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Dissipation mechanisms in granular high T_c superconductors

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Abstract

We have studied the magnetoresistance and I–V characteristics of polycrystalline $La_{2-x}Sr_xCuO_{4-y}Cl_y$ samples as a function of temperature. Measurements were performed at temperatures near T_c and results were modeled taking into account the effect of thermal fluctuations as proposed by the Ambegaokar–Halperin model, the Anderson–Kim flux creep theory and the collective flux creep model (CFC). At low voltage, sub-ohmic results are better described by the CFC model. We found that the temperature dependence of the critical current density without thermal fluctuations indicates the presence of insulating barriers for non-chlorinated samples and metallic barriers for chlorinated samples. The obtained parameter $\mu \simeq 0.25$ for both samples is, within the CFC model, in agreement with a picture where non-interacting vortices are pinned in a bidimensional defect array. © 1997 Elsevier Science B.V.

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1. Introduction

Dissipation mechanisms related to the electrical transport properties of high temperature superconductors (HTS) have received a great deal of attention since their discovery. In the case of single crystals, the intrinsic properties have been studied, and the basic question of whether a real sample is really superconducting in magnetic fields above H_{c1} has been addressed. Theoretical [1] and experimental evidence [2] seems to have settled the issue, supporting the idea that, in random disordered samples, a true superconducting phase may exist in the presence of a penetrating magnetic field below a second-order glass transition temperature, $T_g(H)$. Within the framework of Fisher's vortex glass model [1], an ohmic regime is expected above $T_g(H)$ at low current levels while, below the glass transition, a non-linear response should develop and the voltage should vanish exponentially. However, similar behavior is predicted within the collective flux creep model (CFC) [3,4], but here dissipation is associated with the thermally activated jumps of flux line segments in a collective pinning regime.

On the other hand, in more complex systems such as polycrystalline samples, the presence of weak links at grain boundaries [5] led to the current-voltage (I–V) characteristics, including thermal fluctuations (TF), being described by a modified Ambegaokar–Halperin model (AH) [6] considering the system of weak links as a single effective junction, but agreement between experiment and theory was not clear [7,8], in particular in the low current range. Temperature effects were

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also included in the standard Anderson–Kim creep model (AK) [9,10] which describes the dissipation related to thermally activated flux jumps over barriers between the local minima of a pinning potential. The thermally assisted phase slippage dissipation of a moving vortex in the standard AK creep model is in correspondence with one thermally fluctuating weak link in zero magnetic field [11]. Moreover, the AH and AK predictions for both the temperature and current dependencies of the observed voltage are identical at low current, as will be discussed below.

The observation of a vortex glass phase in polycrystalline YBCO was claimed by Worthington et al. [12] who studied the I–V characteristics in a magnetic field. The transport properties of ceramic LSCO samples in a magnetic field have also been described within this framework [13]. In this case, dissipation is due to the growth of intergranular vortex loops nucleated by thermal fluctuations, forced by the transport current to move and constrained both by the interaction with random pinning sites and the elastic energy of the flux line.

In this work we present magnetoresistance measurements and I–V characteristics for polycrystalline $La_{2-x}Sr_xCuO_{4-y}Cl_y$ samples (LSCOC) at zero applied magnetic field. We have tested the AH, AK and CFC models, where in the AK and CFC cases we assume that at zero applied field there is a correspondence between the dissipation of the fluctuating weak link array and the dissipation due to intergranular vortex loop excitations interacting with a random pinning potential. As will be shown, the CFC model describes our results satisfactorily, and the temperature dependence of the fitted critical current densities provides information on the type of junctions of each sample.

2. Experimental

High quality single phase polycrystalline samples of $La_{2-x}Sr_xCuO_{4-y}Cl_y$ [14–18] were studied for two nominal compositions ($x = 0.15$, $y = 0$ (A) and $y = 0.15$ (B)). The distance between voltage contacts was $\sim$1 cm and the sample section was $\sim 6\times10^{-3}$ cm^2.

We performed electrical resistivity measurements as a function of temperature ($\rho(T)$) applying different magnetic fields in order to characterize the granularity of the samples by the broadening of the superconducting transition [19], separating the contribution of the superconducting grains from junctions to the resistivity. The magnetic field was applied parallel to the transport current to avoid possible contributions from a flux flow process.

