

## Temperature Dependence of Critical Current Density in YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub> Thin Films

Q. Xiong, W. Y. Guan\*, P. H. Hor, and C. W. Chu

*Texas Center for Superconductivity, University of Houston, Houston, Texas 772045932, U.S.A.*

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Well-oriented thin films of YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub> (Y123) with a transition temperature ( $T_c$ ) = 90 K and a critical current density ( $J_c$ ) > 10<sup>6</sup> A/cm<sup>2</sup> have been prepared by magnetron sputtering and laser ablation on SrTiO<sub>3</sub> and LaAlO<sub>3</sub> substrates. The temperature-dependence (T-dependence) of  $J_c$  has been obtained from M-H loops by the ac loss method, which greatly reduces the error due to the trapped magnetic field effect. At higher temperatures, the  $J_c$  vs  $T$  curves were found to have the form  $J_c \propto [1 - (T/T_c)]^2$  across a very broad temperature range. We have shown that ac loss measurement is a preferred reliable method to extract the T-dependence of  $J_c$  of thin films. Our results also demonstrate that this T-dependence of  $J_c$  does not depend on preparation technique, the shape of the sample and the substrate. It seems that the main dissipation mechanism of the best thin films is very similar to that of the weak-link dominated thin films.

The critical current density ( $J_c$ ) in thin-film, oxide, high-temperature superconductors (HTS's) is of fundamental scientific and technological interest. Following Tinkham,<sup>1</sup> when  $J_c$  is limited by flux creep,  $J_c(B, t)$ , where  $B$  is the magnetic field and  $t = (T/T_c) \ll 1$ , is given by

$$J_c(B, t) = J_c(B, 0) [1 - \alpha(B)t - \beta t^2] \quad (1)$$

where  $\alpha$  is a function of  $B$  and  $\beta$  is constant. In the theoretical models, the granular superconductors are considered as an array of identical Josephson-coupled superconducting grains arranged on a cubic lattice.<sup>2-5</sup> For SIS junctions, Ambegaoka and Baratoff<sup>2</sup> predict the T-dependence of  $J_c$  close to  $T_c$  as

$$J_c(t) \propto (1 - t) \quad (2)$$

J. Clem<sup>3</sup> showed that when the coupling energy between the grains is much higher than the condensation energy of a grain,  $J_c(T)$  is given by

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<sup>1</sup> Refereed version of the invited paper presented at the Annual Meeting of the Physical Society of R.O.C., January 24-25, 1992.

$$J_c(t) \propto (1 - t)^{3/2} \quad (3)$$

In the case of SNS junctions, de Gennes<sup>4</sup> used a spatially-dependent pair potential to describe boundary effects in superconductors. In a simplified form of this model, J. Clarke<sup>5</sup> gave the following expression for  $J_c(T)$  of an SNS junction

$$J_c(t) \propto (1 - t)^2 \exp\left[\frac{-a\sqrt{t}}{\xi_N(T_c)}\right] \quad (4)$$

where  $a$  is the thickness of the normal metal barrier and  $\xi_N(T_c)$  is the penetration depth of the electron pairs into the metal. Close to  $T_c$ , J. Clarke<sup>5</sup> found that

