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Highly reliable dc SQUIDs in temperature with laser-MBE $YBa_2Cu_3O_X$ thin films

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Abstract

Highly reliable dc superconducting quantum interference devices (SQUIDs) in temperature with step edge junctions (SEJs) were fabricated with laser molecular beam epitaxy (L-MBE) $YBa_2Cu_3O_X$ thin films. The reflection high-energy electron diffraction oscillation cycles proved that the superconducting films were epitaxially grown on the atomic scale. In the dc SQUID temperature transition curves, the tail structures appear at a temperature close to the transition point. The critical current dependent temperature, $I_C \sim (1 - T/T_C)^2$, shows that the L-MBE SEJ behaves like an SNS type junction. The white noise level, $2.0 \times 10^{-5} \Phi_0/\sqrt{Hz}$ at 200 Hz, triangular wave signal, critical current and other characteristics exhibit no change after 42 temperature cycles and 108 days of storage.

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Since the advent of high critical transition temperature (high T_C) superconductors [1], the research on interference devices based on Josephson junction has developed quickly [2,3]. In order to meet the needs for real applications, one development direction has been focusing on better noise performance, which explains why the Josephson junctions of superconducting quantum interference devices (SQUIDs) have been developed from natural grain boundary junction (GBJ) to bi-crystal grain junction [4], step-edge junction (SEJ) [5,6], and other man-made controllable GBJs [7,8]. On the other hand, real applications require device reliability, especially the reliability upon thermal cycling, since the variations of temperature between liquid nitrogen temperature and room temperature are unavoidable. One possible solution to perform this 'thermal reliability' is to sputter a protection layer on superconducting thin film devices. However, this carries other problems, such as deterioration of device performance due to oxygen loss at high sputtering temperatures, inconvenience for pattern transfer, or even grain boundary destruction owing to expansion differences. The ultimate means to enhance device reliability, therefore, is to exploit high quality thin films, which contain little crystal defect, so as to keep the properties constant either with temperature cycles or with long time storage. Laser molecular beam epitaxy (L-MBE) is a newly developed method, which is atomic-scale controllable [9,10] and combines the merits of both pulsed laser deposition (PLD) and conventional MBE for thin films, especially for high melting point ceramics and multicomponent oxides preparation. Although several Josephson devices [11,12] have been developed by molecular beam expitaxy, they were mainly focused on novel cuprate superconductor [13], anisotropic transport properties [14], or heterogeneous epitaxial growth [15]. In this paper, unit-cell by unit-cell, well-oriented, strict

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epitaxially grown and smooth $YBa_2Cu_3O_X$ thin films sputtered by L-MBE method were used to fabricate dc SQUIDs with SEJs. The devices performances before and after temperature cycling and long time storage are inspected. The characteristics of SEJs at 77 K and reduced temperatures are also reported.

The most commonly used single crystal substrates for epitaxially grown $YBa_2Cu_3O_X$ superconducting films are $LaAlO_3$ and $SrTiO_3$ (STO). The former has better high frequency response while the latter has a better crystal match. Here, only the STO substrate is discussed because dc-SQUIDs are functional at low frequency. When choosing metal as a mask, there are two considerations. One is that the metal should be as hard as possible, and the other is that the metal should be easily removable from the substrate so as not to influence the growth of $YBa_2Cu_3O_X$ superconducting film. Carbon film is one popularly used mask film, but it is hard to be removed thoroughly. Other frequently used metal masks, such as Ti or Cr, are not suitable because their etchant will attack and hurt STO heavily. Here Nb is selected as the metal mask for convenience, though other choices are also reasonable [16].

The STO (100) step substrates were fabricated by Kaufman-type Ar^+ ion milling with a proper thickness of Nb mask and an optimized incident angle. In order to accommodate two junctions and keep these two junctions identical, the fabricated step substrates hold long and straight bank lines, sharp step angles over 65°, and smooth sidewalls. The detailed description of step fabrication can be found in Ref. [17].

Atomically regulated unit-cell by unit-cell $YBa_2Cu_3O_X$ thin films were deposited on the step substrates by the L-MBE method. The fine streak patterns and undamped intensity oscillation were monitored by using in situ reflection high-energy electron diffraction (RHEED) system. As shown in Fig. 1, over 1000 oscillation cycles of undamping intensity were observed during continuous epitaxial growth of single unit-cells, indicating that this growth mode would persist in two-dimensional geometries.

