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Irradiation-induced crossover from point defects to correlated disorder pinning in $Bi_2Sr_2CaCu_2O_x$ single crystals

V. V. Moshchalkov and V. V. Metlushko
Laboratorium voor Vaste Stof-Fysika en Magnetisme, Katholieke Universiteit Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium

G. Güntherodt
2. Physikalishes Institut, Rheinisch-Westfälische Technische Hochschule Aachen, Templergraben 55, W-5100 Aachen, Germany

I. N. Goncharov and A. Yu. Didyk
Joint Institute for Nuclear Research, Dubna, 141980, Russia

Y. Bruynseraede
Laboratorium voor Vaste Stof-Fysika en Magnetisme, Katholieke Universiteit Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium

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The temperature dependence of the critical current $j_{cm}(T)$ in single-crystalline $Bi_2Sr_2CaCu_2O_x$ (BSCCO) changes dramatically with fast ion irradiation. In as-grown BSCCO crystals the $j_{cm}(T)$ curve follows the predictions of the Feigelman-Vinokur theory for collective pinning in the presence of point defects. In irradiated BSCCO we have obtained a good fit of $j_{cm}(T)$ over several decades and in a broad temperature range in the framework of the Nelson-Vinokur theory. The quality of the fit convincingly demonstrates the validity of this theory for the description of $j_{cm}(T)$ in BSCCO with columnar defects.

The flux phases in high-temperature superconductors are essentially influenced by the presence of different types of defects, which act as strong pinning centers, thus promoting the distortion of the periodic flux lattice and the formation of the vortex or Bose glass.[1,2] The mechanisms of vortex pinning are usually analyzed by taking into account the dominant type of disorder in each particular case. *For point defects* different pinning regimes have been considered theoretically in Refs. 3 and 4, including three-dimensional (3D) pinning at low temperatures and collective pinning of small and large flux bundles at higher temperatures. *For correlated disorder* caused by the presence of columnar pins, produced by the irradiation,[5,6] Nelson and Vinokur have analyzed the behavior of critical-current and current-voltage characteristics and predicted different pinning regimes as temperature increases from low temperature, through depinning (T_{dp}) to the Bose-glass temperature.[1,2]

However, these theoretical predictions of specific temperature dependences of critical current $j_c(T)$ both for point defects and for the correlated disorder have not been confirmed yet experimentally. The main obstacle here is a complicated relation between the flux creep barrier U and j.[3,4] Due to the flux creep, the width ΔM of the magnetization hysteresis loop is a function of time t and the magnetic critical current j_{cm}, found from ΔM using the Bean model, is not an equilibrium critical current j_{c0}. There are two possible approaches to the problem of the time dependence of ΔM: (i) The first approach is a "pessimistic" one: since ΔM is a function of t we are not allowed to use $\Delta M(t_0)$ even as a first approximation for j_{c0}. At most, using some complicated schemes with many fitting parameters we may evaluate coefficient μ in the relation $U \propto (j_0/j_c)^{\mu}$. (ii) The second approach is an "optimistic" one: in spite of the fact that ΔM is a function of t, this is a *logarithmically slow function of time* and therefore on a realistic time scale the ΔM value still can be used to calculate j_{c0}, *at least as a first approximation.*

Both approaches have certain advantages and disadvantages. However, in the second approach we gain the freedom of using well-defined theoretical predictions for $j_c(T)$ for the description of $j_{cm}(T)$ curves obtained for each particular type of disorder. In what follows, we shall show that the temperature dependences of the "magnetic" critical current $j_{cm}(T)$ in $Bi_2Sr_2CaCu_2O_x$ (BSCCO) demonstrate dramatic changes caused by the crossover from point defects to the correlated disorder pinning. What is worth emphasizing here is a good qualitative fit of the $j_{cm}(T)$ curves with the Feigelman-Vinokur theory for the unirradiated BSCCO single crystal and with the Nelson-Vinokur theory for the irradiated BSCCO crystals containing columnar defects. In both cases the fit of the normalized current $j_{cm}(T)/j_{cm}(T \rightarrow 0)$ uses the minimum number of fitting parameters (1 or 2) and is valid in a very broad temperature range below as well as above the depinning temperature T_{dp}. From magnetically measured current-voltage characteristics (and such an analysis is valid this time for both "pessimistic" and "optimistic" approaches) we have obtained a convincing evidence for the non-Ohmic variable range hopping behavior predicted by Nelson and Vinokur for the vortex dynamics in fields much lower than the first matching field B_{Φ}, corresponding to exactly one flux line per columnar defect.

