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FLUX CREEP, FLUX PINNING AND CRITICAL CURRENT DENSITY OF Y-, Gd-, AND Tl-BASED SUPERCONDUCTIVE THIN FILMS*

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Magnetic hysteresis loops have been measured for $YBa_2Cu_3O_{6+x}$, $GdBa_2Cu_3O_{6+x}$ and $Tl_2Ba_2Ca_2Cu_3O_{10-y}$ films at different temperatures with a vibrating sample magnetometer. Based on Bean model, magnetic critical current density J_{cm} has been derived approximately. The field and temperature dependence of J_{cm} for all samples can be written as: $J_{cm} = J_{c0}(T) \times f(B,T)$, where $f(B,T) = 1 - A\ln(B/B_0(T))$, which is similar to the transport critical density strongly affected by flux creep: $J_{ct} = J_{c0}(B,T)(1-(k_BT/U_0)\ln(B\Omega d/E_c))$. The extraordinary similarity suggests that J_{cm} is determined not only by flux pinning but also by flux creep. In the first formula, $f(B,T)$ may be correlated with the effect of flux creep on J_{cm}, and $J_{c0}(T)$ is determined by flux pinning. $J_{c0}(T)$ is independent of magnetic field and is proportional to $(T_c - T)$. Similar results have also been found for other samples. It may be the common characteristic of high-T_c superconductors. Magnetic relaxation of $YBa_2Cu_3O_{6+x}$ and $GdBa_2Cu_3O_{6+x}$ films has been measured at LN_2 temperature. Using the equation of Hagen *et al.*, effective activation energy U_0 has been deduced, which is about 0.3 eV, one order bigger than the value obtained by $A = k_BT/U_0$. U_0 is almost independent of the field in the field range selected.

PACC: 7460G; 7460J

I. INTRODUCTION

It is well known that weak links, giant flux creep and volume pinning force density are three important factors of limitation to critical current density J_c for high-T_c superconductors. In high quality samples, such as single crystals and thin films, though links in them are improved, the critical current density is still low and decreases with increasing field strength due to low pinning energy U_0 and low pinning force density. So giant flux creep plays a prominent role in critical current density for high quality samples, and can, in large part, explain temperature and field dependence of the critical current density.

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For studying flux pinning mechanism, the field and temperature dependence of the pinning potential U_0 and volume pinning force density F_p must be obtained first from experiments. Based on critical state model and Anderson-Kim flux creep model, scientists usually study flux pinning by measuring magnetization relaxation and critical current density $J_c(B,T)$. But for high-T_c superconductors, critical current density is controlled by both flux pinning and flux creep simultaneously. Thus, we must separate the contribution of flux pinning to J_c from that of flux creep so as to deduce the real volume pinning force density $F_p(B,T)$. The pinning energy U_0 can also be estimated from the contribution of flux creep to J_c.

Of course, there are many methods for studying flux pinning and flux creep. Recently, many experiments such as transport critical density, I-V curve, magnetic relaxation and resistive transition broadening measurements have been conducted for studying the flux pinning and flux creep in various films. Many experimental results such as $J_c \propto 1/B$, $J_c \propto H^{1/2}$, $J_c \propto \exp(-T/T_0)$, $J_c \propto (1-t)^n$, etc.[1-9] have been reported and explained. But no one points out how to separate the effect of flux creep on J_c from that of flux pinning so as to study flux pinning and flux creep separately.

In this paper we present a new temperature and field dependence of magnetic critical current density $J_{cm} = J_{c0}(T) \times (1 - A \times \ln(B/B_0(T)))$, which is obtained by measuring magnetic hysteresis loops at different temperatures on Y-, Gd-, and Tl-based thin films. Field dependence of pinning energy U_0 deduced from magnetic relaxation at 77 K is also presented. All experimental results can be explained by flux pinning together with flux creep.

II. SAMPLE PREPARATION

Superconducting $YBa_2Cu_3O_{6+x}$ and $GdBa_2Cu_3O_{6+x}$ thin films were prepared by rf and dc magnetron sputtering. The substrate temperature was kept at 600–670 °C during deposition and a subsequent in situ plasma oxidation treatment was performed at 480–520 °C. The films were deposited on single-crystal $SrTiO_3(100)$. Dimensions for $YBa_2Cu_3O_{6+x}$ are 4 mm×11 mm×240 nm, surface roughness is ±10 nm, T_c=90 K. For $GdBa_2Cu_3O_{6+x}$ film, T_c=92 K, dimensions are 5 mm×10 mm×900 nm, surface roughness is ±200 nm.