$$J_c(T) \propto (1 - t)^2 \quad (5)$$

and at low  $T$ , the exponential term dominates

$$J_c(t) \propto \exp[-b\sqrt{t}] \quad (6)$$

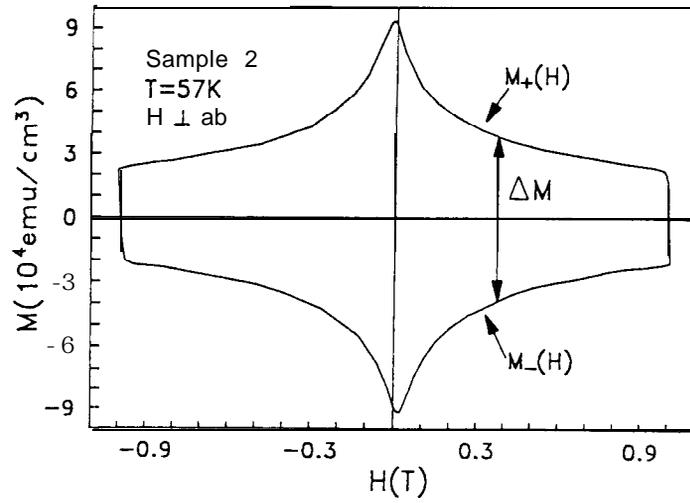
where  $b$  is a constant. As seen from Eqs. (1)-(6), the  $T$ -behavior of  $J_c$  is an important source of information about the quality and the mechanism limiting the  $J_c$ .

In this paper we report detailed  $J_c(T)$  measurements using a variable-temperature vibrating sample magnetometer at moderate fields (up to 1 T) on high quality  $c$ -axis oriented Y123 films which were prepared by dc-magnetron sputtering on a SrTiO<sub>3</sub> substrate (Sample 1) and laser deposition on a LaAlO<sub>3</sub> substrate (Samples 2 and 3). The dimensions of the samples were 10 mm x 5.7 mm x 220 nm (Sample 1) and 9.45 mm x 5.7 mm x 220 nm (Sample 2). To fabricate Sample 3, 220 nm-thick films were cut from Sample 2 and were patterned into the form of a ring (inner radius = 2.4 mm, outer radius = 2.5 mm) using an ion beam etching technique.  $T_c$  was measured with the standard ac four-probe method. The  $T_{c0}$  was 90 K for all samples. The field was applied perpendicular to the surface of the films (e.g. parallel to the  $c$ -axis of the samples). The temperature of the sample was measured at  $H = 0$  with a calibrated Platinum thermometer. A very low frequency alternating cycle was simulated by sweeping the field at a constant rate from  $+H_{\max}$  to  $-H_{\max}$  and back. Such loops were drawn for the same value of  $H_{\max}$  at different  $\nu$ 's.

Figure 1 shows a typical magnetization curve  $M(H)$  for Sample 2 with sweep amplitude  $H_{\max}$  of 1 T at 57 K. The ac-loss method was used to obtain the  $T$ -dependence of  $J_c$  with very small error from the trapped magnetic field effect. The hysteresis loss for the frequency  $\nu$  per cycle<sup>6</sup> was

$$W = - \int_0^{\frac{1}{\nu}} dt \oint \frac{c}{4\pi} \vec{E} \times \vec{H} \cdot d\vec{s} \quad (7)$$

from Eq. (7), one can get<sup>6</sup>

FIG. 1. Magnetization curve of Sample 2 ( $T = 57$  K;  $H \perp a,b$ -plane)

$$W = \int_0^{\frac{1}{v}} dt \int \int \int_v dr \vec{E}(\vec{r}, t) \cdot \vec{J}_c(\vec{r}, t) \quad (8)$$

and

$$W = \frac{V}{4\pi} \oint dH(-4\pi M) \quad (9)$$

where  $V$  is the volume of the sample,  $1/4\pi \oint dH(-4\pi M)$  is the area of the hysteresis loop in a magnetization experiment, and  $t$  is time. There are many models for the  $T$ - and  $H$ -dependence of  $J_c$ , including

$$J_c = \mathbf{J}(T) \quad (7) \quad (10)$$

$$J_c = J_c(T)/(1 + H_i/H_o) \quad (8) \quad (11)$$

$$J_c = J_c(T) (1 - H_i/H_o) \quad (9) \quad (12)$$

$$J_c = J_c(T) \cdot (H_i/H_o)^{-n}, n = 0.25 \text{ to } 1 \quad (10,11) \quad (13)$$

$$J_c = J_c(T) [\exp(-H_i/H_o)] \quad (12) \quad (14)$$

where  $H_i$  is the local magnetic field and  $H_o$  is a material parameter with the dimension of a magnetic field. In this work, we assume