The BSCCO single crystals, grown by the self-flux method, have typical dimensions of $1 \times 1 \times 0.01$ mm^3 and a transition temperature $T_c \approx 95$ K.[7] The flux-creep processes were studied in the regime of remanent magnetization ($H = 0$) measured after sweeping the magnetic field up to $H = 20$ kG. This field is larger than the characteristic field for the complete field penetration. In this case the flux-creep and critical-current measurements for $H=0$ are, in fact, performed in a trapped field H_t. At $T=20$ K H_t is about 130 G, at $T=40$ K $H_t \approx 50$ G. This field depends on temperature but is always lower than the dimensional crossover field H_{2D}. The pure two-dimensional (2D) case[8] is valid when the flux line lattice constant a_v becomes smaller than the Josephson bending length $R_J=\Gamma^{1/2}s$,[9] where Γ is the anisotropy ($\Gamma=m_c/m_{ab}$) and s is the separation between the CuO_2 planes. With $s=1.5$ nm and $\Gamma \approx 3000$ (Ref. 10) measured for BSCCO at relatively high temperatures, the lowest limit of the crossover field is $H_{2D}=\Phi_0/R_J^2 \sim 1$ kG (Φ_0 is the flux quantum). As it follows from the experimental observation of the 3D flux lines in neutron-scattering experiments,[11] the 3D flux lines are seen at least up to fields $H_{2D} \sim 1$ kG. From these data we conclude that at low temperatures the fields $H \sim H_t$ used in our experiments are below H_{2D} and therefore BSCCO is in the 3D regime.[12]

The irradiation with fast Ar and Kr ions with energy 0.6 GeV and 0.42 GeV, respectively, with the flux doses $\Phi \approx 10^{11}$ ions/cm^2 was done at the Joint Institute for Nuclear Research in Dubna. The one-to-one correspondence between the number of amorphous tracks and the number of flux lines occurs in magnetic field $B_\Phi \approx 20$ kG. After irradiation the T_c value is reduced to 85–87 K. All the measurements were performed in a magnetic field applied parallel to the c axis, i.e., parallel to the columnar tracks.

Figure 1 shows the temperature dependence of the magnetic critical current $j_{cm} \sim \Delta M$, measured as a function of time (data were taken at $t=1$, 3, 10, 20, and 60 min for the as-grown BSCCO single crystal in the trapped magnetic field. It is clearly seen from this figure that in spite of the flux creep the main features of the $j_{cm}(T)$ curve [the crossover from a very strong exponential at low temperatures to a weaker j_{cm} vs T variation at high temperatures, the kink on the $j_{cm}(T)$ curve, etc.] are not washed out at all due to the time dependence of ΔM. In irradiated BSCCO single crystals the measured flux-creep rates are lower and therefore we may consider $j_{cm} \sim \Delta M$ (Fig. 2) as a *first approximation* for j_{c0}, at least in a time window $t=(1-10^4)$ sec.