Tl-2223 thin film was deposited in 50 mTorr Ar atmosphere on yttrium-stabilized zirconia (YSZ) substrate by using dc magnetron sputtering system with two targets. The temperature of substrate was kept at 100 °C, deposition rate was 7 nm/min, direct current was 25 mA. Finally, the film was annealed in flowing oxygen at 870–900 °C for a short time and then furnace cooled. The thickness of the film is 800 nm and $T_c > 110$ K.

III. EXPERIMENTS AND RESULTS

Magnetic hysteresis loops have been measured for $YBa_2Cu_3O_{6+x}$, $GdBa_2Cu_3O_{6+x}$ and $Tl_2Ba_2Ca_2Cu_3O_{10-y}$ films with the applied field perpendicular to the film surface at different temperatures using a vibrating sample magnetometer. Field scanning velocity is about 200 G/s and the sensitivity of the apparatus is 10^{-5} emu.

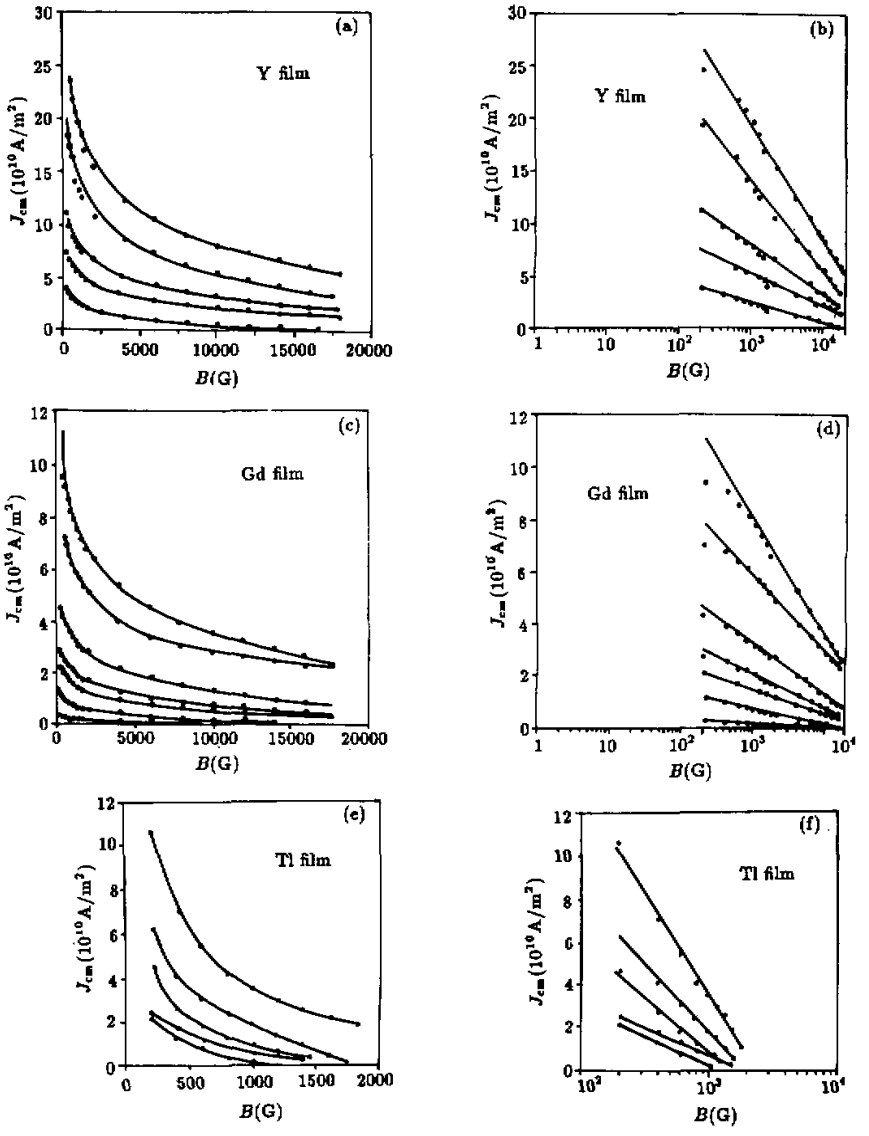

Fig. 1. Field dependence of $J_{cm}(B,T)$ at different temperatures for $YBa_2Cu_3O_{6+x}$, $GdBa_2Cu_3O_{6+x}$ and $Tl_2Ba_2Ca_2Cu_3O_{10-y}$ films. Fitting function is $J_{cm} = J_{c0}(T)(1 - A\ln(B/B_0(T)))$. For (a), (b) Y film, T=57.6, 63, 70.1, 74, 77.5 K, J_{c0} = 