We also report I–V curves as a function of temperature near T_c using a four-point contact DC technique. Low resistance contacts ($R < 1$ Ω) were obtained by baking silver paste on previously gold sputtered contacts and no overheating was observed for applied currents below 10 mA.

3. Results and discussion

Typical results for magnetoresistance and I–V characteristics measurements for samples A and B are shown in Figs. 1 and 2, respectively. The magnetic field broadens the resistive transition which can be separated into two regions [19]: first, a steep decrease is observed due to the transition of grains to the superconducting state ($T_{cs} < T < T_{c0}$) and then the curves split from a single point (T_{cs}) for different applied magnetic fields until zero resistance is obtained at T_c.

The presence of weak links is responsible for the extreme sensitivity of critical currents (J_c) at low magnetic fields. The problems to be solved are the nature of the weak links, whether the junctions are SIS (superconductor–insulator–superconductor) or SNS (superconductor–normal–superconductor) type and the origin of the structure observed in $\rho(T)$ for the LSCOC samples even at zero applied field. We note that if the temperature is sufficiently low to make TF negligible, the nature of the junction may be established by fitting the experimental data to the equation [20,21]:

$$I_c^{NF}(T) = I_{c0}^{NF}\left(1 - \frac{T}{T_{cs}}\right)^n, \qquad (1)$$

where NF indicates no fluctuations. For a SIS or a SNS junction we should have $n = 1$ or $n = 2$, respectively.

However, when TF are relevant ($k_BT \simeq E_j$, where E_j is the coupling energy of the junction) fitting of the experimental data to Eq. (1) gives different values for the parameter n, depending on the threshold criterion (V_0) chosen to determine $I_c(T)$ from the I–V characteristics. Thus, in the following, we consider different

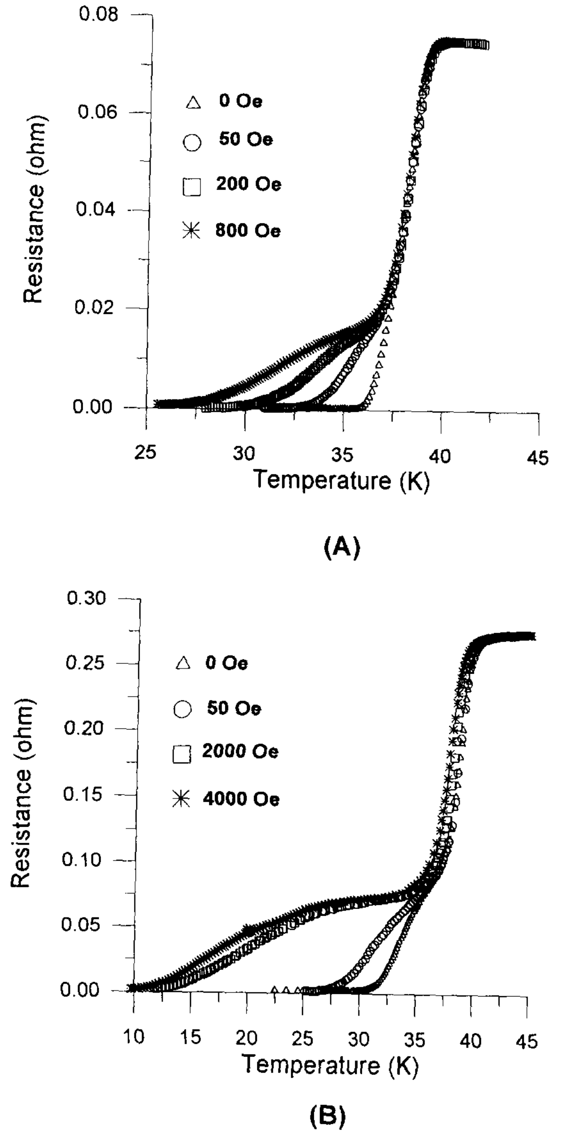

Fig. 1. Magnetoresistance as a function of temperature for (A) pure ($x = 0.15$, $y = 0$) and (B) chlorinated ($x = 0.15$, $y = 0.05$) LSCOC samples.