To evaluate the effect of the temperature variation of H_t, we also measured hysteresis loops for all fixed temperatures at which j_{cm} data are taken. Using these hysteresis loops we were able to recalculate the $j_{cm}(T)$ values for the same fixed effective internal magnetic field (applied field $+H_t$) $H_{\mathrm{eff}}=130$ and 50 G [see triangles and squares in Fig. 1(a)]. The resulting shift from $j_{cm}(T,H_t)$ to $j_{cm}(T,H_{\mathrm{eff}})$ at $T \lesssim 30$ K turns out to be smaller than the shift due to the flux creep. Since we are attempting to use j_{cm} data only as a first approximation limited mainly by the flux-creep phenomena, more detailed analysis of the H_t effect seems to be unnecessary.

In the unirradiated BSCCO single crystal a pronounced kink shows up in the $j_{cm}(T)$ curve (Figs. 1 and 2) at $T=T^{\mathrm{CR}}$. This temperature also defines the crossover current j_c^{CR}. Below T^{CR} ($j_{cm}>j_c^{\mathrm{CR}}$) the critical current j_{cm} demonstrates a very strong exponential decrease with increasing temperature which is observed simultaneously with a very weak field dependence of $j_{cm}(T,H)$ [see Fig. 1(b)]. Above T^{CR} ($j_{cm}<j_c^{\mathrm{CR}}$) the temperature variation of j_{cm} is much smaller, but $j_{cm}(T,H)$ is strongly suppressed by applied field. In comparison with the $YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystals which are usually heavily twinned and also may contain relatively large oxygen-deficient domains in the Cu-O planes, BSCCO single crystals are untwinned and the oxygen atoms in the BSCCO structure are much less mobile than in YBCO. Therefore it is reasonable to expect that contrary to the YBCO single crystals with the *planar correlated disorder* arising from the twin boundaries, BSCCO as-grown single crystals most probably are characterized by the dominant *point disorder*, related to a few missing oxygen atoms in the crystalline structure. At the same time a larger anisotropy Γ of BSCCO [$\Gamma \approx 3000$ (Ref. 10)] in comparison with that of YBCO [$\Gamma \approx 25$ (Ref. 13)], strongly reduces the tilt modulus c_{44} (Ref. 14), thus making the flux lines in BSCCO sufficiently flexible to adjust themselves properly to an available distribution of the point defects. These arguments seem to justify the applicability of the Feigelman-Vinokur results of the collective pinning in the presence of point disorder for the description of the $j_{cm}(T)$ data in unirradiated BSCCO single crystals.