25.6 × 10^{10}, 19.94 × 10^{10}, 12.01 × 10^{10}, 8.38 × 10^{10}, 4.7 × 10^{10} A/m^2, A=0.187, 0.187, 0.169, 0.165, 0.18, B_0=260, 200, 135, 110, 75 G; (c), (d) Gd film, T=56, 63.8, 72, 77.2, 80, 83.6, 87.8 K, J_{c0} = 9.76 × 10^{10}, 7.45 × 10^{10}, 4.55 × 10^{10}, 3.05 × 10^{10}, 2.25 × 10^{10}, 1.31 × 10^{10}, 0.41 × 10^{10} A/m^2, A=0.2, 0.17, 0.19, 0.19, 0.18, 0.2, 0.17, B_0=400, 280, 220, 180, 150, 130, 60 G; (e), (f) Tl film, T=54.7, 64.5, 71, 79.5, 80.7 K, J_{c0} = 12 × 10^{10}, 8.2 × 10^{10}, 6 × 10^{10}, 3.2 × 10^{10}, 2.9 × 10^{10} A/m^2, A=0.14, 0.14, 0.16, 0.16, 0.17, B_0=114, 95, 90, 84, 83 G.

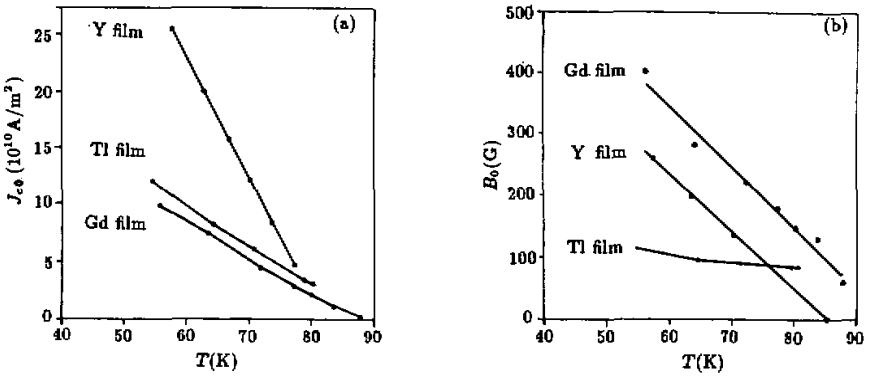

Fig. 2. Temperature dependence of $B_0(T)$ and $J_{c0}(T)$ for $YBa_2Cu_3O_{6+x}$, $GdBa_2Cu_3O_{6+x}$ and $Tl_2Ba_2Ca_2Cu_3O_{10-y}$ films. Solid lines present fitting functions. For Y film, $J_{c0} = (86.73 - 1.06T) \times 10^{10}\,A/m^2$, $B_0 = (783.4 - 9.18T)\,G$. For Gd film, $J_{c0} = (26.5 - 0.3T) \times 10^{10}\,A/m^2$, $B_0 = (929.7 - 9.78T)\,G$. For Tl film, $J_{c0} = (30.9 - 0.35T) \times 10^{10}\,A/m^2$, $B_0 = (171.9 - 1.12T)\,G$.