$$J_c = J_c(T) f(\vec{B}) \quad (15)$$

where  $f(B)$  is any function of  $\vec{B}$ . Combining Eqs. (15) and (8), we get

$$W = J_c(T) \int_0^1 dt \int \int \int_v dr E(\vec{r}, t) f(\vec{B}(\vec{r}, t)) \quad (16)$$

for  $H_{\max} \gg H_p$  (about 100 Gauss in these thin films), where  $H_p$  is the field of full penetration in the critical model. When the external field  $H$  changes from  $H_{\max}$  to  $-H_{\max}$ ,  $B(r)$  will vary approximately from  $H_{\max}$  to  $-H_{\max}$  as well. We also know that

$$\nabla \times \vec{E}(r, t) = \left(-\frac{1}{c}\right) \frac{\partial \vec{B}(r, t)}{\partial t}$$

Since  $\partial B/\partial t \approx \partial H/\partial t$ ,  $E(r, t)$  is approximately a function of the external field,  $H$ . So we get

$$W \approx J_c(T) F(H_{\max}, v) \quad (17)$$

Equation (17) implies that if  $H_{\max}$  and  $v$  are kept at constant values,  $F(H_{\max}, v)$  should not change with  $T$ . So, from Eqs. (17) and (9), we conclude that the  $T$ -dependence of  $W$  determines the  $T$ -dependence of  $J_c$ . Fig. 2 is the plot of reduced hysteresis losses  $W/W(25K)$  vs  $(1-t)$ , where  $t = T/T_c$ , in log-log scale. The broken line in Figs. 2 and 3, given by  $[(1-t)^2/(1-25/T_c)^2]$  shows that  $J_c \sim (1-t)^2$  for all samples we measured across a very broad temperature range.

According to Bean's model, the relationship between  $J_c$  and AM is given by the formula<sup>13</sup>

$$J_c = 10 [M_+(H) - M_-(H)] / A, [1 - (A_1/3A_2)] V \quad (18)$$

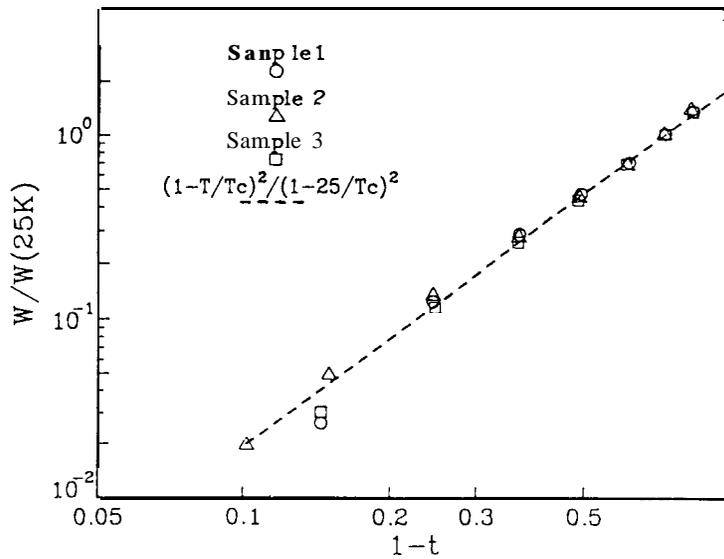


FIG. 2. The reduced ac losses,  $W(T)/W(25K)$ , vs  $(1-t)$  for Samples 1, 2, and 3 in log-log scale