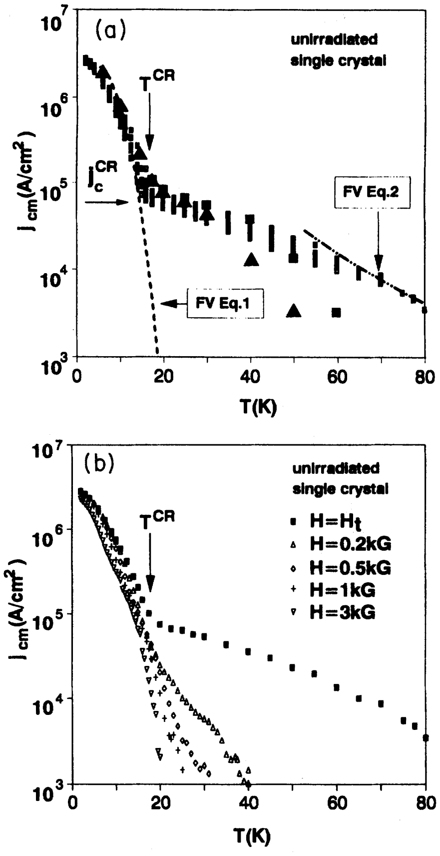

FIG. 1. (a) Temperature dependence of the critical current $j_{cm}(T,t)$ in the trapped field for an as-grown $Bi_2Sr_2CaCu_2O_8$ single crystal measured for different delay times t (1, 3, 10, 20, and 60 min). The dashed and dashed-dotted lines are the calculated j_c values, using Eq. (1) ($j_{cm}>j_0/\kappa^2$) and Eq. (2) ($j_{cm}<j_0/\kappa^2$), respectively, with the following fitting parameters: $\kappa=200$, $T^* \approx 2$ K, $(\gamma_m/\gamma)=16$, $j_0=j_c^{\mathrm{CR}}\kappa^2$, $H_{c2}(0)=40$ T. The triangles and squares correspond to the $j_{cm}(T,H_{\mathrm{eff}})$ data renormalized to the same fixed fields $H_{\mathrm{eff}}=130$ and 50 G, respectively. (b) Temperature dependences of the critical current $j_{cm}(T,H)$ for different fixed applied magnetic fields.

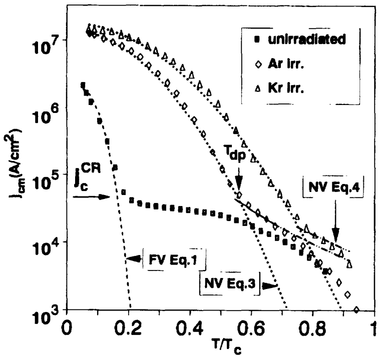

FIG. 2. Temperature dependence of the critical current $j_{cm}(T)$ in $H=H_t$ for as-grown (■), Ar- (◇) and Kr-irradiated (△) $Bi_2Sr_2CaCu_2O_8$ single crystals. The dashed line is calculated j_c values, using Eq. (1) ($j_c > j_0/\kappa^2$), dotted lines are calculated j_c values, using Eq. (3) [$T_{dp}(Ar)=0.402T_c$, $j_c(0)=1.4\times10^7$ A/cm^2 for Ar-irradiated and $T_{dp}(Kr)=0.495T_c$, $j_c(0)=1.75\times10^7$ A/cm^2 for Ar-irradiated single crystals], dashed-dotted lines are calculated using Eq. (4) with the same fitting parameters as for Eq. (3).

Following the ideas briefly outlined in Ref. 15, the different pinning regimes for unirradiated BSCCO single crystals may be identified as follows: at low temperatures $T<T^{CR}$ the exponential dependence[3,4] can be used to fit the $j_{cm}(T)$ data:

$$j_c \propto j_0\left[1+\frac{T}{T_T^*}\right]^{1/2} \exp\left[-\pi\sqrt{2}\left(\frac{B}{H_{c2}}\right)^{3/2}\frac{\gamma_m}{\gamma}\left(1+\frac{T}{T_T^*}\right)^3\right]. \tag{1}$$

Here j_0 is the depairing current, γ is the characteristic strength of the pinning potential, $\gamma_m=(H_c^2\xi^2)^2\xi$ is the value of the parameter γ corresponding to an extremely strong short-scale disorder, B is the magnetic induction, $T_T^* \propto B^{1/2}$ (Ref. 3) is the temperature at which the thermal fluctuations are larger than the coherence length: $\langle u^2\rangle \gg \xi^2$ and H_{c2} is the upper critical field.[3] This temperature range, except for the very low temperatures where $j_{cm}\approx$const, corresponds to the collective pinning of the small bundles with the strong dispersion. The term "collective" here emphasizes, in fact, that (1) *many pinning centers* are involved and (2) *a few flux lines* are forming a flux bundle. In this case the current j_c (Fig. 1) follows an exponential dependence. A very weak field dependence $j_{cm}(T,H)$ [see Fig. 1(b)] may be interpreted as a result of the remarkable cancellation of the $B^{3/2}$ and $[1+T/T_T^*(B)]^3 \approx B^{-3/2}$ (Ref. 3) in the argument of the exponent in Eq. (1).