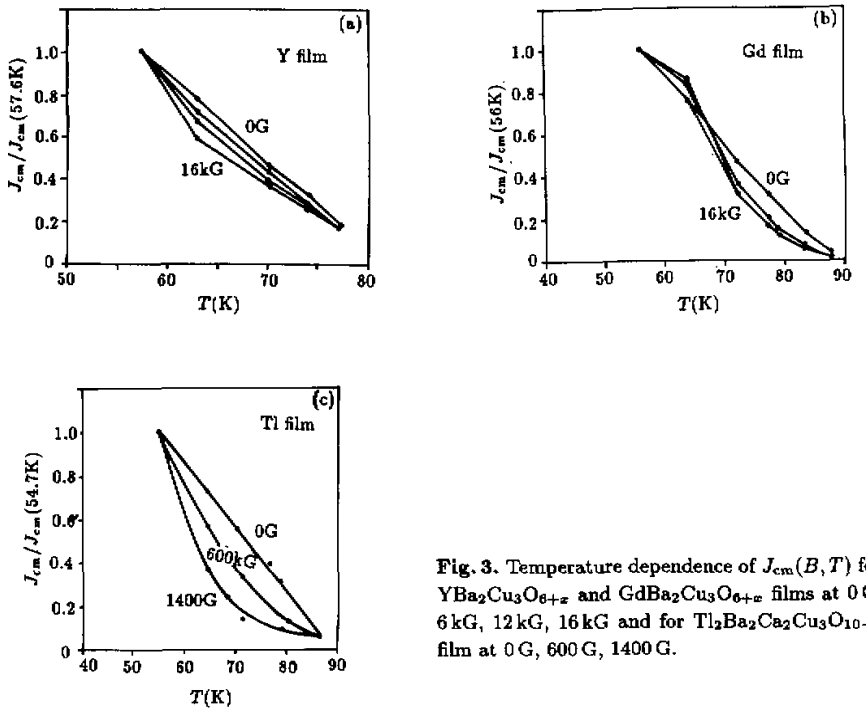

Fig. 3. Temperature dependence of $J_{cm}(B,T)$ for $YBa_2Cu_3O_{6+x}$ and $GdBa_2Cu_3O_{6+x}$ films at 0 G, 6 kG, 12 kG, 16 kG and for $Tl_2Ba_2Ca_2Cu_3O_{10-y}$ film at 0 G, 600 G, 1400 G.

In the framework of Bean model, the magnetic critical current density can be deduced from magnetic hysteresis ΔM for a rectangular sample: $J_{cm} = 20\Delta M/(\omega(1-\omega/3l))$. Figure 1 shows the field dependence of J_{cm} at different temperatures for Y-123, Gd-123 and Tl-2223 films. The dots represent experimental data and solid lines are fitting curves. The fitting function is $J_{cm} = J_{c0}(T)(1 - A\ln(B/B_0(T)))$, where A=const; $J_{c0}(T)$ and $B_0(T)$ are functions of temperature.

As shown in Fig.2, $J_{c0}(T) = J_0(1-t), B_0(T) = b_0(1-t), t = T/T_c$. So $J_{cm} = J_0(1-t)(1 - A\ln(B/b_0(1-t)))$.

Figure 3 shows the temperature dependence of J_{cm} in different fields. $J_{cm} \propto (1-t)^n$, where n increases from 1 to 2 with increasing field.

Magnetic relaxation has been measured at LN_2 temperature. According to Hagen *et al.*, $M(t,B,T) = M(0,B,T)(1 - (k_BT/U)\ln(1 + t/\tau))$. For t=50 s and $\tau = 10^{-6}, \cdots, 10^{-12}$, $U/k_BT = S^{-1} = 24.63 \pm 6.9$, S=$-d\ln M/d\ln t$[10]. Field dependence of U_0 at 77 K is shown in Fig.4.

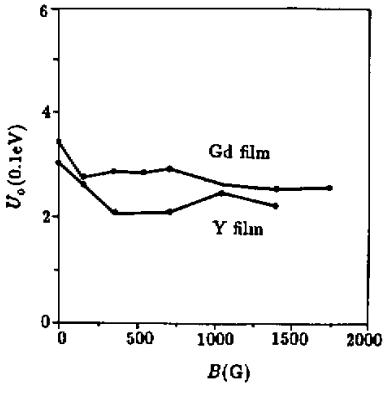

Fig. 4. Field dependence of pinning energy U_0 for $YBa_2Cu_3O_{6+x}$ and $GdBa_2Cu_3O_{6+x}$ films at LN_2 temperature.

IV. ANALYSIS AND DISCUSSION

According to Anderson-Kim flux creep model, the mean electric field induced by flux creep is

$$E = B\Omega d \times \exp(-U_0/k_BT) \times \sinh\left(U_0J/(k_BTJ_{c0})\right), \quad (1)$$

where U_0 is the pinning energy, d is the average distance of pinning centers, Ω is related to the attempt frequency. J is the transport current density and J_{c0} is the critical current density in critical state (no flux creep). The critical current density J_c can then be deduced

approximately by electric field criterion E_c:

$$J_c = J_{c0}\Big(1 - (k_B T/U_0)\ln(B\Omega d/E_c)\Big) = J_{c0} \times f(B,T)\ , \tag{2}$$

where J_{c0} is controlled by flux pinning, and $f(B,T)$ presents the effect of flux creep.

In magnetic measurements, magnetic hysteresis loops are influenced by field scanning volecity $\mathrm{d}H/\mathrm{d}t$, and magnetic critical current density J_{cm} is affected directly by $\mathrm{d}H/\mathrm{d}t$. For $E \propto \mathrm{d}\phi/\mathrm{d}t \propto \mathrm{d}H/\mathrm{d}t$, $\mathrm{d}H/\mathrm{d}t$ corresponds to voltage criterion E_c. Hence, the effect of $\mathrm{d}H/\mathrm{d}t$ on J_{cm} is the same as Eq. (2). Based on this view, some discussions about experimental results will be given as follows.