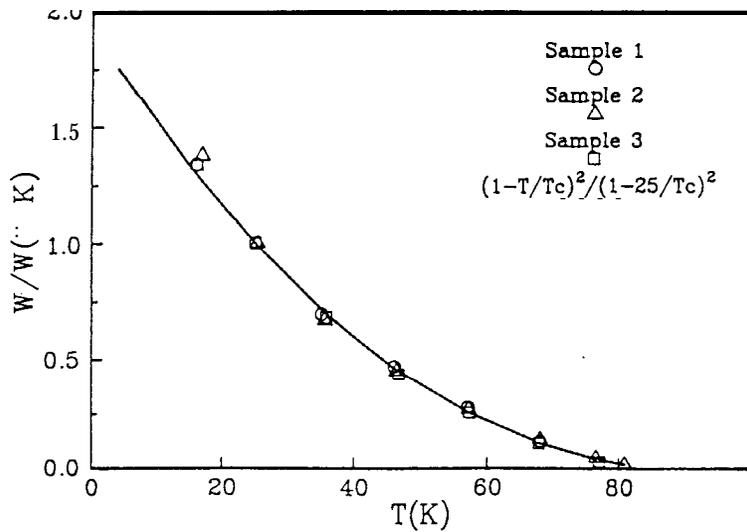


FIG. 3. The reduced ac losses,  $W(T)/W(25K)$ , vs  $t$  for Samples 1, 2, and 3.

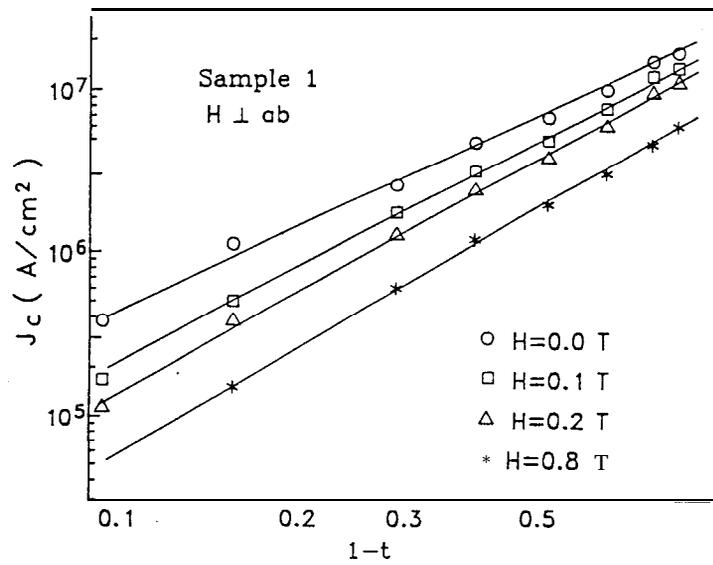
where  $A_1$  and  $A_2$  are the short and long sides of the sample, respectively, in cm;  $M_+(H)$  and  $M_-(H)$  are the magnetization of the decreasing and increasing field branches, respectively, in emu (see Fig. 1); and  $V$  is the volume of the thin film in  $\text{cm}^3$ . In this calculation, we neglected the anisotropic effect of  $J_c$  in the a,b-plane of the crystal. We also assumed that  $J_c$  is independent of  $B$ .

For Sample 3, the ring, Bean's model gives

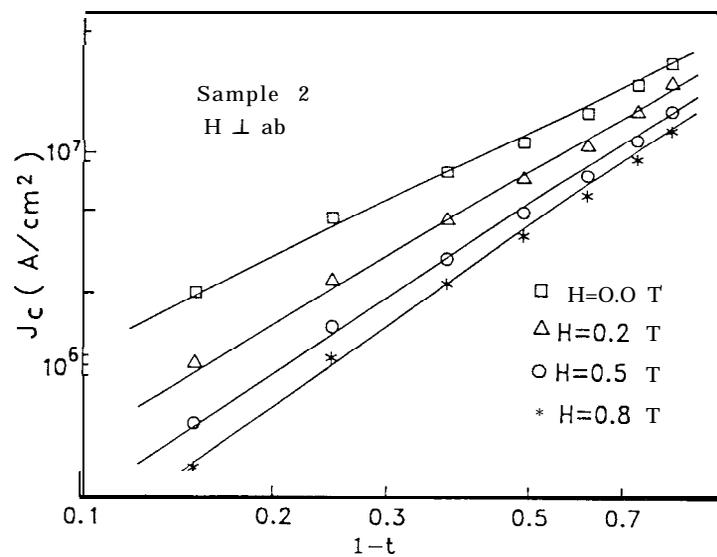
$$J_c = 30[M_+(H) - M_-(H)]/2\pi d(R_2^3 - R_1^3) \quad (19)$$

where  $d$  is the thickness of the ring and  $R_1$  and  $R_2$  are the inner and outer radii of the ring, respectively.

