Two pinning mechanisms in single crystals of the $Bi_{2+x}Sr_{2+y}Ca_{1+z}Cu_2O_t$ phase

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(Submitted 11 February, 1991; resubmitted 20 March 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **53**, No. 9, 466–469 (10 May 1991)

The critical current density j_c in $Bi_{2+x}Sr_{2+y}Ca_{1+z}Cu_2O_t$ single crystals has been observed to increase sharply (by a factor of tens) after bombardment with Ar^+ ions. Analysis of the flux creep, the temperature dependence of j_c, and the field dependence of j_c reveals an intrinsic low-temperature pinning mechanism and also a defect-related high-temperature mechanism.

Although single crystals of the $Bi_{2+x}Sr_{2+y}Ca_{1+z}Cu_2O_t$ phase have been under study for a fairly long time now,[1-3] we do not yet have adequate information on the critical current density j_c over a broad temperature range, on the effect of various types of pinning centers on this current density, or on flux creep.

In this letter we are reporting a study of the temperature dependence $j_c(T)$ in the basal plane for single crystals of the $Bi_{2+x}Sr_{2+y}Ca_{1+z}Cu_2O_t$ phase[3] and of how this dependence is affected by bombardment with argon ions at an energy of 15 MeV/nucleon. The value of j_c was found from the hysteresis of the magnetic moment measured after the external field was raised above the level at which vortices penetrate all the way to the center of the sample, and after the external field was reduced to zero.

A characteristic feature of the $j_c(T)$ dependence (Fig. 1a) is the presence of two temperature intervals. At low temperatures ($T < T^* \approx 24$ K for a sample with $T_c = 92$ K) we find a dependence $j_c(T) = j_{c1}(0)\exp(-T/T_{01})$. The value of T_{01} is anomalously low ($T_{01} \approx 3.8$ K), and it decreases with decreasing T_c. For all the samples studied, which had T_c values in the interval 68–92 K, and which were prepared under various processing conditions, the value of $j_{c1}(0)$ turned out to be essentially constant at $(4\text{–}6)\times 10^6$ A/cm^2. Above T^*, the $j_c(T)$ dependence weakens; it can again be described fairly accurately by an exponential law, but with a lower value $j_{c2}(0) \approx (2\text{–}5)\times 10^4$ A/cm^2 and a higher parameter $T_{02} \approx 10\text{–}20$ K. As can be seen from Fig. 1, the values of the parameters $j_{c2}(0)$ and T_{02} depend strongly on the conditions under which the sample was prepared.

A study was also made of the relaxation of the remanent magnetization (the sample was cooled in a field, and the field was turned off after desired temperature was reached). It was found in these measurements that relaxation processes have a strong effect on the measured value of j_c; the effect is strongest in the temperature interval 8–

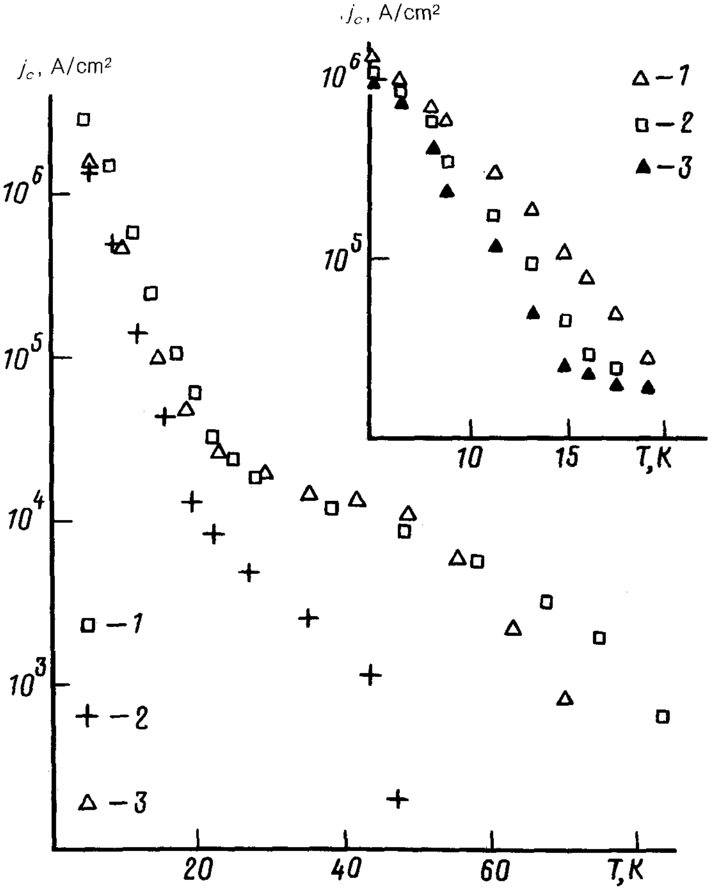

FIG. 1. The temperature dependence $j_c(T)$ for $Bi_{2+x}Sr_{2+y}Ca_{1+z}Cu_2O_t$ single crystals with $T_c = 92$ K (curve 1), 68 K (2), and 78.5 (3). The inset shows $j_c(T)$ as found without consideration of relaxation (curve 1), after relaxation for 2 min (2), and after relaxation for 30 min (3).