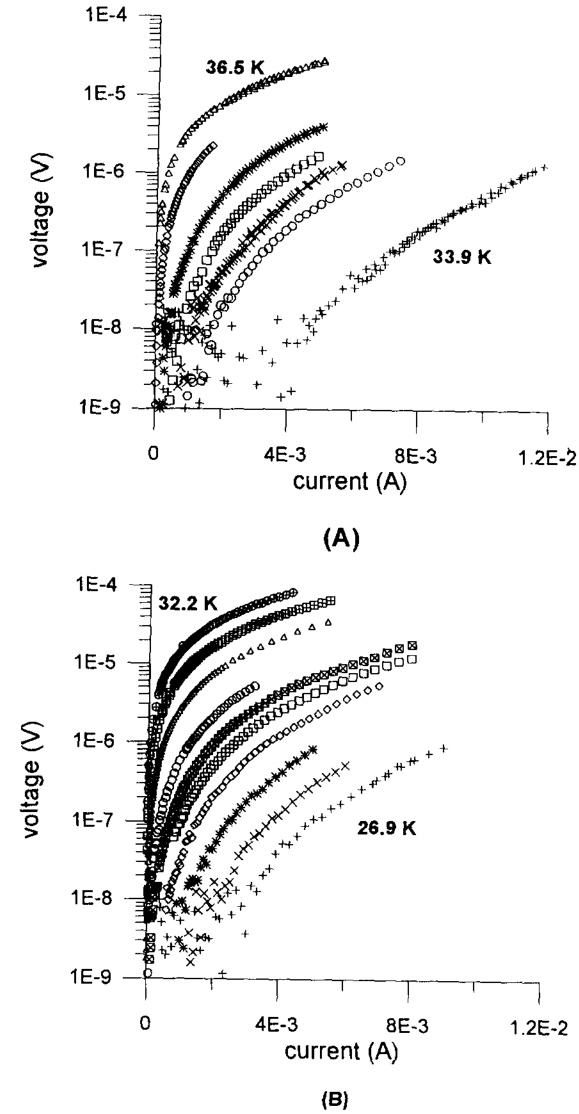

Fig. 2. I–V characteristics at different temperatures for (A) pure ($x = 0.15$, $y = 0$) and (B) chlorinated ($x = 0.15$, $y = 0.05$) LSCOC samples.

models that include TF effects in order to obtain information related to I_c^{NF}.

We first consider the AH model where the measured DC voltage, V, is given by

$$v = \frac{V}{I_c^{NF} R} = \frac{4\pi}{\gamma} \left\{ (e^{\pi\gamma\alpha} - 1)^{-1} \left[\int_0^{2\pi} f(\varphi) d\varphi \right] \times \left[\int_0^{2\pi} \frac{1}{f(\varphi')} d\varphi' \right] + \int_0^{2\pi} d\varphi \int_\varphi^{2\pi} d\varphi' \frac{f(\varphi)}{f(\varphi')} \right\}^{-1}, \quad (2)$$

where $f(\varphi) = \exp(-U(\varphi)/T)$, $U = -\frac{1}{2}\gamma T(\alpha\varphi + \cos\varphi)$, $\gamma = \hbar I_c^{NF}(T)/(ekT)$, $\alpha = I/I_c^{NF}(T)$ and I is the applied current.

This equation can be simplified in some convenient limits obtaining analytical expressions:

$$v = \alpha, \qquad \gamma \to 0, \tag{3}$$

$$\begin{aligned} v &= \sqrt{\alpha^2 - 1}, & \gamma \to \infty, \ \alpha > 1, \\ v &= 0, & \gamma \to \infty, \ \alpha < 1, \end{aligned} \tag{4}$$

$$v = 2\sqrt{1-\alpha^2}\exp\left\{-\gamma\left[\sqrt{1-\alpha^2} + \alpha\sin^{-1}(\alpha)\right]\right\} \times \sinh(\pi\gamma\alpha/2), \quad \gamma\,\text{large}, \alpha < 1, \tag{5}$$

$$\lim_{\alpha\to 0}\frac{v}{\alpha} = \left[I_0\left(\frac{\gamma}{2}\right)\right]^{-2}, \tag{6}$$

where I_0 is the modified zero-order Bessel function.