In Figs. 4-6, the plots in log-log scale of  $J_c$  vs  $(1-t)$  are shown. The data was deduced from  $AM(H)$ , using Eqs. (18) and (19) with different fields for Samples 1, 2, and 3. As  $H$  varies from 0.0 T to 0.08 T,  $n$  varies from 1.5 to 2.2 where  $n$  is given by  $J_c(T) \propto (1-t)^n$ . The plots of  $n$  vs  $H$  appear in Fig. 7. We can see that  $n$  changes very rapidly as it approaches  $H = 0$ . When  $H = 0$ ,  $n = 1.71$ , 1.65, and 1.57 in Samples 1, 2, and 3, respectively, where  $H \gg H_p$  and  $n \approx 2$  for all samples. According to Bean's model, one always has a field gradient inside the sample in the critical state. Using Eqs. (18) and (19),  $J_c$  is calculated over a range of  $H$ . Fig. 8 shows  $J_c$  vs  $H$  for Samples 2 and 3 at  $T = 57$  K. In our experiment, Samples 2, a rectangle, and 3, a ring, were fabricated from the same sample. Therefore, it is expected that  $J_c$  should be the same in Samples 2 and 3. However, Fig. 8 shows that the  $J_c$  for the two samples is quite different near

FIG. 4. T-dependence of  $J_c$  for Sample 1

$H = 0$ . When  $H$  is higher, both  $J_c$ 's become the same value, which is predicted by Bean's model. This is because the trapped field effect becomes important at low  $H$  field. Samples with different shapes have different  $B$  fields trapped inside. We also know that trapped  $B$  is proportional to  $J_c$  in thin films. Experimental values also show that, as  $T$  changes from 4.2 to 77 K,

FIG. 5. T-dependence of  $J_c$  for Sample 2

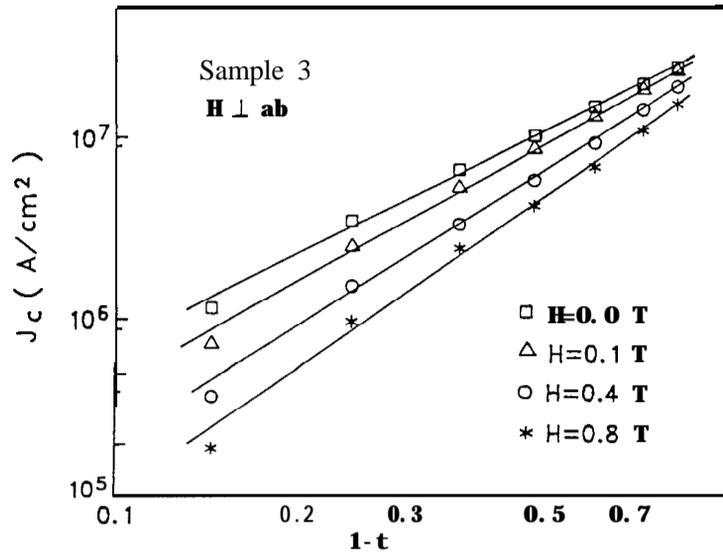


FIG. 6. T-dependence of  $J_c$  for Sample 3.