24 K. Inset 1 in Fig. 1 shows the time evolution of j_c. It can be seen from this figure that T_{01} decreases as the relaxation time increases to 30 min. The decrease is from 3.8 K to 2.2 K, while $j_{c1}(0)$ remains essentially constant. The point T^* shifts into the low-temperature region. At $t = 30$ min, we find $T^* \approx 16$ K. The time evolution of the moment M (see inset 1 in Fig. 2) is approximately logarithmic after a sufficiently long time. From the relaxation time $S = (1/M_0) \cdot dM/d \ln t$, normalized to half the width of the hysteresis loop on the plot of the magnetization M_0, and from the formula[4] $S = kT/U_0(T)$, we determined the activation energy for flux creep, $U_0(T)$ (Fig. 2). Since the relaxation rate was determined for long times, it should be compared with $j_c(T)$ at $t = 30$ min. In accordance with the temperature dependence $j_c(T)$, the temperature dependence $U_0(T)$ has two regions: a low-temperature region ($T < T_{tr} \approx 15.5$ K), with $U_0(T) \approx 120$ K, and a high-temperature region ($T > T_{tr}$), with $U_0(T) \approx 630$

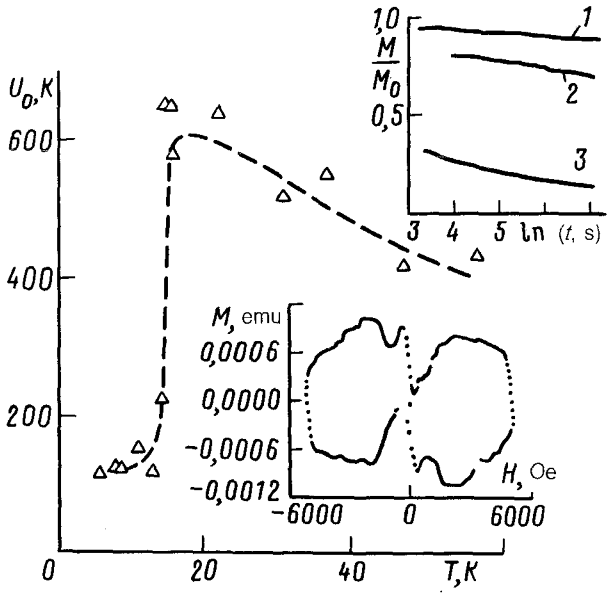

FIG. 2. Temperature dependence of the activation energy U_0. Inset 1 (at the top) shows the time evolution of the moment M at several temperatures. 1—5.2 K; 2—25.3 K; 3—15.6 K. Inset 2 shows the $M(H)$ hysteresis curve at $T = 16.2$ K.

K. In the region $T \approx 15.5$ K we find a sharp increase in U_0, from ≈ 120 K to 630 K. The jump in U_0, by a factor of about 30, stands out above the experimental error and was reproduced on two different samples. A slope change on the plot on $\log(j_c(T))$, corresponding to the jump in U_0, was found on 11 samples. The error of the temperature regulation in the course of prolonged measurements (for ≈ 30 min) with the PARC 155 magnetometer is ≈ 0.2 K, so it was not possible to study the temperature region near $T_{\rm tr}$ in more detail. At short times, at temperature near $T_{\rm tr}$, we also observed a significant and fast relaxation.[5]

To produce some pinning centers artificially, we used Ar^+ ions with an energy of 15 MeV/nucleon. As these ions pass through the high-T_c superconductor, they produce tracks in which the structure becomes amorphous. For xenon ions ($E = 3.5$ GeV), the radius of these tracks is[6] ≈ 60 Å. Figure 3a shows $j_c(T)$ for a bombarded sample. It can be seen from this figure that the bombardment causes a sharp increase in $j_{c2}(0)$ (by a factor of several tens), while causing essentially no change in the parameters $j_{c1}(0)$, T_{01}, and T_{02}. The field dependence $j_c(H)$ is approximately exponential above 30 K (Ref. 4): $j_c(H) = j_c(0)\exp(-H/H_0)$. This is true before and after the bombardment. Figure 3b shows $H_0(T)$; the parameter H_0 is essentially unaffected by the bombardment. This result suggests that the defects produced by the bombardment have properties similar to those of the defects which determine the second pinning mechanism.

