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Critical current in polycrystalline Bi-Ca-Sr-Cu-O films

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Thin films of Bi-Ca-Sr-Cu-O were prepared by rf magnetron sputtering a sintered $Bi_2CaSr_2Cu_2O_{8-y}$ target. The films were deposited on a MgO(100) substrate. The data reported here have a T_c (50%) of about 86 K and a transition width $\Delta T_c = 90-81$ K (90%–10%). Temperature-dependent *I-V* characteristics examined over wide ranges reveal that the critical current is proportional to $(1-T/T_c)^{3/2}$ near T_c. The implication of the $\frac{3}{2}$ power dependence will be discussed.

Experiments on new oxide superconductors have excited an enormous growth of research activity in this field. Recently Maeda *et al.*[1] and several other workers[2,3] have reported new high-T_c superconducting oxides in the Bi-Ca-Sr-Cu-O system. In addition to the study of bulk materials, considerable activity[4-6] is focusing on exploring ways of depositing high-quality films of these new oxides. These studies show that most of the films are polycrystalline in nature; therefore it is of interest to understand the transport properties of the polycrystalline films.

The superconducting critical current, I_c, of polycrystalline films is mainly controlled by the nonsuperconducting materials existing between the grains. For example, if the grains are separated by insulating and normal material, then the film may form *SNIS* (S=superconductor, N=normal material, I=insulator) junctions. The model of the proximity effect[7-9] predicts $I_c \sim (1-T/T_c)^{3/2}$ for T near T_c. If the grains are separated by insulating materials, the film forms *SIS* junctions which were described in a Josephson tunneling model by Ambegaokar and Baratoff.[10] In that model the temperature of I_c near T_c is $I_c \sim (1-T/T_c)$.

The models mentioned above show different features in different temperature ranges. It would be interesting to see whether there is a correlation between the films and the possible type of junctions. In this work we report the temperature dependence of I_c for Bi-Ca-Sr-Cu-O films in different temperature ranges in order to study the granular superconductivity of the films.

Thin films of the Bi-Ca-Sr-Cu-O system were deposited by rf magnetron sputtering a sintered (2:1:2:2) target followed by a post-deposition anneal. The (2:1:2:2) target was prepared by initially mixing Ba_2O_3, $SrCO_3$, $CaCO_3$, and CuO thoroughly. The mixture was then annealed in air at 870 °C for 12 h. The mixture was reground and sintered in air at 870 °C for 12 h. The final mixture was then pressed into a 5-cm circular target and sintered at 870 °C for 1 h. The target prepared this way had T_c=83 K (50% resistive transition). The target was then loaded onto a 5 cm rf magnetron sputtering source (US Gun II). MgO(100) substrates were mounted on a vertical sample holder which rotated at constant speed via a rotatable feedthrough. A vertical substrate holder in this sputtering system prevented fine particles from contaminating samples or targets. The substrate-to-target distance was 4 cm. The sputtering chamber was evacuated to a base pressure of 4×10^{-7} torr range before introducing pure $Ar:O_2$ (70:30) gas into the chamber. After presputtering the target for 30 min, the film was deposited on substrates. The sputtering power was 125 W and the sputtering pressure was 50 mtorr. The final substrate temperature was about 100 °C.

The electrical resistivity was measured using a conventional four-probe method. The *I-V* characteristic was measured by passing a current (Keithley model 220) to the sample and monitoring the voltage by a nanovoltmeter (Keithley 181). The geometry of the sample was a stripe shape with a width of about 2 mm as shown in the inset of Fig. 1. The voltage probe was 0.3 cm apart and the thickness of the film was about 1 μm as determined from a Dektak 3030. The temperature of the sample was controlled by a temperature controller (Model 130, Linear Research, Inc.) which is stable to within 0.05 K. We made contact to the film with silver paint extending across the superconducting region. The data were collected automatically by an IBM PC/XT via an IEEE 488 interface. In the I_c measurement the data-acquisition system was programmed to monitor simultaneously the current and temperature. Heating effects were negligible in the I_c measurement in the entire temperature range as long as the current was biased below the critical one I_c. However, at low temperature ($T < 20$ K) where the biased current is large, the heating effects were found after voltage developed across the sample. The temperature uncertainty was about 1 K. The value of the critical current was chosen to be the one at which the generated voltage rose to 1 μV.

We have taken x-ray data for most samples and they are polycrystalline in nature with the c axis perpendicular to the surface of the substrate. The data show predominantly (2:1:2:2) structures.