$J_c$  changes by one order of magnitude. So  $\bar{B}$  is not the same at different  $J_c$ 's near  $H = 0$ . This implies that when  $H = 0$  for different  $T$ 's,  $\bar{B}$  changes. Because of this,  $J_c$  calculated by Bean's model at different  $T$ 's had different  $\bar{B}$ 's.  $\bar{B}$  depends on the size and shape of the sample, as well as  $T$  at low  $H$  field. Fig. 1 shows that AM changes very rapidly near  $H = 0$ . This means that

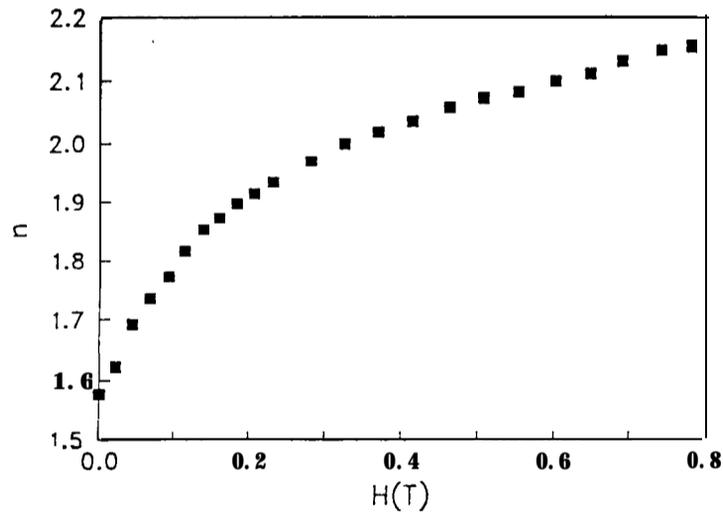


FIG. 7.  $n$  vs  $H$  for Sample 3

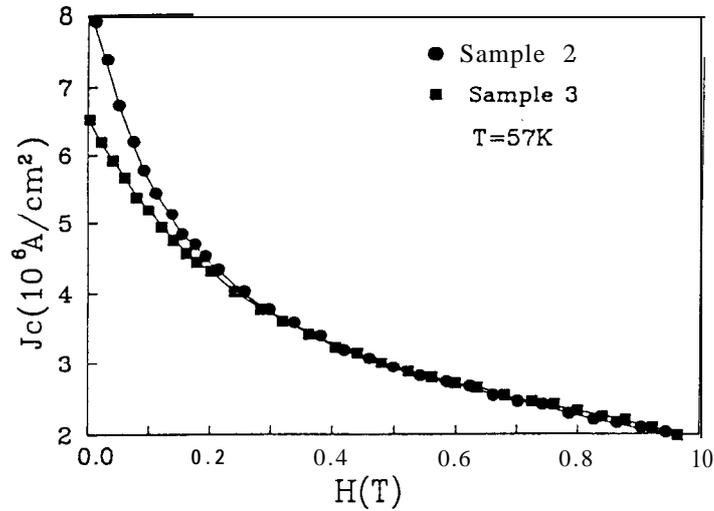


FIG. 8.  $J_c$  vs  $H$  at 57 K for Samples 2 and 3.

small changes in  $\mathbf{H}$  will cause large changes in  $J_c$  near  $\mathbf{H} = \mathbf{0}$ . If  $J_c(T, B) = J_c(T) \cdot f(B)$ , the  $T$ -dependence of  $J_c$  calculated by keeping  $\mathbf{H}$  constant, does not give the actual  $T$ -dependence of  $J_c(T)$ . The  $T$ -dependence will be affected by  $f(B)$ , since  $\bar{B}$  changes rapidly with  $\mathbf{T}$  near  $\mathbf{H} = \mathbf{0}$ . This effect may explain why a sample has different  $J_c$ 's when it has different shapes and why  $J_c \propto (1-t)^n$  ( $n = 1.5$  to  $2.2$ ) has been obtained in this work when a trapped  $B$  field was not considered. We already know that Bean's model is good for  $\mathbf{H} \gg \mathbf{H}_p$ . Our experiment shows that when  $\mathbf{H} \gg \mathbf{H}_p$ , the  $T$ -dependence of  $J_c$  is of the form  $J_c \propto (1-t)^n$ ,  $n \approx 2$ . The value is consistent with the value calculated by the ac-loss method.