Fittings using Eq. (5) with γ and I_c^{NF} as free parameters, while R_n is obtained from magnetoresistance measurements as $R_n = R(T_{cs})$, are discussed. Results for sample A are shown in Fig. 3A and they are consistent with the stated limits for the applicability of Eq. (5). Clearly, the low current region is not well described because the AH model predicts ohmic behaviour between V and I, while experimental data show a sub-ohmic dependence.

We have also tested the AK model, which considers dissipation originated by thermally activated movement of vortices over pinning potential barriers U_c. In this case, the DC voltage is given by

$$V = V_0\,\mathrm{e}^{-F_0/kT}\sinh\left(\frac{F_0}{kT}\frac{I}{I_c^{NF}}\right), \tag{7}$$

where $V_0 = 2v_0 dB$, d is the distance between voltage contacts on the sample, B the magnetic induction field, v_0 the vortex velocity and F_0 the activation energy.

Fittings to Eq. (7) are also unsatisfactory, as shown in Fig. 3B for sample A, even using three free parameters (V_0, F_0 and I_c^{NF}). This result is not surprising because for $I/I_c^{NF} \to 0$, Eqs. (5) and (7) are equivalent and describe a similar situation.

The correspondence between fluxon motion in bulk material and thermally activated phase slippage in a Josephson junction (JJ) has been widely established [11]. The description of the dissipation in a JJ array using a formalism based on flux motion, even at zero external magnetic field, is well understood.

Both the AH and AK models predict ohmic behavior for the I–V characteristics in the low current limit ($I \ll I_c^{NF}$). As we can see from Fig. 3, experimental data follow well defined sub-ohmic behavior that cannot be described within the preceding framework.

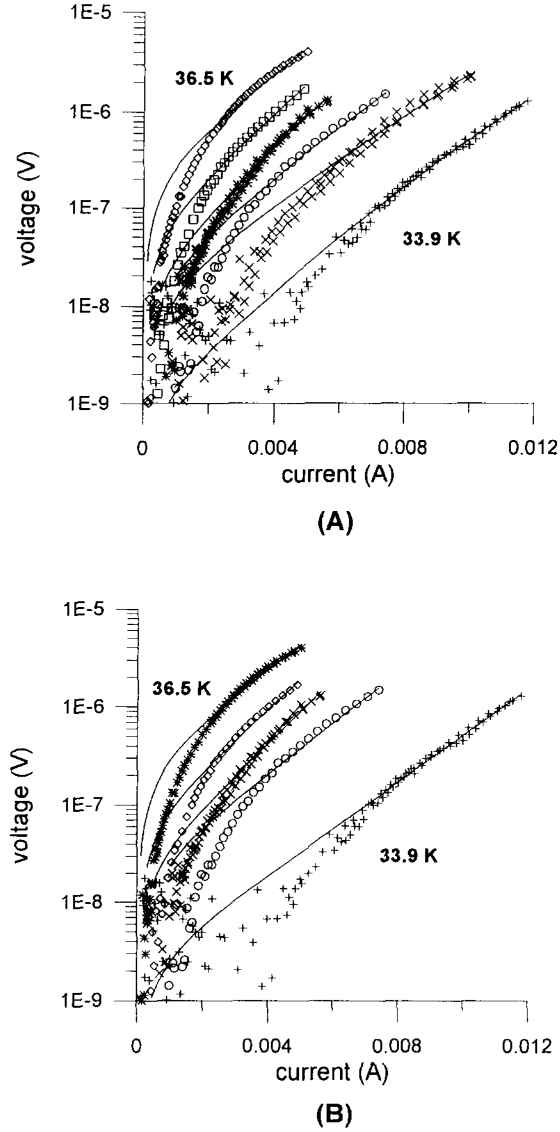

Fig. 3. Fitting of the I–V characteristics: (A) AH model and (B) AK model, both for sample A. Experimental data follow clear sub-ohmic behavior in the low current regime.

In the CFC model the hopping of vortex bundles determines a current-dependent effective pinning potential $U_c(I)$. Within this model, the related dissipation can be expressed as:

$$V = V_0\exp\left[-\frac{U_{c0}}{kT}\left(\frac{I_c^{NF}}{I}\right)^{\mu}\right] \quad \text{if } I \ll I_c^{NF}, \tag{8}$$

$$V = V_0\exp\left[-\frac{U_{c0}}{kT}\left(1 - \frac{I}{I_c^{NF}}\right)^{\alpha}\right] \quad \text{if } I \to I_c^{NF}, \tag{9}$$

where U_{c0} is the effective pinning potential at zero current, μ is given by the effective dimensionality of the flux-line lattice [1] and α depends on the interactions between vortices [4]. In Anderson's original proposal $\alpha \simeq 1$.