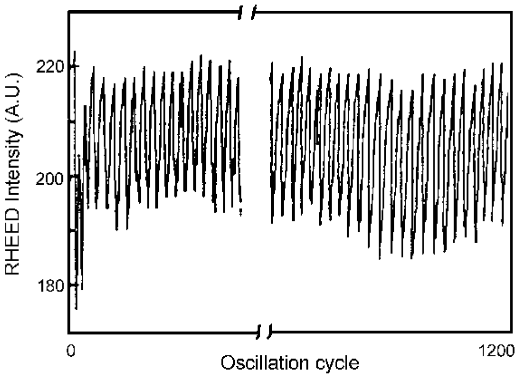


Fig. 1. RHEED monitoring oscillations when $YBa_2Cu_3O_X$ film was unit cell by unit cell grown on $SrTiO_3$ substrate, oscillations showed no damping sign over 1000 times.

When the substrate temperature was held in the range of 700 to 720 °C, the growth rate was about 1 Å per second. X-ray diffraction analysis showed that the thin film was single phase with c-axis orientation. The surfaces of films were atomically smooth with mean square root roughness of 72 Å [18]. The measured critical transition temperature was about 87 K, which located $2I_C$ value within 50–200 μA at 77 K, so as to keep the coupling energy larger than the thermal energy [19]. The step height was about 250 nm, while the film thickness ranged from 200 to 230 nm, which brought out a film-to-step ratio of 0.8 to 0.9. It was a relatively high value, which backs up the fact that the step edge grain boundary is quite narrow.

The dc SQUIDs pattern was composed of two 3-μm width bridges and one square washer. In order to enhance the flux focus ability of single chip device, the washer geometry contained a large outer length of 3.6 mm with an inner length of 30 μm. After patterned with AZ1350, the $YBa_2Cu_3O_X$ thin films were etched by ion milling. The Ar Kaufman-type ion source for dry etching was operated at energy of 500 eV and beam current of 20 mA. The $YBa_2Cu_3O_X$ thin films should be well cooled when etching so as to prevent oxygen loss. After silver electrodes were prepared, the characteristics of dc SQUIDs were measured at liquid nitrogen temperature and reduced temperature under a magnetically shielded environment.

In order to learn the properties of L-MBE SEJs, the temperature dependence of both the SQUID shunted resists and the critical current close to T_C were inspected. The $R-T$ curve plotted in Fig. 2 shows a very sharp drop of the resistance starting above $T = 87$ K, which came from the transition of the large grains, and a tail structure at lower temperature caused by the grain boundary Josephson junction. At further reduced temperatures, the grain boundary resistance, R, is constant, which is the same as the other boundary junction performance. According to the theory of Ambegaokar-Baratoff [20], the relation $I_C(T) \sim (1 - T/T_C)^n$ exists between critical current I_C and transition temperature T_C when temperature T changes near T_C. The

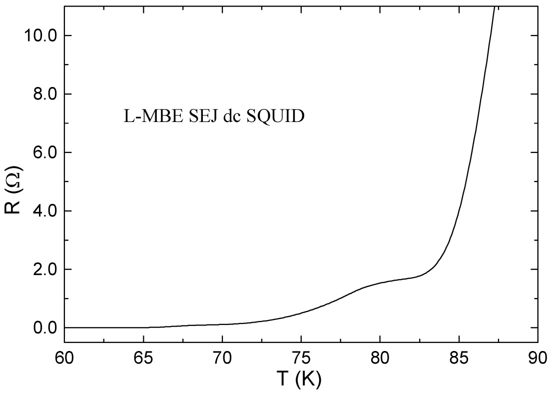


Fig. 2. Tail structure of resistance plotted as a function of temperature.

exponential index n is defined by the junction type. $n = 1$ is expected for a SIS junction close to T_C, while for SNS-type junction exhibits a value of $n = 2$. The log relation between critical current and transition temperature is plotted in Fig. 3, the L-MBE SEJ behaved like SNS-type junction with an observed slope of $n = 2.0$. Similar results were obtained in measurements of the current-voltage characteristics close to T_C over four decades [21].

Fig. 4 shows a typical current–voltage curve (IVC) of L-MBE dc SQUID at 77 K. The little turnup slightly above I_C agrees with the description of a resistively shunted junction (RSJ) model [22]. At higher voltages, the IVC approaches an ohmic line, $V = I_C R_N$. Here, normal resistance R_N is about 1.04 Ω, in accordance with the RSJ model, too. The SQUID critical current $2I_C$ is about 140 μA, which gives a current density of $J_C \sim 10^4\ A/cm^2$, two orders of magnitude lower than that in the bulk area.