In the transitional region of temperatures, near $T_{\rm tr}$ ($T = 13$–26 K), we also see a peak on the $j_c(H)$ curve, similar to that in Ref. 7 (see inset 2 in Fig. 2). It appears to us that these results can be explained on the basis of the model proposed in Ref. 8.

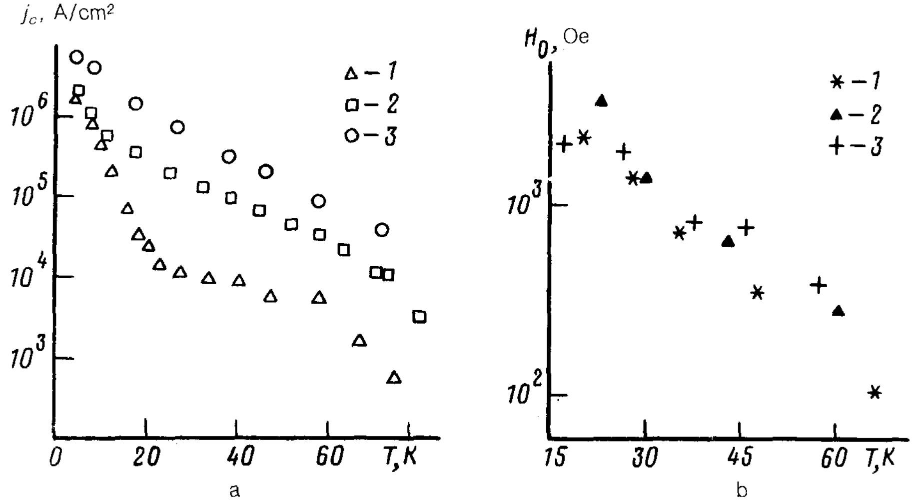

FIG. 3. a: $j_c(T)$ for a sample bombarded with Ar^+ ions with an energy of 15 MeV/nucleon. *1*—Before bombardment; *2*—flux of 9×10^{11} cm^{-2}; *3*—1.8×10^{12} cm^{-2}. b: Temperature dependence of the parameter H_0. *1*—Before bombardment; *2*—flux of 9×10^{11} cm^{-2}; *3*—1.8×10^{12} cm^{-2}.

According to that model, an increase in j_c stems from a suppression of two-dimensional fluctuations by the magnetic field, as the result of an increase in the stiffness of the vortex lattice. The temperature T_{tr} can be identified with the temperature of a fluctuational depinning. The particular external magnetic field at which the peak effect is seen is $H\approx1$ kOe, but the field inside the sample may be higher than the field of the transition to the two-dimensional regime which was determined in Refs. 8 and 9, because of demagnetizing effects (the demagnetizing factor of this sample was $n\approx0.97$).

The particular nature of the pinning centers in $\mathrm{Bi}_{2+x}\mathrm{Sr}_{2+y}\mathrm{Ca}_{1+z}\mathrm{Cu}_2\mathrm{O}_t$ single crystals is not yet clear. The first mechanism, which is correlated only with T_c, may involve a collective pinning by small-radius intrinsic defects, which exist regardless of the particular procedure used to prepare the sample. These defects might be oxygen vacancies.[10] In addition, this first mechanism may be associated with charge density waves[11] or a motion of dislocations of the vortex lattice.[12] The second (high-temperature) pinning mechanism is probably associated with defects in the crystal with dimensions greater than the coherence length in the *ab* plane but smaller than the penetration depth. The pinning energy for pinning at centers of this sort is determined by the condensation energy of a vortex core and should depend only weakly on the particular nature of these centers. These defects may be dislocations, the boundaries of superstructural blocks, and other imperfections of the single crystal. The laminar mixed state predicted in Ref. 13, with normal regions of macroscopic dimensions, may also be realized in the region between the irreversibility line and $H_{c2}(T)$. If such a state does exist, the reason for the radiation-induced increase in j_c would be the rough equality of the sizes of the normal regions in the laminar mixed state and of the radiation-induced defects.

This work was supported by the Scientific Council on the Problem of High-Temperature Superconductivity and was carried out at the BAZIS temporary scientific collective within the framework of projects 90061 and 421 of the State Program "High-Temperature Superconductivity."

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Translated by D. Parsons