TEMPERATURE DEPENDENCE OF THE CRITICAL CURRENT DENSITY IN Y–Ba–Cu–O THIN FILMS

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We present a study of the temperature dependence of the critical current J_c of several dc magnetron sputtered thin Y–Ba–Cu–O films on single crystalline $SrTiO_3$, ZrO_2 and Al_2O_3 substrates. Near the critical temperature T_c it is found that $J_c \sim (1 - T/T_c)^n$ with $n = 3$ for the $SrTiO_3$ and ZrO_2 substrates, while $n = 1{\cdot}3$ for the Al_2O_3 substrate. The temperature dependence in our samples approximately agrees with standard theories for weak links or with the Ambegaokar-Baratoff equation.

Recently several authors have succeeded in producing high-T_c epitaxial thin films with critical current densities J_c ranging from 10^5 to 5×10^6 A/cm^2 at 77 K [1–3]. This is in contrast to the bulk ceramic samples which show critical current densities usually much lower than 2×10^4 A/cm^2 at 77 K. Also, a large decrease by two orders of magnitude of J_c at very low magnetic fields ($10^{-4} - 10^{-2}$ T) in bulk sintered samples was reported. These results have led to the assumption that the very low J_c is a result of Josephson junctions or weak links effect and that these junctions (weak links) are very probably located at the grain boundaries. The latest available data [2] on J_c of Ho–Ba–Cu–O thin film prepared by rf magnetron sputtering on MgO substrate also support this conclusion. Such films contain only few defects such as grain boundaries. If weak links are really located at the grain boundaries, then the decrease of J_c in Ho–Ba–Cu–O film at low magnetic fields will be smaller. Such behaviour was confirmed and even under the application of a magnetic field of 1·5 T the critical current density sustained at 10^6 A/cm^2 at 77·3 K [2]. The first direct demonstration that grain boundaries are indeed the cause of very low critical currents was reported in [4].

In view of these important developments we decided to study the temperature dependence of the transport critical current density J_c to examine whether high-J_c films deposited on different substrates follow the behaviour predicted by tunnelling calculations based on BCS theory [5].

Highly textured thin superconducting films of Y–Ba–Cu–O, *c*-axis oriented perpendicular to the substrate surface, have been prepared on single crystalline $SrTiO_3$, ZrO_2 and Al_2O_3 substrates by dc magnetron sputtering using a two-step procedure [6]. The films were deposited at substrate temperature between 720 and 860 °C. The deposition rate was 0·5 nm/s and the sputtering time was 30 minutes. In situ heat treatment at 400 °C in pure oxygen atmosphere followed and the films exhibited superconductivity with zero resistance transition temperatures T_c of 82·2, 87·8 and 84·3 for $SrTiO_3$, ZrO_2 and Al_2O_3, respectively. The value of the critical current was determined from the current-voltage characteristics of the films measured at different temperatures at which the generated voltage rose above 1 μV. Critical current densities were obtained by dividing the maximum zero-voltage current by the cros-sectional area of the thin film bridges patterned onto the films. The typical width of the bridges was approximately 50 μm and the length ranged from 500 to 1000 μm. The film composition was tested by Rutherford backscattering with 2 MeV $^4He^+$ ions and the film structure by x-ray diffraction in a similar manner as described in [3, 7]. Figure 1 shows the critical current density values for $SrTiO_3$, ZrO_2 and Al_2O_3 substrates as functions of temperature. High values of J_c are observed for films on $SrTiO_3$ and ZrO_2, e.g. at 77 K are 3×10^6 and 5×10^5 A/cm², respectively. However, the J_c value for the film on Al_2O_3 at 77 K is only 10^3 A/cm². These values are in very good agreement with the data reported in [3]. In Fig. 2 we show a logarithmic

