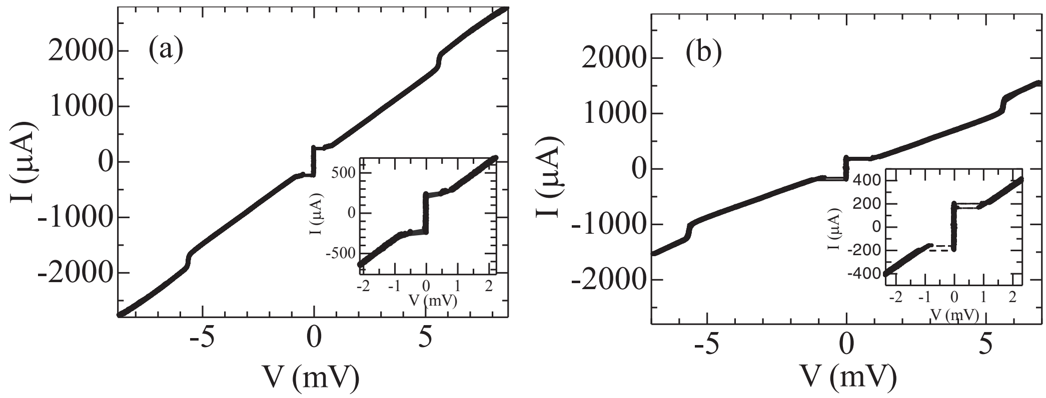

Fig. 4 Current – voltage characteristics of NbN/AlN/NbN junctions. Junction size in (a) is 1.4× 1.4 μm^2 and critical current density J_c is 10 kA/cm^2. Junction size in (b) is 1 × 1 μm^2 and J_c is 21 kA/cm^2. Inset is the *I-V* curves in the region of lower currents.

5.4 and 5.6 mV, and R_{sg}/R_N = 37 and 11, respectively. Here, R_{sg} is the gap resistance at 4mV and R_N is the junction resistance at 10 mV. Also, gap voltage width ΔV_g is below 0.15 mV, which indicates that there is a clear NbN electrode – AlN barrier interface.

Figure 3 shows the AlN barrier thickness d_{AlN} dependence of J_c. The d_{AlN} was estimated from the sputtering rate and the AlN deposition time. We observed an almost exponential dependence of *J*c vs. AlN thickness with Jc's ranging from 10^2 to 10^4 A/cm^2. Our experimental results in the barrier thickness range of 9 -16 Å show the good fit to the exponentially barrier thickness dependence. Using the Simmon's model, the effective barrier height is 0.86 eV [7]. This value is in good agreement with our previous report [8]. Therefore, we believe that the relation between J_c. and d_{AlN}, and the *J*c controllability have repeatability.

In Fig. 4 we show the measured *I – V* curve of NbN/AlN/NbN junctions with parallel Mo resistors. The junction sizes were 1× 1 μm^2 with J_c of 21 kA/cm^2 (Fig. 4(a)) and a 1.4 × 1.4 μm^2 with 10 kA/cm^2 (Fig. 4(b)). The *I – V* curve clearly shows an overdamped *I – V* behavior. However, in Fig. 4(a), hysteresis is observed in the *I – V* characteristics. The damping behavior is characterized by the McCumber parameter [9,10]:

$$\beta_c = 2\pi I_c R_N^2 C/\Phi_0, \tag{1}$$

where *C* is the capacitance of the junction, and Φ_0 is the flux quntaum. While, using fiske step for 2 × 5 μm^2 junction, the junction capacitance is estimated [11]. In Fig. 4(a), the overdamped Josephson junctions with parallel Mo resistors having a nominal sheet resistance of 1.2 Ω showed non-hysteretic *I- V* characteristics for the junctions with J_c of 10 KA/cm^2 and the McCumber factor β_C of 1. On the other hand, the junctions of Fig. 4(b) had $\beta_c \sim 1.9$ with hysteretic *I- V* characteristics. In the case of Fig. 4(a), the value of β_c meets the essential requirement of SFQ integrated circuits ($\beta_c \leq 1$). This results suggests that high speed SFQ integrated circuits is realized by using NbN/AlN/NbN tunnel junctions with externally shunted resistor.

4. Conclusion

We have fabricated and evaluated NbN/AlN/NbN tunnel junctions with or without parallel Mo resistors. The $I-V$ curve of the shunted junctions clearly showed an overdamped non-hysteretic behavior. Meanwhile, we observed an almost exponential dependence of J_c vs. AlN thickness with J_c's ranging from 100 to 10^4 kA/cm^2. Overdamped Josephson junctions are obtained by choosing the appropriate ranges for the principle fabrication parameters.

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