When *the current* j_c *decreases below a certain threshold level* $j_c^{CR}\approx(4-5)\times10^4$ A/cm^2, we enter the temperature region $T>T^{CR}$. At these temperatures the strong exponential decrease of j_c with T is converted into a much weaker temperature dependence. The field suppression of $j_{cm}(T,H)$, however, is much stronger in this regime than at $T<T^{CR}$. Both weaker temperature dependence and stronger field dependence can be related in this case to the *large-flux-bundle weakly dispersive collective pinning*. The theory[3] predicts a power-law dependence for $T>T^{CR}\approx20$ K:

$$j_c \approx \frac{10j_0}{\kappa^2}\left[\frac{\gamma}{\gamma_m}\right]^2\left[\frac{H_{c2}}{B}\right]^3\left[\frac{T_T^*}{T+T_T^*}\right]^{11/2}, \tag{2}$$

where κ is the Ginzburg-Landau parameter. The kink in $j_c(T)$ at $T=T^{CR}$ corresponds to the crossover current $j_c^{CR}\approx j_0/\kappa^2$ (Ref. 3) which results from the transition from the exponential [Eq. (1)] to the power-law [Eq. (2)] dependence. The experimental value of the crossover current (Fig. 1) $j_c^{CR}\approx(4-5)\times10^4$ A/cm^2 is close to the theoretical estimate:[3] $j_c^{CR}\approx j_0/\kappa^2\approx10^4-10^5$ A/cm^2 with $\kappa=80-200$.[3] The power law [Eq. (2)] indeed gives a reasonable fit of our experimental data for currents $j_c(T)<j_0/\kappa^2$ (see dashed-dotted line in Fig. 1). Contrary to the regime at $T<T^{CR}$ [Eq. (1)] the field-dependent terms ($1/B^3$ and $[T_T^*/(T+T_T^*)]^{11/2}$ in Eq. (2)) are now not canceled, which may explain a strong field sensitivity of j_{cm} at $T>T^{CR}$.

The $j_{cm}(T)$ fits with Eqs. (1) and (2) are hindered by the temperature dependence of H_t. However, it is worth noting here that the $H_t(T)$ effect upon the $j_{cm}(T,H_t)$ data turns out to be diminished due to the particular combination of field and temperature dependences at $T<T^{CR}$ and $T>T^{CR}$. Indeed, at $T<T^{CR}$ the variation of j_{cm} and H_t is large, but the $H_t(T)$ effect can be neglected due to a very weak field dependence of j_{cm}. At $T>T^{CR}$ the field dependence of j_{cm} is quite strong, but the overall temperature variation of H_t is much weaker [see the broad $j_{cm}(T,H_t)$ plateau at $T>T^{CR}$ in Fig. 1].

In irradiated BSCCO single crystals, the critical current $j_{cm}(T)$ is strongly enhanced and the temperature suppression of j_{cm} becomes noticeably weaker (Fig. 2). In this case the dominant pinning centers are irradiation-induced columnar defects and therefore the Nelson-Vinokur theory[1,2] should be used for the description of $j_{cm}(T)$. As is shown in Fig. 2, the theoretical curve, corresponding to the j_c vs T dependence for the line correlated disorder in the temperature range $T_1<T<T_{dp}$:[2]

$$j_c(T)\approx j_c(0)\exp[-3(T/T^*)^2] \tag{3}$$

indeed gives a very good fit to our experimental $j_{cm}(T)$ data with only two fitting parameters [$j_c(0)$ and T^*]. Equation (3) works very well over 2.5 orders of magnitude variation of j_c and in a broad temperature range $T/T_c\approx0.1-0.6$ (Ar irradiated) and $T/T_c\approx0.1-0.75$ (Kr irradiated). The kink of the j_{cm} vs T curve for the irradiated samples can be interpreted as a depinning temperature T_{dp}. Then, if $T>T_{dp}$, the critical current should fall off more slowly:

$$j_c(T)=j_c(0)\left[\frac{b_0}{d}\right]^3\left[\frac{T^*}{T}\right]^4, \tag{4}$$

