Transport properties of $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ Bicrystal Grain Boundary Josephson Junctions and SQUIDs

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Abstract: Josephson junctions and SQUIDs on 36.8° SrTiO_3 bicrystal substrates were prepared from epitaxial $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ thin films with critical temperatures around 95K. The current-voltage characteristics are well described by the resistively and capacitively shunted junction model. $I_c R_n$ products of $50\mu\text{V}$ at 77K and 0.7mV at 4.2K have been reached. The $I_c(B)$ dependence is symmetric to $B = 0$ with an I_c suppression of 90% in the first minimum. Nevertheless it turns out, that the junctions are inhomogeneous on a μm scale. SQUID modulations observed at 78K indicate a flux-voltage transfer function of $2.7\mu\text{V}/\Phi_0$ at this temperature.

1 Introduction

The investigation of artificial grain boundaries led to a better understanding of the limiting factors of the critical current density in high temperature superconductors and a technology for preparing reproducible Josephson junctions (JJ) and superconducting quantum interference devices (SQUIDs) [1]. Most of the research has been done on $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ grain boundary junctions (GBJs) [2], although for achieving large $I_c R_n$ products and high operation temperatures other superconducting materials can be advantageous. Using epitaxial $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ films could yield a big improvement due to transition temperatures above 100K and large critical current densities [3, 4]. Due to the difficult preparation, only few data on $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ GBJs have been published so far [5].

2 Sample Preparation

The films were deposited on SrTiO_3 substrates by dc-sputtering from a single target. The target input power was 70W and the pressure during deposition was kept at 3mbar in pure oxygen

atmosphere. A precise control of the substrate temperature at nominal 835°C was crucial to get high quality $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ thin films. After the deposition the samples are kept in 6mbar pure oxygen at 835°C for 30min and at 820°C for 90min. Resistively measured transition temperatures T_c ($R \approx 0$) close to 100K are achieved on 1.2mm thick SrTiO_3 substrates (see fig.1). The mean field transition temperature reaches 110K.

In Fig. 2 it is shown that the films meet the requirement of high critical current densities. For fields smaller than 0.15T we find $j_c(T = 77\text{K}) \geq 10^6 \text{ A/cm}^2$ and even at 90K $j_c(B = 0) = 4 \cdot 10^5 \text{ A/cm}^2$. The suppression of j_c by the magnetic field is weaker than for $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ but stronger than for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$.

Figure 1:

Temperature dependence of the resistivity of an epitaxial $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ film. The insert shows the resistive transition, note that the inflection point is at 110K.

Figure 2:

Measured magnetic field dependence of the critical current density at 77K, 85K and 90K. At 77K j_c exceeds 10^6 A/cm^2 for $B \leq 0.15\text{T}$ and at 90K we find $j_c(B = 0) = 4 \cdot 10^5 \text{ A/cm}^2$.

The JJ and SQUIDS are prepared on 1.0mm thick commercially available SrTiO_3 bicrystals and reach T_c ($R \approx 0$) $\approx 95\text{K}$. The X-ray diffraction pattern in Bragg-Brentano geometry exhibits only $(0\ 0\ \ell)$ reflections of the $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ phase. The parallel alignment of the crystallographic a- and b- axis of $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ with the $(1\ 1\ 0)$ and $(\bar{1}\ 1\ 0)$ directions of the SrTiO_3 substrate is confirmed by additional Φ -scans. For transport measurements contacts were made by evaporating Au pads which were annealed for 30min at 500°C in 6mbar O_2 . The patterning was done by standard photolithography and wet chemical etching with diluted HNO_3 . Cu wires were attached to the contact pads with silver paint.

3 Current Voltage Characteristics

Figure 3:

Current voltage characteristics of a 10μm wide stripline across a 36.8° grain boundary in a thin epitaxial $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ film.

Figure 4:

Magnetic field dependence of a 10μm wide Josephson junction.

The current voltage characteristics (IVCs) of a 10μm wide single JJ patterned in a 1000Å thick film are shown in Fig. 3. The experimental data are well described by the resistively and capacitively shunted junction (RCSJ) model. At high temperatures the IVCs are rounded due to thermally activated phase slippage (TAPS) [6]. For $T \geq 50\text{K}$ the hysteresis parameter $\beta_c = 2\pi I_c R_n^2 C / \Phi_0$ of the JJ is negligible. The IVCs follow the relation $V = I_c R_n \sqrt{(I/I_c)^2 - 1}$ according to the RSJ model. Below 50K considerable deviations from the RSJ description occur since β_c is not negligible.

From the hysteresis in the IVC at 4.2K we find $\beta_c \approx 1.5$ and an effective junction capacitance of $15\mu\text{F}/\text{cm}^2$. We obtained an $I_c R_n$ product for the junction of $50\mu\text{V}$ at 77K and 0.7mV at 4.2K. The temperature independent normal state area resistivity ρ_n is about $4 \cdot 10^{-8}\Omega\text{cm}^2$ and the critical current density across the grain boundary reaches $J_c^{gb} = 1.7 \cdot 10^4 \text{A}/\text{cm}^2$ at 4.2K. Note that the critical current depends linear on temperature, indicating a superconductor-insulator-superconductor (SIS) type of junction [7]. Compared to 36.8° high quality $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ GBJs the $I_c R_n$ product of the junctions at 4.2K is 30% smaller, whereas the critical current density is about 10% higher [8]. Both values are significantly higher than the best results reported for $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ [9, 10]. Recently Ohbayashi et al. published an $I_c R_n$ value of 1mV for $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ on a 24° GBJ [5]. Considering that $I_c R_n$ values for 24° $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ GBJs are usually about 5 times higher than for 36.8° GBJs, higher $I_c R_n$ products seem possible for $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ films on a 24° GBJ.