Figure 1 shows the temperature dependence of the normalized resistance for sample B. The sample was annealed in air at 880 °C for 30 min and slowly cooled to

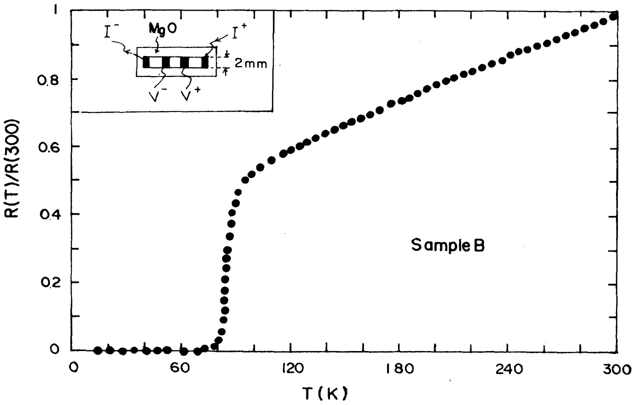

FIG. 1. Temperature dependence of normalized resistivity with T_c (50%) at 86 K, and transition width $\Delta T_c = 90-81$ K (90%–10%). Room-temperature resistivity of this sample is about 0.8 mΩ cm.

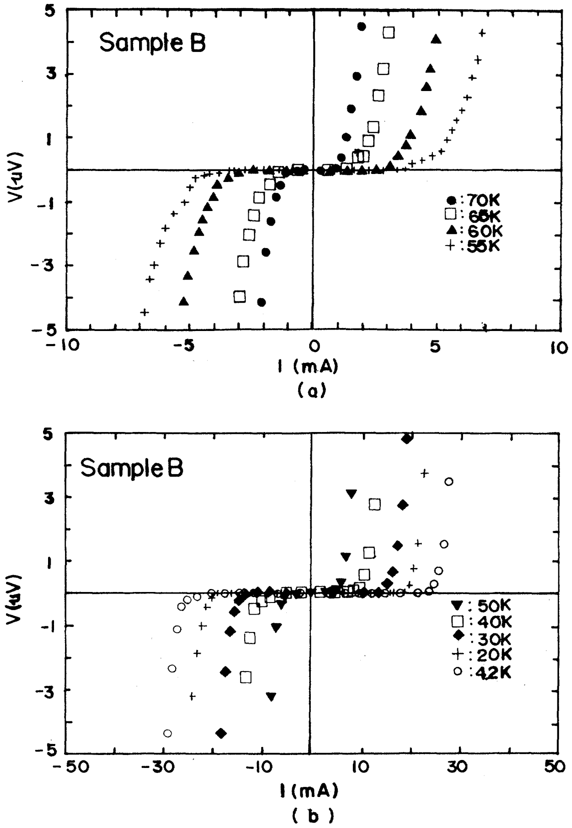

FIG. 2. I-V characteristics at various temperatures for sample B.

room temperature in about 8 h. The room-temperature resistivity was about 0.8 mΩ cm. The temperature dependence of the resistance is essentially linear at high temperature. The superconductive transition temperature T_c (50%) is 86 K (resistive) and the transition width is ΔT_c (90%–10%) $=90-81$ K. The resistance decrease of about 5–6 orders of magnitude was taken as the criterion to define T_{cf} which is about 76 K for the sample.

I-V characteristics of thin oxide films as a function of temperature have been studied systematically by England *et al.*[11] They found a coherence transition in which isolated grains coupled to form a bulk superconductor. The transition manifests itself in the scaling behavior $V \sim (I-I_c)^x$, where I_c is the critical current, and x is closely related to the dimensionality of the granular superconductor and the order-parameter correlation function. In Fig. 2 typical I-V curves are shown for sample B at different temperatures. At $T > T_c$, where the superconducting grains are not coupled, the I-V characteristic is Ohmic. At low temperature, the I-V characteristics follow $V \sim (I-I_c)^x$ and the temperature dependence of the critical exponent, x, was found to vary from $x=1$ to $x=2.0 \pm 0.1$ ($T=74$ K) as one decreases the temperature from $T > T_c$ ($T=90$ K) to lower temperature as shown in Fig. 3. The observation is similar to that reported by England *et al.* and that in Ref. 12 suggesting that there is a coupling between grains in granular superconducting films.

The proximity tunneling model (*SNIS*) and the Josephson tunneling model (*SIS*) assume as BCS-like state for the superconductor and it is not clear whether these models apply to the new oxide films or not. However, to make progress, it is worthwhile to compare our results with the prediction of the models mentioned above. In Fig. 4 the temperature dependence of the critical current is shown for sample B. It can be seen clearly that the nature of I_c is different over different ranges of T. The temperature dependence of I_c at low temperature tends to saturate while for T near T_c the temperature dependence is of the form $I_c = A(1-T/T_c)^{3/2}$, where A is a constant. The $\frac{3}{2}$ power law is demonstrated in the $I_c^{2/3}$ vs T plot as shown in the inset of Fig. 4. The proximity tunneling model based on the de Gennes' theory[7] is perhaps applicable for the temperature dependence of I_c. This tunneling model and its applications have been discussed in Refs. 8 and 9 in the context of their experimental studies of the proximity effect in the Pb/Al/AlO$_x$/Pb system and would predict a $\frac{3}{2}$ power dependence. We found that the temperature