where $2b_0$ is a columnar track diameter, d is an average separation between columnar tracks, and kT^* is the characteristic energy scale for the columnar pin. The validity of Eq. (4) is confirmed by our experimental data in the high-temperature range $T>T_{dp}$ (see dashed-dotted lines in Fig. 2). As a result, the whole $j_c(T)$ curve can be nicely fitted by the Nelson-Vinokur theory[2] with very reasonable fitting parameters: $j_c(0)=1.4\times10^7$ A/cm^2 and $T^*=0.4T_c$ for the Ar-irradiated crystal and $j_c(0)=1.7\times10^7$ A/cm^2 and $T^*=0.5T_c$ for the Kr-irradiated crystal. These parameters correspond to $b_0/d \sim 0.1-0.2$. Since close to T_c the temperature dependences of λ, ξ, and H_{c2} are essential, while this was not taken into account in Refs. 1 and 2, we are not discussing here an enhanced rolloff of j_{cm} at $T/T_c > 0.85$.

In order to elucidate further the flux-line dynamics in different temperature regimes we determined the current-voltage characteristics in the picovolt range from the magnetization measurements.[16] Since we worked with magnetic fields $B \ll B_\Phi \approx 20$ kG, we used the following expression for the electric field E:[2]

$$E \propto \exp\left[-A_1\left(\frac{E_k}{T}\right)^{3/2}\left(\frac{j_0}{j}\right)^{1/2}\right], \qquad (5)$$

where $E_k \sim T^* d$ is a characteristic energy and A_1 is a constant. Equation (5) is valid for the case of a nearly empty band of localized states, i.e., for the number of the flux line being much smaller than the total number of columnar defects.[2] In the $\log_{10}E$-$j^{-1/2}$ plot the current-voltage characteristics are indeed linear at least for the temperature interval $T/T_c \approx 0.1-0.5$ (see the inset in Fig. 3). From the slope of the $\ln E$ vs $j^{-1/2}$ curves we determined the behavior of the coefficient $n = -A_1(E_k/T)^{3/2} j_0^{1/2}$ in Eq. (5). As is seen from Fig. 3, the n vs T follows the expected $n \sim (1/T)^{3/2}$ decay for the $B \ll B_\Phi$ case.[2]

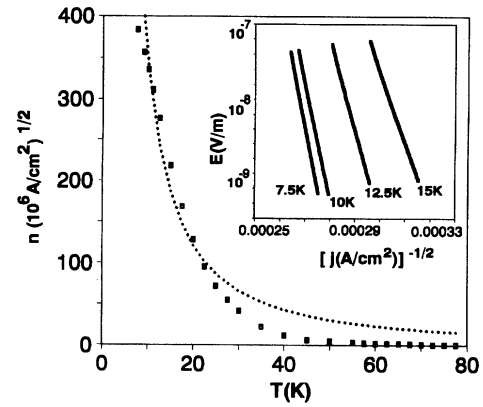

FIG. 3. Temperature dependence of the coefficient $n = -A_1(E_k/T)^{3/2} j_0^{1/2}$ relating current j and electric-field E in Eq. (5) for the Kr-irradiated $Bi_2Sr_2CaCu_2O_8$ single crystal. Inset: $\log_{10}E$-$j^{-1/2}$ plot of the current-voltage characteristics measured magnetically for the Kr-irradiated $Bi_2Sr_2CaCu_2O_8$ single crystal.

In conclusion, by analyzing the temperature dependence of the critical currents in as-grown and irradiated BSCCO single crystals, we have demonstrated the applicability of the point defects[3,4] and linear correlated disorder[1,2] models to obtain a very good quantitative fit of the experimental $j_{cm}(T)$ data over several decades of j_c. The kink on the j_{cm} vs T curve for the irradiated BSCCO single crystals has been interpreted as a depinning temperature $T_{\rm dp}$ in the Nelson-Vinokur model.[1,2] In addition, current-voltage characteristics for $B \ll B_\Phi$ are also in agreement with the Nelson-Vinokur theory for the case of a nearly empty band of localized states.

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