The two previous equations can be condensed into a single equation which includes the two limits, depending on the relation between I and I_c^{NF}:

$$V = V_0 \exp\left[-\frac{U_{c0}}{kT}\left(\frac{I_c^{NF}}{I} - 1\right)^{\beta}\right], \tag{10}$$

where $V_0 = V(I_c^{NF})$; $\beta \to \mu$ when $I/I_c^{NF} \ll 1$ and $\beta \to \alpha$ when $I \to I_c^{NF}$.

We fitted the experimental data to Eq. (10) with I_c^{NF}, U_{c0} and β as free parameters and good agreement was obtained, as shown in Fig. 4 for both samples. V_0 was taken as 1 mV [22,23] and this choice will be discussed below after a description of the method we propose to use to determine $I_c^{NF}(T)$ from experimental data.

In this method we establish different threshold criteria V_{0i} and we obtain for all the measured temperatures T_j, $(T_j, I_{ci}^{NF}(T_j))$ pairs for each criterion. These pairs can be fitted to Eq. (1) and $J_{c0}^{NF}(V_{0i})$ and $n(V_{0i})$ can be obtained, allowing us to conclude whether junctions are of the SIS or SNS type. In order to avoid overheating of the sample, most of our curves did not reach sufficiently high V_0 values, but this was solved by choosing different values for V_0 in Eq. (10) and fitting our data to obtain $(I_{ci}^{NF}(T_j)$, U_{c0i} and $\beta_i)$ parameters for each V_{0i}. Again, $(T_j$ and $I_{ci}^{NF}(T_j))$ were fitted to Eq. (1). The results are shown in Fig. 5, where parameters show asymptotic behavior the value of which is almost constant for $V_{0i} > 1$ mV, indicating that the limit $I/I_c^{NF} \ll 1$ was reached. Results for β_i are shown in Fig. 6.

The obtained critical current densities were:
sample A

$$J_c^{NF}(T) = 20\frac{A}{\mathrm{cm}^2}\left(1 - \frac{T}{37.7\ \mathrm{K}}\right), \tag{11}$$

sample B

$$J_c^{NF}(T) = 100\frac{A}{\mathrm{cm}^2}\left(1 - \frac{T}{36.5\ \mathrm{K}}\right)^{2.3}, \tag{12}$$

These results indicate that sample A (non-chlorinated) and sample B (chlorinated) are mainly composed