The  $T$ -dependence of  $J_c$  in these thin films is of the form  $(1-t)^n$  over a very broad  $T$ -range. The range of  $\mathbf{T}$  is much wider than the  $T$ -range ( $\mathbf{T}$  near  $\mathbf{T}_c$ ) which was suggested by the SNS model. D. W. Chang et al.<sup>15</sup> reported on the analysis of Y123 films using  $\chi''(T)$  measurement. It was found that when  $J_c < 10^6$  A/cm<sup>2</sup>, the  $T$ -dependence of  $J_c$  still behaves as  $J_c \propto (1-t)^2$  near  $\mathbf{T}_c$ .

In summary, we have prepared well-oriented Y123 HTS films on single-crystal SrTiO<sub>3</sub> and LaAlO<sub>3</sub> using a magnetron sputtering technique and laser deposition. Magnetization curve measurements were performed using a vibrating-sample magnetometer over a wide range of temperatures. The  $T$ -dependence of  $J_c$  was calculated from the magnetic hysteresis loops by the ac-loss method, which greatly reduces the error due to the trapped magnetic field effect. The  $J_c$  vs  $\mathbf{T}$  curves were found to have the form  $J_c \propto [1-(t)]^2$  over a very broad  $T$ -range. This  $T$ -dependence of  $J_c$  does not depend on preparation technique, the shape of the sample, or the

substrate on which the sample is deposited. It seems that the main dissipation mechanism of the best thin films is very similar to that of the weak-link dominated thin films.

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#### REFERENCES

\* Present Address: National Tsing Hua University, Department of Physics, Hsinchu, Taiwan 30043, R.O.C.

1. M. Tinkham, *Helv. Phys. Acta* **61**,443 (1988).
2. V. Ambegaoker and A. Baratoff, *Phys. Rev. Lett.* **10**,486 (1963).
3. J. R. Clem, B. Bumble, S. I. Raider, W. J. Gallagher, and Y. C. Shin, *Phys. Rev. B* **35**,6637 (1987).
4. P. G. de Gennes, *Rev. Mod. Phys.* **36**,225 (1964).
5. J. Clarke, *Proc. R. Soc. A* **308**,447 (1969).
6. H. S. Wu, W. Y. Guan, and H. C. Li, *Superconductivity: Type II Superconductors and Weak Link Superconductivity* (Beijing: Chinese Scientific, 1979), p. 199.
7. C. P. Bean, *Phys. Rev. Lett.* **8**,250 (1962); C. P. Bean, *Rev. Mod. Phys.* **36**, 31 (1964).
8. Y. B. Kim, C. F. Hempstead, and A. R. Strand, *Phys. Rev. Lett.* **9**,306 (1962); Y. B. Kim, C. F. Hempstead, and A. R. Strand, *Phys. Rev. B* **129**,528 (1983).
9. J. H. P. Watson, *J. Appl. Phys.* **39**, 3406 (1968).
10. Y. Yeshurun, A. P. Malozemoff, T. K. Worthington, R. M. Yandrofski, L. Krusin-Elbaum, F. H. Holtzberg, T. R. Dinger, and G. V. Chandrasekhar, *Cryogenics* **29**,258 (1989).
11. Y. Yeshurun, A. P. Malozemoff, F. H. Holtzberg, and T. R. Dinger, *Phys. Rev. B* **38**, 11828 (1988).
12. W. A. Fietz, M. R. Beasley, J. Sicox, and W. W. Webb, *Phys. Rev. A* **335**, 136 (1964).
13. E. M. Gyrogy, R. B. van Dover, K. A. Jackson, L. F. Schneemeyer, and J. V. Waszczak, *Appl. Phys. Lett.* **55**,283 (1989).
14. M. Daümling and D. C. Larbalestier, *Phys. Rev.* **40**, 9350 (1989).
15. D. W. Chung, I. Maartense, T. L. Peterson, and P. M. Hemenger, *J. App. Phys.* **68**, 3772 (1990).