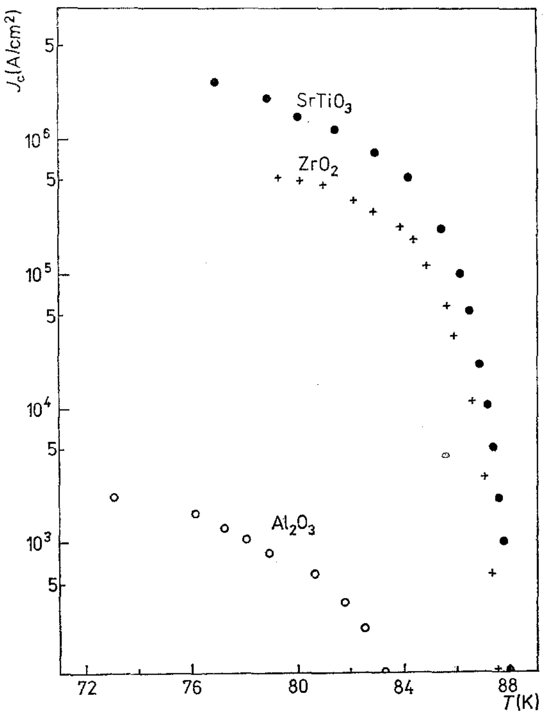

Fig. 1.

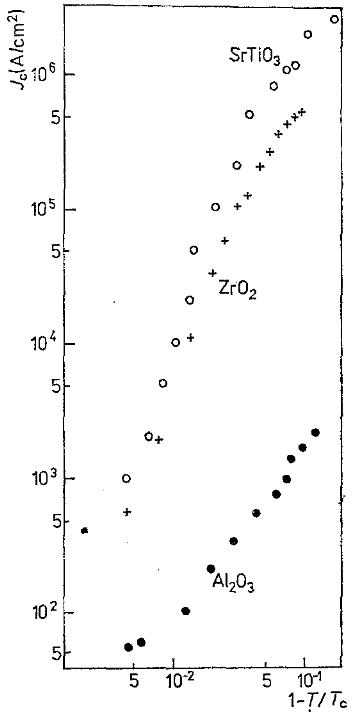

Fig. 2.

Fig. 1. The critical current density versus temperature for Y-Ba-Cu-O thin films on $SrTiO_3$ (○ ○ ○), ZrO_2 (+ + +) and Al_2O_3 (● ● ●) substrates.

Fig. 2. The critical current density versus $(1 - T/T_c)$ for Y-Ba-Cu-O thin films on $SrTiO_3$ (○ ○ ○), ZrO_2 (+ + +) and Al_2O_3 (● ● ●) substrates.