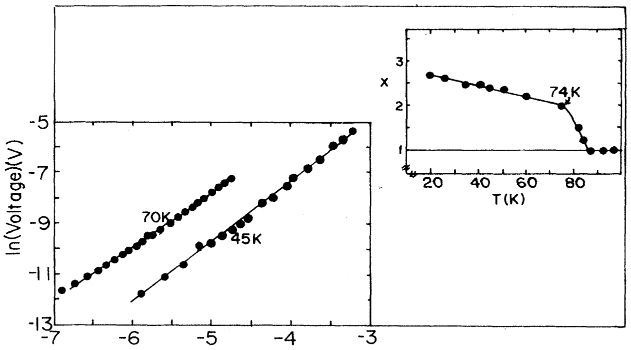

FIG. 3. Temperature dependence of the exponent, x, in $V \sim (I-I_c)^x$, where x varies from 1.0 to about 2.0 ± 0.1 (74 K) as one lowers the temperature, suggests that there is a coupling between grains as one lowers the temperature. Also shown is $\ln V$ vs $\ln(I-I_c)$ at 70 and 45 K.

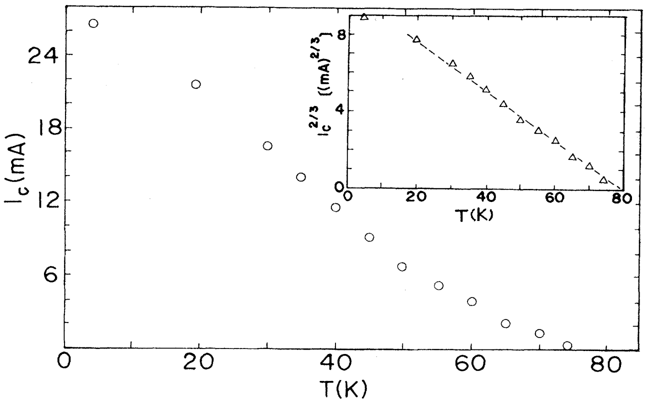

FIG. 4. I_c vs T for sample B. $I_c^{2/3}$ as a function of T is shown in the inset.

dependence of I_c is proportional to $(1-T/T_c)^{3/2}$ at T near T_c in Bi-Ca-Sr-Cu-O films. So the proximity tunneling model could work for the $\frac{3}{2}$ power dependence. We note that the straight line of $I_c^{2/3}$ vs T appears to intercept around 80 K. This is about midway between T_{cf} and the midpoint of the transition. If the proximity tunneling model holds in the granular superconducting films, the intercept will give us the extrapolated transition temperature of the superconducting bank, i.e., the grains. The $\frac{3}{2}$ power dependence reported here is different from that of other tunneling structures such as *SNS* or *SIS* junctions. For *SNS* junctions,[8] the temperature dependence of I_c has been reported in Refs. 8 and 9, and I_c at T near T_c is $I_c \sim (1-T/T_c)^2$, while for *SIS* Josephson junctions, the theoretical prediction of I_c at T near T_c is $I_c \sim (1-T/T_c)$. Another cause for the $\frac{3}{2}$ power law is possibly the effects of inhomogeneity. For example, suppose the intrinsic dependence of I_c corresponds to a square power, as reported by Setsune *et al.*,[13] but only a fraction of the material was superconducting near the nominal value of T_c. Therefore, the sample might have several conducting channels with bridges or other structures. Then some upward feature of the type seen might arise. This is possible in the films studied here and cannot be completely ruled out

With regard to studies of critical current in granular superconducting films, de Vries *et al.*[14] have investigated the critical current as a function of temperature in thin $YBa_2Cu_3O_{7-y}$. Near the critical temperature T_c it is found that $I_c \sim (1-T/T_c)^\tau$ with τ between 1.5 and 2 depending on the exact value of T_c chosen. Yuan *et al.*[15] have done a study of the critical current in Y-Ba-Cu-O films. They obtained an exponent for the temperature dependence of I_c that was 1.5 close to T_c and 2 farther away. Ogale *et al.*[16] have observed a $\frac{3}{2}$ power dependence in I_c for T near T_c in polycrystalline films of $YBa_2Cu_3O_{7-y}$ and attribute the dependence to a proximity tunneling model. Setsune *et al.*[13] have reported electrical measurements in high-T_c Bi-Ca-Sr-Cu-O thin films. They obtained $I_c \sim (T-T_c)^2$ and attributed the dependence to layered structures in the films. Our present results show a $\frac{3}{2}$ power dependence in contrast to the square law. Perhaps the intrinsic temperature dependence of I_c is a square power law. However, other factors such as inhomogeneity in the films at T near T_c change the features of the dependence. Perhaps that is why different values in the exponent, which varies between 1.5 and 2.0, have been reported in the granular superconducting oxide films at T near T_c.

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