Scaling of critical currents in high-temperature superconducting superlattices and thin films

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We report the measurement of transport critical current densities in a wide variety of high-temperature superconducting (high T_c) superlattices and thin films. We find that the temperature dependence of the critical current density J_c for all samples may be collapsed into a single curve through the scaling relation $J_c(t)=J_c(0)(1-t)^{1.6}$, where $t=T/T_c(H,\Theta)$. This scaling relation remains valid in fields of up to 5 T and in all field directions Θ with respect to the c axis of the sample with the field kept perpendicular to the current.

The anisotropic layered structure of the $RBa_2Cu_3O_x$ (RBCO) high T_c superconductor results in a strong anisotropy of the critical current, resistivity, and critical fields. In recent years, there has been a growing interest in the measurements of critical currents in high T_c films, since they may aid in the understanding of high T_c superconductivity and because of their possible future technological applications.

Several groups have recently reported critical current density (J_c) measurements in single film, superconducting/superconducting, and superconducting/normal superlattices.[1–13] Regardless of the absolute values obtained, the *anisotropy* of J_c is usually explained in terms of either the Tachiki and Takahashi[14,15] or Kes *et al.*[16] models. Both models depend on an intrinsic pinning mechanism of the vortices and assume that the coherence length at $T=0$ along the c axis, $\xi_c(0)$, is smaller than the c-axis lattice parameter. For homogeneous superconductors, the *temperature* dependence of J_c is influenced by a flux creep, which causes vortices to thermally jump from one pinning center to another, and flux flow, which occurs when the applied current is sufficiently large for the Lorentz force to overcome the vortex pinning force. In this case, the movement of vortices causes a measurable resistive voltage to appear in the sample. For granular superconductors, the temperature dependence is described by SNS or SIS weak-link systems.[17,18] These models are based on the Ginzburg–Landau theory, which in principle is only applicable for temperatures close to T_c.

In this letter, we show that the critical current $J_c(H,T,\Theta)$, where Θ is the angle between H and the c axis with H perpendicular to J, follows the simple universal scaling law

$$J_c(H,T,\Theta)=J_c(H,0,\Theta)[1-T/T_c(H,\Theta)]^n \qquad (1)$$

where $T_c(H,\Theta)$ is the temperature at which $J_c(H,\Theta)=0$, and $n=1.6\pm0.1$. This scaling law applies to a wide variety of high T_c thin films and superlattices, independently of field, angle, thickness, and type of material. We note that Yeshurun and Malozemoff[19] used a phenomenological scaling law of this same type, but with $n=2.5$, in analyzing their magnetization relaxation data in terms of a thermally activated flux-creep model.

Transport critical current measurements were made on homogeneous GdBCO thin films, superconducting/superconducting YBCO/GdBCO, and superconducting/normal YBCO/PrBCO superlattices. All samples were grown on MgO substrates by *in situ* dc magnetron sputtering using the not aligned chopped power oscillatory (NACHOS) technique.[20] The observed x-ray spectra of all films used in the present work show c-texture growth with typical (00l) Bragg peak full width half maxima values of 0.3°–0.7° for YBCO/GdBCO superlattices, 0.4°–1.0° for YBCO/PrBCO superlattices, and 0.3°–0.4° for homogeneous GdBCO films.[21] The sample characteristics are summarized in Table I. Most films were photolithographically patterned into bridges 500 μm long and 50 μm wide. Silver contacts were sputtered before patterning in order to ensure low contact resistance and thus avoid sample self-heating. Typical contact resistances were less than 1 Ω at 77 K. The critical current density $J_c(H,T,\theta)$ was measured with H perpendicular to the applied current. The critical current was defined as the current which induced 1 μV across the bridge, although other voltage criteria yielded equivalent results. The angular resolution of the experimental setup was 0.5°. During measurements, the sample temperature was stabilized with an accuracy of 10 mK.

Figure 1 shows some of the $J_c(T)$ data for all samples used in this work. These data include measurements with and without applied fields for different values of Θ. Clearly, there is a large range of absolute values of J_c for a given temperature and field, especially close to T_c. No systematic changes in the absolute value of J_c were found when comparing data from different sample types. We note, however, that all J_c curves have similar temperature dependencies. This is evident in Fig. 2, where the normalized critical current density $J_c(H,T,\Theta)/J_c(0)$, with $J_c(0)$ being the extrapolated critical current density at $T=0$ K, is plotted as a function of the reduced critical temperature $t=T/T_c(H,\Theta)$. Both $T_c(H,\Theta)$ and $J_c(0)$ were obtained by fitting a power law to the data. Clearly, all the data collapse into a single curve. The inset shows a log-log plot of the

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TABLE I. System, name, modulation (X and Y are the number of unit cells in the superlattice), critical temperature in zero field, T_c, width of transition ΔT_c, and thickness of the samples are shown.

System	Sample name	X u.c./Y u.c.	T_c (K)	ΔT_c (K)	Thickness (Å)
YBCO/GdBCO	YGd 13	4/4	85.0	2.2	2000
YBCO/GdBCO	YGd 15	1/1	84.1	1.9	2000
YBCO/GdBCO	YGd 19	4/4	87.2	2.2	2000
YBCO/PrBCO	YPr 14	4/2	76.4	4.5	2000
YBCO/PrBCO	YPr 24	2/16	59.3	17.5	2000
YBCO/PrBCO	YPr 25	2/1	72.8	9.5	2000
GdBCO	Gd5-32		88.6	2.3	2000
GdBCO	Gd5-37		87.5	2.8	2000
GdBCO	Gd5-41		85.3	2.3	2000
GdBCO	Gd11-*b*		86.5	2.0	750

data; the scatter close to $T_c(H,\Theta)$ is possibly due to difficulties in determining $T_c(H,\Theta)$, or to sample inhomogeneities which may affect the measured value of J_c. Also shown in Fig. 2 are the results of a flux creep model[3] represented by the dashed line. This model does appear to fit the data quite well throughout most of the temperature range, except close to $T_c(H,\Theta)$ (see inset). This discrepancy, however, should not be taken too seriously since it is precisely in this temperature range that the data is least reliable. It should be noted, however, that an interpretation in terms of this model implies that the flux creep activation energy scaled by $T_c(H,\Theta)$ is sample independent.