To test the device reliability, a harsh treatment of devices was followed by quick changing of the temperature between liquid nitrogen and room atmosphere. The device characteristics were measured intermittently. Fig. 5 shows a comparison of V–B curves before and after 42 temperature cycles and 108 days of storage without device protection. Calculated from R.G. Seed theory [23], the ΔV value is about 5 μV, in reasonable accordance with the value of 4.2 μV measured at 77 K. Before and after the treatment, the triangular waves illustrated undetectable difference with the same modulation amplitude and period. Other parameters, such as R_N, I_C and flux noise level, were kept unchanged as well. The temperature reliability of L-MBE dc SQUIDs set a good sample to provide a promising means for other high T_C superconducting devices and applications.

Another fact, the A_{eff}/dD ratio (A_{eff} is effective area derived from flux quantum Φ_0 and magnetic field period, d and D are inner and outer lengths of washer) is of about 0.97, substantiates that the L-MBE thin film is good enough to endure the flux spinning force focused to central hole area. R. Gross [24] found that the magnitude and the frequency dependence of the voltage noise were identical for both the single junction and the complete SQUID, which suggested the $1/f$ noise originated not from the magnetic flux noise in thin film but the GBJs. Therefore, it is not unexpected that the measured white noise level, $2.0 \times 10^{-5}\Phi_0/\sqrt{Hz}$ (at 200 Hz), of L-MBE dc SQUIDs exhibited a similar value to that of PLD SEJ dc SQUIDs with the same parameters made in our group.

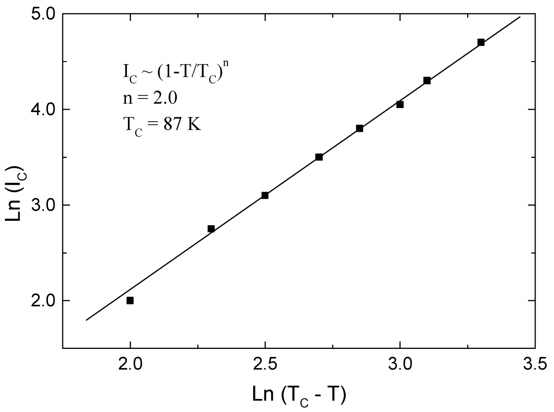


Fig. 3. Log plot of critical current changes dependent temperatures close to T_C, the L-MBE SEJs behaved like SNS junction with the observed slope of $n = 2.0$.

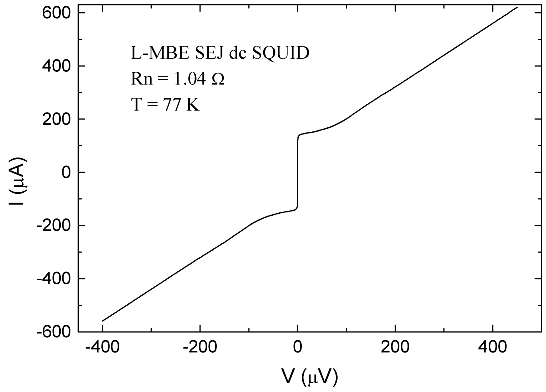
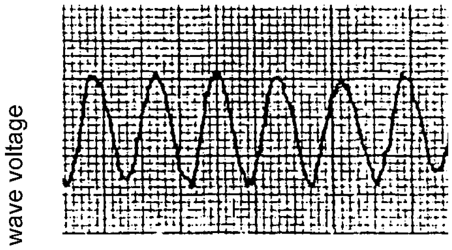
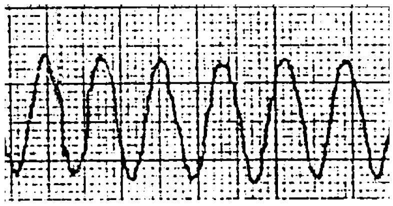


Fig. 4. Current–voltage characteristic of a L-MBE SEJ dc SQUID at 77 K, the critical current of shunted junction was 140 μA.

In summary, high temperature reliable SEJ dc SQUIDs were synthesized by using L-MBE superconducting thin films. The junctions showed an SNS type characteristic. The large value of A_{eff}/dD ratio indicated the L-MBE thin film was rather compact. This is the main reason why the devices could endure temperature cycles and long time storage without protection.



(a) No temperature cycles at 77 K



(b) After 42 times temperature cycles

Fig. 5. V–B characteristic curves of L-MBE SEJ dc SQUIDs for (a) without temperature cycle (b) after 42 times temperature cycles and 108 days storage (vertical scale: 3 μV/div; horizontal scale: 22.0 nT/div).

Acknowledgements

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