plot of J_c versus $(1 - T/T_c) = 1 - t$, t being the reduced temperature T/T_c. For the values of $(1 - t)$ from 0·005 to 0·05 the dependence is approximately of the form $(1 - t)^n$ with $n = 3$ for $SrTiO_3$ and ZrO_2 substrates, while for Al_2O_3 substrate and $(1 - t)$ from 0·01 to 0·1 $n = 1{\cdot}3$. Moriwaki et al. [8] employed thin films of La–-Sr–Cu–O with $T_c = 17$ K and transition width of 13 K and observed an approximately square power dependence of J_c for the values of $(1 - t)$ from 0·2 to 0·8. These authors concluded that the nature of Josephson junctions is different in high-T_c materials compared to the electronically similar Ba–Pb–Bi–O system, where a $n = 3/2$ power dependence close to the T_c was observed [9]. However, their films have very large transition width in comparison with T_c and for the values of $(1 - t)$ higher than 0·2 such interpretation is not justified, because the 3/2 power dependence of J_c is predicted at temperatures only near T_c. Ogale et al, [10] performed critical current measurements on Y–Ba–Cu–O thin films deposited on $SrTiO_3$ substrates. For the values of $(1 - t)$ between 0·02 and 0·1 they observed the 3/2 power dependence, while at lower temperatures with $(1 - t)$ values higher than 0·3 the dependence of J_c changes to approximately $(1 - t)^2$. Mogro-Campero et al. [11] reported the critical current density on thin films of Y–Ba–Cu–O with three types of *c*-axis alignement using oxidized silicon and $SrTiO_3$ substrates. In spite of the large differences in absolute values of J_c of these films $(1 : 10^2 : 10^4)$, a similar temperature dependence of J_c was observed. At low temperatures a linear temperature dependence was established, which these authors interpreted using a flux creep behaviour. At temperatures close to the T_c (up to $1 - t = 0{\cdot}01$) they observed the power law exponent n between 1·2 and 1·5. The temperature dependence of the critical current in bulk samples of Y–Ba–Cu–O and Dy–Ba–Cu–O [12] show that the linear temperature dependence of the critical current is consistent with a percolative network of grains coupled to each other through Josephson junctions. Mannhart et al. [13] provided evidence that only the intragranular (basal plane) critical current is limited by flux creep and the intergranular transport properties display a usual Josephson weak-link behaviour. Thus, it seems probable that the nature of the linear temperature dependence reported in [11] has a similar origin as in bulk samples. Allen et al. [14] presented results on the temperature and field dependence of J_c for two Y–Ba–Cu–O films deposited on $SrTiO_3$ substrates. For the values of $(1 - t)$ in the region from 0·03 to 0·3 (approximately above 50 K) a very good fit to the data with $n = 3{\cdot}3$ was obtained. As these authors stated in their paper, they have no explanation of why the measured power exponent n is so high. This is the only work to our knowledge, besides ours, where such a high value of n was observed. De Vries et al. [15] reported the critical current measurements as a function of temperature of several triode-sputtered Y–Ba–Cu–O films on $SrTiO_3$ substrates. For the values of $(1 - t)$ in the region from 0·002 to 0·01 they obtained $n = 1{\cdot}8$. From approximately 0·01 to 0·1 these authors find $n = 2{\cdot}5$. The results below about $0{\cdot}6T_c$ can be well analysed in terms of the de Gennes proximity junction model [16]. The existence of different measured values of the exponent n, usually from 1·5 to 2, can be explained using the temperature dependence of J_c in SNINS junction near T_c [17]. The tunnelling current depends strongly on temperature and on the position of the dielectric layer (I) relative to the normal metal layer (N). For a symmetric SNINS junction the exponent $n = 2$ is similar to that for a usual SNS junction. When a dielectric layer is at an asymmetric position relative to the normal metal layers and the tunnelling transparency is small, the exponent n decreases to 1·5. However, no microscopic evidence for NIN structure at the grain boundary was found up to now. In Fig. 3 the normalized critical-current densities are plotted as function of the reduced temperature for our three films. Solid lines AB 1 and AB 2 are the dependences