We also note that neither the SIS nor SNS models[17,18] fit the data throughout the whole temperature range (see Fig. 2). When $J_c(t)$ is calculated from the SIS model, it has the wrong curvature. In the framework of the SNS model, $J_c(t)$ has the wrong power law behavior in the low-temperature limit ($n=2$), thus making it impossible to fit our data. We note that in calculating the SIS and SNS curves, we have chosen reasonable parameters which best approximate the data.

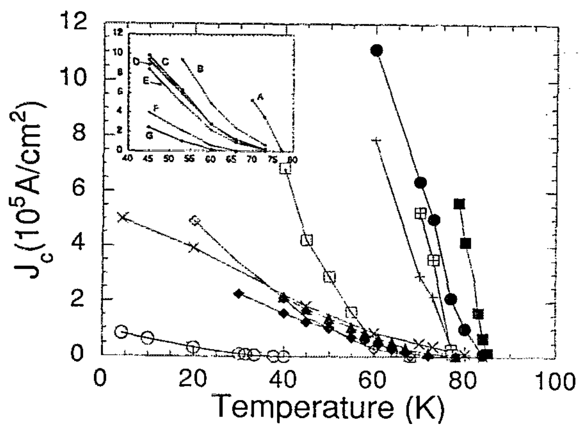

FIG. 1. Transport critical current density J_c as a function of temperature for the samples listed in Table I. (■) sample YGd 15; (●) sample YGd 19; (□) sample Gd5-37; (+) sample Gd5 41; (×) sample Gd5-32; (⊞) sample YPr 25; (◇) sample YPr 14; (◆) sample YGd 13 (H=2.5 T, $\Theta=0°$); (▲) sample YGd 13 (H=2.5 T, $\Theta=90°$); (○) sample YPr 24. The inset shows data for sample Gd5-37. Curve (A) corresponds to $H=0$ T, (B) to $H=1$ T, $\Theta=90°$, (C) to $H=1$ T, $\Theta=0°$, (D) to $H=3$ T, $\Theta=90°$, (E) to $H=5$ T, $\Theta=90°$, (F) to $H=3$ T, $\Theta=0°$, and (G) to $H=5$ T, $\Theta=0°$. The solid lines are guides to the eye.

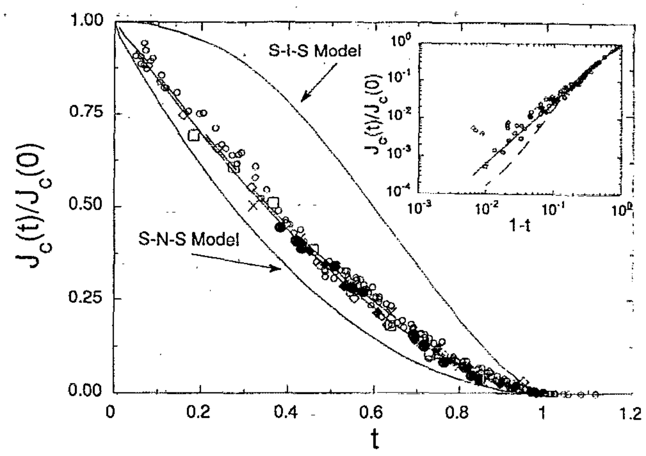

FIG. 2. Reduced critical current density $J_c(t)/J_c(0)$ as a function of reduced temperature $t=T/T_c(H,\Theta)$. (○) indicate all samples indexed in Table I; (●) NbGe sample (Ref. 22); (×) YBCO sample (Ref. 11); (□) PbMoS sample (H=10 T, Ref. 23); (◇) PbMoS sample (H=1 T, Ref. 23); (▲) BISCO sample (Ref. 12). Solid line indicates linear fit to the data of the power law. Dashed line represents fit to flux-creep model, with $u_0=10$ and $c=5\times10^{-6}$ (after Ref. 3). Inset shows a log-log plot of data, emphasizing points near T_c. SNS[3] [with $a_N/\xi_N(T_c)=0.1$] and SIS[17] [with $2\Delta(0)=2.5k_BT_c$ and $\epsilon_0=1$] models are also indicated.

It is surprising that the temperature dependence of J_c follows a universal behavior over such a large temperature range, considering that its absolute value varies by more than three orders of magnitude from sample to sample. This suggests that the pinning mechanism which gives rise to the temperature dependence of J_c, whatever its origin (defects or intrinsic), is the same in all systems, i.e., homogeneous thin films, superconducting/superconducting, and superconducting/normal superlattices. Moreover, in Fig. 2, we have included data of NbGe compounds,[22] PbMoSi,[23] and two high T_c systems (YBCO[11] and BISCO[12]) from other groups, which indicates that the scaling law is applicable beyond RBCO materials.

In summary, we have measured transport critical current in homogeneous GdBCO thin films, superconducting/superconducting YBCO/GdBCO superlattices, and superconducting/normal YBCO/PrBCO superlattices. Our results demonstrate that the temperature dependence of J_c follows a universal scaling law over a wide temperature range.

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