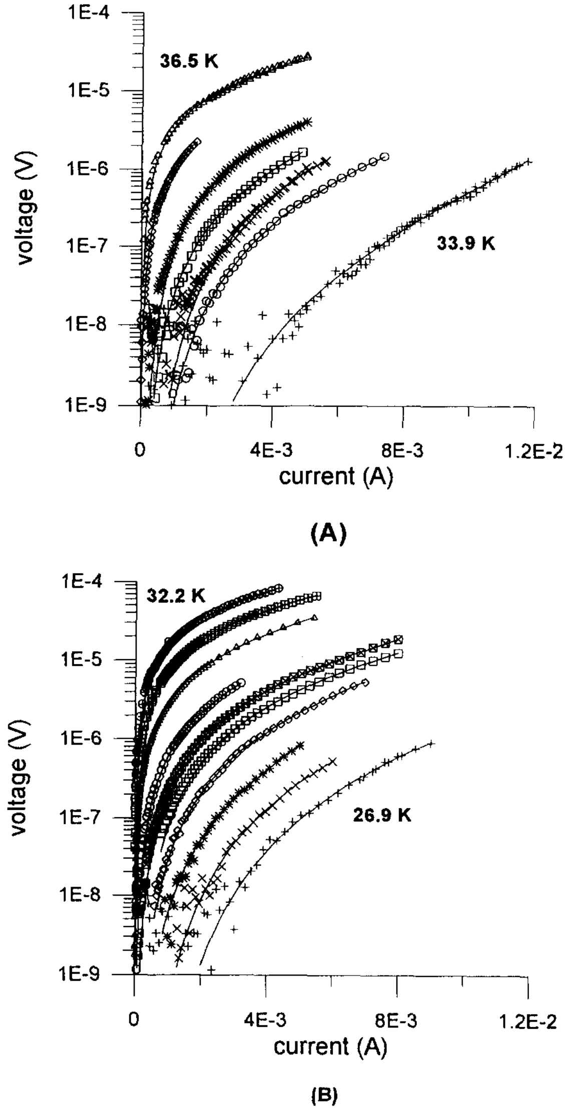

Fig. 4. Fitting of the I–V characteristics with the CPC theory for (A) pure ($x = 0.15$, $y = 0$) and (B) chlorinated ($x = 0.15$, $y = 0.05$) LSCOC samples.

of SIS and SNS junctions, respectively. J_{c0}^{NF} reflects a lower cohesion of ceramic grains for the LSCO sample than for the chlorinated version, as is also corroborated by SEM studies [24]. Near T_{cs}, $J_{c0}^{NF}(\mathrm{A}) > J_{c0}^{NF}(\mathrm{B})$; this can explain the characteristic foot-shape observed for the LSCOC samples, implying that $\rho(T)$ is dominated by TF in this temperature regime. It should be pointed out that the foot shape in the resistive transition, even at zero field, is characteristic of all the tested samples y = 0.02, 0.05 and 0.1 but is

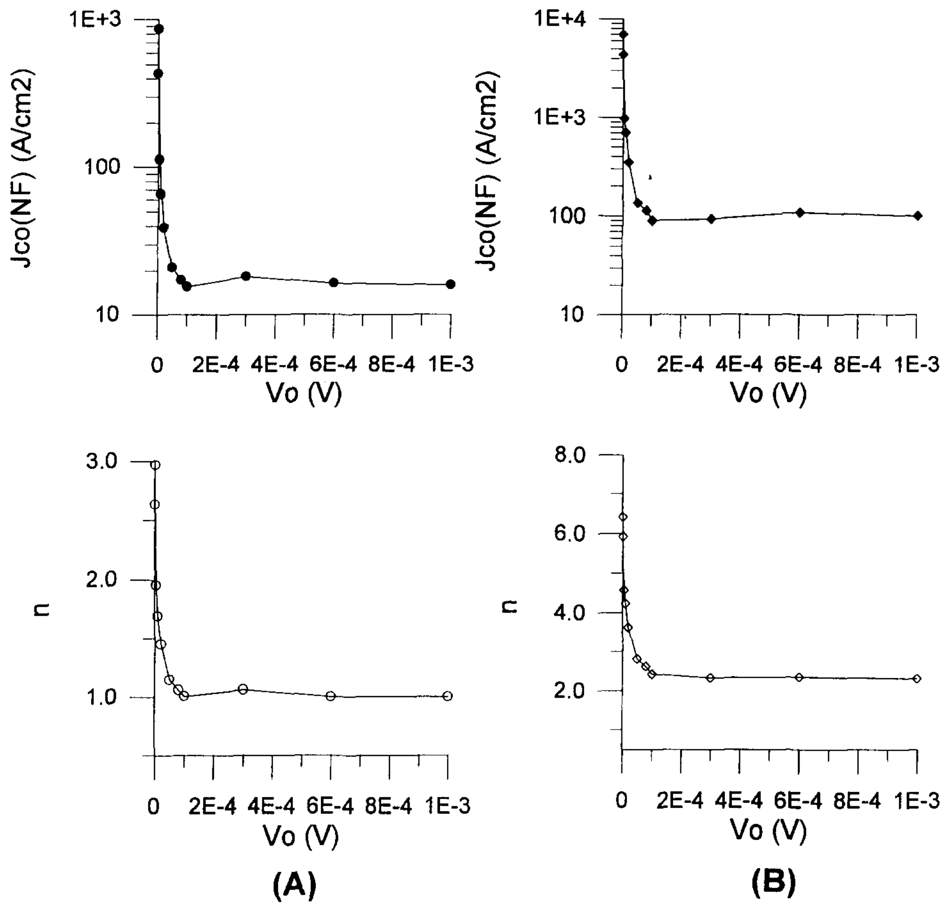

Fig. 5. $I_{c0}^{NF}(V_0)$ and $n(V_0)$ for samples A and B.

not shown here [25].