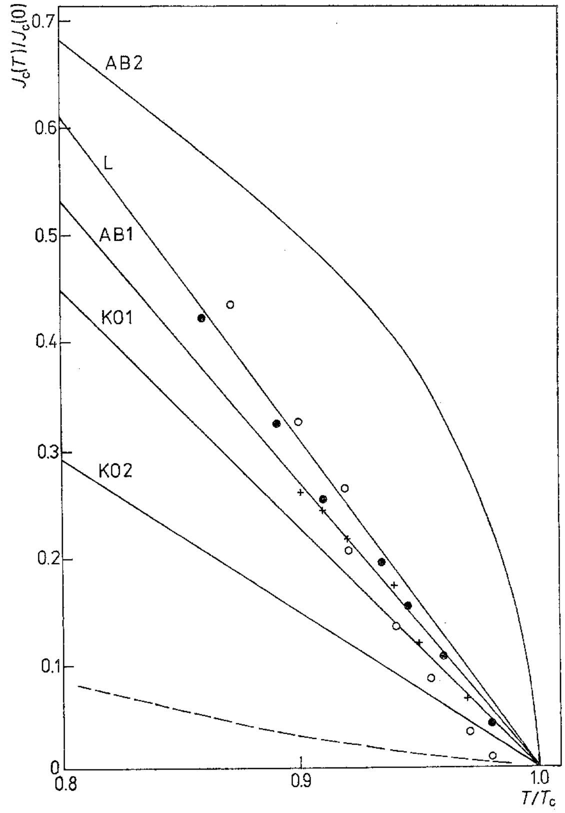

Fig. 3. Normalized critical current density versus reduced temperature T/T_c. KO 1 and KO 2 are the dependences predicted by Kulik and Omel'yanchuk for weak links in the dirty and in the clean limits, respectively (Ref. [18]). The lines labelled AB 1, AB 2 and L correspond to the theories of Ambegaokar-Baratoff (Ref. [5]) and Likharev (Ref. [19]) respectively. The dashed line roughly represents the data obtained by Ogale et al. (Ref. [10]). $J_c(0)$ is the extrapolated value of critical current at $T = 0$ K and equals approximately 6×10^6 A/cm^2, 2×10^6 A/cm^2 and 5×10^3 A/cm^2 for our Y-Ba-Cu-O films on $SrTiO_3$ (○ ○ ○), ZrO_2 (+ + +) and Al_2O_3 (● ● ●), respectively.

predicted by Ambegaokar and Baratoff [5] and correspond to $\Delta_1(0)/\Delta_2(0) = 0{\cdot}5$ and $\Delta_1(0) = \Delta_2(0)$, respectively. The dashed line approximately represents results obtained by Ogale et al. [10]. Other models also predict $J_c(T)$ for weak links. KO 1 and KO 2 are the dependences predicted by Kulik and Omel'yanchuk for weak links in the dirty and in the clean limits, respectively [18]. The temperature dependence KO 1 and KO 2 have been calculated for short weak links with $l/\zeta \to 0$, where l is the length of the weak link and ζ is the coherence length. Since the thickness of the grain boundary, l and ζ are comparable in high-T_c thin films, it seems that such an approximation ($l/\zeta \to 0$) is unrealistic. In Fig. 3 we show also the temperature dependence calculated by Likharev (the curve labelled L) for $l/\zeta_N(T_c) = 2$, where $\zeta_N(T_c)$ is the coherence length of the normal layer at T_c. This behaviour is consistent with the data reported in [13]. Fiory et al. [20] determined from kinetic inductance the $a-b$ plane penetration depth $\lambda(T)$ of c-axis oriented epitaxial Y–Ba–Cu–O films grown on (100) $SrTiO_3$. For temperatures not too close to T_c the weak-coupling mean-field BCS theory with $\Delta(0) = 1{\cdot}76kT_c$ and $\lambda(0) = 0{\cdot}15\ \mu m$ describes the temperature dependence of $\lambda(T)$ for the thinnest films (~ 50 nm). The value of $\lambda(0) = 0{\cdot}15\ \mu m$ is very close to the microscopic values $0{\cdot}14\ \mu m$ determined from muon-spin resonance. They observed also enhanced $\lambda(0)$ values in thicker films ($\lambda(0) = 0{\cdot}21\ \mu m$ for the 200 nm film) and successfully explained such a behaviour by Josephson coupling between grains in the film using Ambegaokar and Baratoff expression for the critical current.

In conclusion, we have studied the temperature dependence of the critical current density J_c of epitaxial Y–Ba–Cu–O films on three different substrates close to T_c. The functional form of the temperature dependence of J_c is similar for the $SrTiO_3$ and ZrO_2 substrates with the power law exponent $n = 3$ and for the Al_2O_3 substrate with $n = 1{\cdot}3$. The observed temperature dependence of J_c is approximately consistent with either a SNS type weak link behaviour or with the Ambegaokar-Baratoff equation.

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