A. Field dependence

Based on experimental results, magnetic critical current density $J_{cm} = J_{c0}(T)(1 - A\ln(B/B_0(T)))$ is similar to Eq. (2). J_{c0} and U_0 seem to be independent of field. It is possible that J_{c0} and U_0 change with field slowly and their changes are covered by $\ln(B/B_0)$, as a result, J_{cm} varies with field in a logarithm law. The same results have been found by Venturini[5] in Tl film, Hettinger *et al.*[6] in Y film, Itozaki *et al.*[7] in Bi film. We have also found the same result in high quality Bi tape, which will be published elsewhere.

At low temperature, flux creep can be neglected and critical current density is mainly determined by flux pinning. Since $J_{c0}(T)$ is independent of field, the transport J_{ct} is constant and the magnetic hysteresis loops are rectangular, which is in agreement with Bean model.

England *et al.*[1] found $J_c \propto 1/B$ between 2 – 10 T for Y films. Zhukov *et al.*[2] found $J_c \propto 1/(B + B_0)$ for Y films in high fields. This may be explained as follows. In high fields, U_0 is small and the electric field deduced by flux creep may be written as $E = B\Omega d \times U_0 J/k_B T J_{c0} \times \exp(-U_0/k_B T)$. Therefore, $J_c = E_c J_{c0} \times k_B T/B\Omega d \times \exp(U_0/k_B T)$, i.e. $J_c \propto 1/B$.

B. Temperature dependence

Both $J_{c0}(T)$ and $f(B,T)$ are functions of temperature. As B and T cannot be separated in the expression of J_{cm}, the shape of J_{cm}-T curve is relative to the applied field, as shown in Fig.3. In zero field, $J_{cm} \propto (1-t)$. For higher fields, J_{cm}-T curves deviate from linearity and tend to $(1-t)^2$. This result is consistent with the results of others[3] and similar to the results of Bi tape and sintered samples[8,9]. For $t < 1$, fitting function may be reduced to $J_{cm} = J_0 \times (1-t) \times (1 - A\ln(B/b_0) - A \times t)$. For low fields, $B/b_0 \to 1$, $\ln(B/b_0) \to 0$, $A \times t \ll 1$, so $J_{cm} \propto J_0 \times (1-t) = J_{c0}(T)$. For high fields, $B \gg b_0$, 1-$A\ln(B/b_0)$ is small. If 1-$A\ln(B/b_0) = A$, $J_{cm} = J_0 \times A \times (1-t)^2$.

As for $B_0(T) = b_0(1-t)$, it may be considered that $B_0(T) = E_c/\Omega d$, where Ω increases

with increasing temperature, hence $B_0(T)$ decreases with rising T.

For $A = k_BT/U_0$=const., $U_0 \propto k_BT/A$, which agrees with many results of others (see Ref.[10]). For $A = 0.2$, U_0 is deduced to be 0.033 eV at 77 K, one order smaller than the value of U_0 obtained by magnetic relaxation measurement.

C. Pinning mechanism

The field and temperature dependence of $J_{c0}(T)$ and U_0 suggests that there is some pinning mechanism similar to center pinning. Pinning energy may be assumed as $H_c^2 \times \xi^3/8$, the same as the model of Savvides[9]. By linearity summation, volume pinning force density $F_p = B/\phi \times f_p = B/\phi \times H_c^2 \times \xi^2/8$, and $J_c = H_c^2 \times \xi^2/8/\phi$, both J_{c0} and U_0 are independent of field and $J_{c0} \propto (1-t)$.

It seems contradictory that J_{c0} decreases while U_0 increases with rising temperature. Some explanations of this have been given[11]. Here we suggest a new explanation. With increasing T, the magnetic flux lattice softens gradually until melting. So the summation method of f_p changes with T, and $F_p = S(B,T) \times f_p$, which results in different T dependence of U_0 and J_{c0}.

V. CONCLUSION

Based on the experimental results and discussions stated above, we can draw the following conclusions: (1) Critical current density is controlled by both flux pinning and flux creep. (2) Giant flux creep plays an important role in the limitation of J_c. For high quality samples, it is crucial to induce big U_0 pinning centers to increase J_c in high field. (3) In superconductive materials, there is some pinning mechanism similar to center pinning. U_0 and J_c change very slowly with field, U_0 increases while J_c decreases with increasing T.

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