The U_{c0} values ($100\ K < U_{c0} < 200\ K$) are within the interval obtained in magnetic relaxation experiments on single crystals [26–28].

For $V_0 \simeq 1$ mV our measurements are effectively in the $I/I_c^{NF} \ll 1$ range and, consequently, $\beta \to \mu$. The asymptotic value is $\beta \simeq 0.25$. Following the CFC theory, this value determines that the junction array acts as a 2D defect network where fluxons should cross potential wells related to the coupling of superconducting grains. This network might reflect the disorder of the JJ array together with the random distribution of coupling energies, giving an adequate scenario for the applicability of the CFC model.

On the other hand, when the current is increased ($I/I_c^{NF} \leqslant 1$) all the models analysed here are in good agreement with experimental data, indicating the existence of a common limit for the three models.

4. Conclusions

The I–V characteristics of polycrystalline $La_{2-x}Sr_x$-$CuO_{4-y}Cl_y$ samples as a function of temperature are correctly described by the CFC model. Although we are aware, as pointed out in Ref. [12], that the small local distortion of a hexagonal lattice, implicit in the CFC model, is not the best choice for a ceramic sample, the important feature is the current dependence of the effective pinning potential ($U_c(J)$) which is essential to reproduce the sub-ohmic behavior of the experimental data in the low current regime.

A method was proposed to determine the critical current in the absence of thermal fluctuations I_c^{NF}.

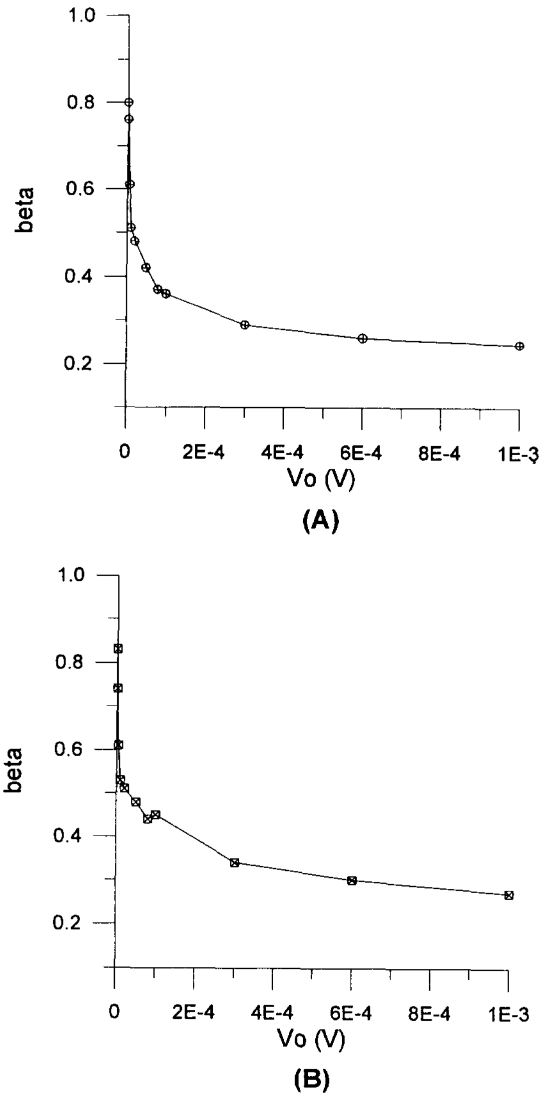

Fig. 6. Parameter $\beta(V_0)$ of Eq. (10) for samples A and B.

The results suggest the presence of insulating junctions (SIS) in the non-chlorinated sample and metallic junctions (SNS) in the chlorinated sample. Further work should be carried out to gain an understanding of the microscopic structure which leads to this effect.

For the low current regime ($I/I_c^{NF} \ll 1$) the asymptotic value of the β parameter for both samples is in agreement with the CFC model and corresponds to the case where non-interacting vortices are pinned in a bidimensional defect array ($\mu = 0.25$). This is understood within the picture in which vortex interactions can be ignored for small magnetic fields.

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