Highly reliable dc SQUIDs in temperature with laser-MBE YBa$_2$Cu$_3$O$_x$ 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$_2$Cu$_3$O$_x$ 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, $I_C(T) = (1 - T/T_C)^2$, 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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epitaxially grown and smooth YBa$_2$Cu$_3$O$_x$ 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$_2$Cu$_3$O$_x$ 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$_2$Cu$_3$O$_x$ 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$_2$Cu$_3$O$_x$ 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.

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$_2$Cu$_3$O$_x$ 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$_2$Cu$_3$O$_x$ 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

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![Fig. 1. RHEED monitoring oscillations when YBa$_2$Cu$_3$O$_x$ film was unit cell by unit cell grown on SrTiO$_3$ substrate, oscillations showed no damping sign over 1000 times.](image1)

![Fig. 2. Tail structure of resistance plotted as a function of temperature.](image2)
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 \( n = 2 \). 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 \( \Omega \), in accordance with the RSJ model, too. The SQUID critical current \( 2I_C \) is about 140 \( \mu A \), 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 \( \Delta V \) value is about 5 \( \mu V \), in reasonable accordance with the value of 4.2 \( \mu V \) 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 \( \Phi_0 \) 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.

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.
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References