4 Magnetic Field Dependence of the Critical Current

The current distribution inside the junction was investigated by measuring the magnetic field dependence of the critical current I_c (Fig. 4). At fixed temperature the IVCs at different magnetic fields were taken and I_c was determined by a $10\mu\text{V}$ criterion. The $I_c(B)$ pattern is symmetrical to $B = 0$ and no hysteresis could be detected for field sweeps in opposite directions.

The Josephson penetration depth λ_J was determined from: $\lambda_J \approx \phi_0 / (4\pi\mu_0\lambda_{ab}j_c)$, with the London penetration depth $\lambda_{ab}(0) = 1940\text{\AA}$ taken from [11]. The temperature dependence of the London penetration depth $\lambda_{ab}(T)$ was calculated with the two fluid approximation according to $\lambda_{ab}(T) = \lambda_{ab}(0)[1 - (T/T_c)^4]^{1/2}$.

At 45K the ratio of the geometrical width $w = 10\mu\text{m}$ and the Josephson penetration depth $\lambda_J = 2.6$ is smaller than 4 and the critical current is suppressed by more than 90% in the first minimum. At 4.2K I_c is only reduced by 70 % which is due to large junction effects since $W/\lambda_J \approx 5$. The $I_c(B)$ pattern deviates from the expected ideal Fraunhofer pattern because the third maximum is larger than the first and the second one. An array of three junctions with holes inbetween shows this kind of magnetic field dependence. Another deviation from the expected $I_c(B)$ dependence is the spacing of the minima and maxima which corresponds to a junction width of about $3\mu\text{m}$.

The modifications of the ideal Fraunhofer pattern are caused by inhomogenities of the current distribution in the junctions. From the linear $I_c(T)$ dependence mentioned above, we think that the junctions are of (SIS) type. In that case, small changes of the barrier thickness could yield quite large inhomogenities of the critical current across the grain boundary, since the critical current depends exponentially on the barrier thickness.

5 Temperature Dependence of the SQUID Modulations

A SQUID was made of two $10\mu\text{m}$ wide JJ with a $30 \times 40\mu\text{m}^2$ hole. The geometrical inductance $L_{geo} = 1.25\mu_0\sqrt{ab}$ of the SQUID was 55pH. An upper bound for the kinetic inductance was estimated from $L_{kin} = \frac{\ell m^*}{N_{we}^2} \leq 5\text{pH}$ [12], where we used the geometrical length $\ell = 40\mu\text{m}$ and width $w = 10\mu\text{m}$ of the striplines. The lower bound of the carrier concentration per unit area $N \approx 1.75 \cdot 10^{20}\text{m}^{-2}$ was calculated from Hall measurements on the same films and for the effective mass we took $m^* \approx 5m_e$.

In Fig. 5 the temperature dependence of the flux-voltage transfer function $dV/d\Phi$ is shown, together with a fit according to an expression given by Enpuku et al. [13]:

$$V_\Phi = dV/d\Phi = 4 \frac{I_c R_n}{\Phi_0(1 + \beta_L)} \left(1 - 3.57 \frac{\sqrt{k_B T L}}{\Phi_0} \right),$$

with the $I_c R_n$ product determined in a separate measurement. The qualitative agreement is obvious but there is still a quantitative difference, which we believe is due to noise from the measuring setup for the determination of the flux-voltage transfer function. Nevertheless, as

Figure 5:

Temperature dependence of the flux-voltage transfer function. The squares show the measured data which were taken at the optimal bias current. The circles represent the data calculated from [13], with I_c and R_n values determined in an independent measurement. The insert shows the flux-voltage transfer function at 78K.

shown in the insert of Fig. 5, we still find a modulation of $2.7\mu\text{V}/\Phi_0$ at 78K. The transfer function reaches its maximum of $65\mu\text{V}/\Phi_0$ at $T = 37\text{K}$.

6 Conclusion

The IVCs of $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_{10+\delta}$ grain boundary junctions are well described by the RCSJ model, where the hysteresis parameter β_c can be neglected for $T \geq 50\text{K}$ and $\beta_c \approx 1.5$ at 4.2K. High $I_c R_n$ products of 0.7mV at 4.2K and $50\mu\text{V}$ at 77K were achieved. Measuring the magnetic field dependence of the critical current showed inhomogeneities of the critical current density on a μm scale, probably due to changes of the insulating barrier thickness. A SQUID with a geometrical inductivity of 55pH has a flux-voltage transfer function of $2.7\mu\text{V}/\Phi_0$ at 77K and $65\mu\text{V}/\Phi_0$ at $T = 37\text{K}$. Increasing the transition temperature of the films and the homogeneity of the current distribution across the junctions will yield further improvements.

Acknowledgments

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