# Current-induced vortex glass transition in $YBa_2Cu_3O_x$ thin films

M. Acosta, Víctor Sosa and C. Acosta.
*Dept. of Applied Physics, CINVESTAV-IPN Unidad Mérida,*
*A.P. 73 Cordemex, 97310 Mérida, Yuc., México*

Nonlinear current–voltage curves were measured in c-oriented $YBa_2Cu_3O_x$ thin films at zero external magnetic field. We demonstrated that even in this case the vortex glass model can be used to extract from a critical scaling analysis the indexes *z* and *n*. We associated this behavior to the vortex excitations induced by the applied current. Our results showed that small *z* and large glass temperature values are related with a wide and inhomogeneous distribution of pinning forces. The broadening of this distribution was caused by a slight grain misalignment formed during the growth process.

*Keywords*: YBCO thin film, vortex glass transition, and current voltage characteristics.

## 1. Introduction

Current-transport measurement is one of the most used methods to study the flux motion, vortex pinning mechanism and dimensional crossover in high-temperature superconductors (HTSC). To explain the current-voltage (*I-V*) characteristic of any particular material is very difficult due to the many simultaneous processes that can induce the appearance of an electric field (*E*). Different models to study this dissipative behavior have been used: thermally assisted flux-flow [1,2], flux-creep [3], glassy transitions (bose glass [4-6] and vortex glass (VG) [7-10]), that predicted very similar shapes for the *I-V* curves.

Much attention has been focussed in the VG transition since Fisher et al. proposed it in 1989 [7], taking into account the pinning and collective effects on the vortex lines. This model established a second-order phase transition from a resistive vortex-liquid phase to a superconducting vortex glass for disordered three-dimensional type-II superconductors.

Experimental evidences for the VG transition have been observed extensively in HTSC under magnetic fields of a few Tesla [11-13] and only recently in absence of magnetic field [14]. The interactions between vortices are fundamental in the high-field regime. At zero magnetic field the applied current density *J* induces vortex excitations with a characteristic length given by $\left( k_B T / f_0 J \right)^{1/2}$ where $k_B$ is the Boltzmann constant, *T* is the temperature and $f_0$ the magnetic flux quantum. So, the nonlinearity of the *I-V* curves can be explained as excitations of the vortex pairs in the vortex lattice. In recent reports the relation between the parameters of the VG scaling with the properties of the material was studied for different HTSC [15,16 ]. In this work we present the *I-V* characteristics of two $YBa_2Cu_3O_x$ (YBCO) thin films at zero magnetic field, exhibiting the common VG scaling. We found that the scaling indexes and the glass temperature (*Tg*) of these samples could be related with their structural characteristics. In our case *Tg* was larger and the dynamical index *z* was smaller for the sample with a greater amount of structural imperfections.
The static index *n* was similar for both samples within the error margins.

## 2. Experimental Details

Two YBCO thin films, $S_1$ and $S_2$, oriented with the c axis perpendicular to the film plane were prepared by RF magnetron sputtering onto $SrTiO_3$ substrates under conditions described previously [17]. Both samples were grown in the same conditions except that the substrate used for $S_2$ was positioned 2 cm below the position of the substrate for $S_1$, respect to the center of the target.

The superconducting critical temperature (*Tc*), critical current density ($Jc \sim 10^5$ A/cm$^2$ at 77 K) and the current-voltage characteristics were measured by the four-point probe technique. *Tc* value was defined as the maximum of the dR/dT curve, using a bias current of 10 µA. Films were patterned using a mechanical method, resulting in bridges with typical dimensions of 150-µm width and 100-µm long. A Hewlett Packard 34420A nanovoltmeter, with a 50-nV resolution, was used to measure the voltage signal. A Keithley 220 programmable current source supplied a current in the range from 1 nA to 100 mA. The temperature was determined using a silicon diode.

The current was supplied in pulses with a proper time duration and sufficient time between pulses to avoid the film heating. Measurements were realized in zero magnetic field, using a computer for data acquisition and control. Thickness of the samples was estimated by using Scanning Electron Microscopy (SEM) observations, and a typical value of about 200 nm was determined. Structural analysis by x-ray diffraction (XRD), i.e., Bragg-Brentano diffraction patterns, were performed with a Siemens D500 diffractometer.

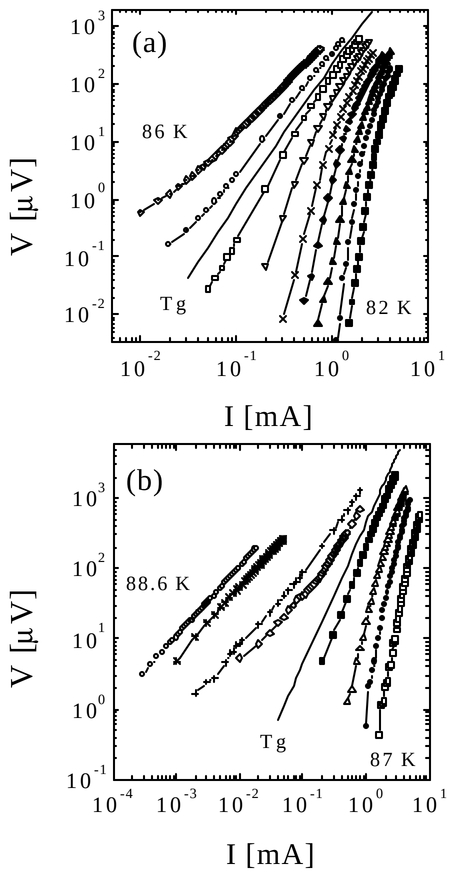


**Figure 1.** Log-log plot of the *I-V* curves for (a) $S_2$ and (b) $S_1$. The solid line represents the isotherm at glass temperature, *Tg*.

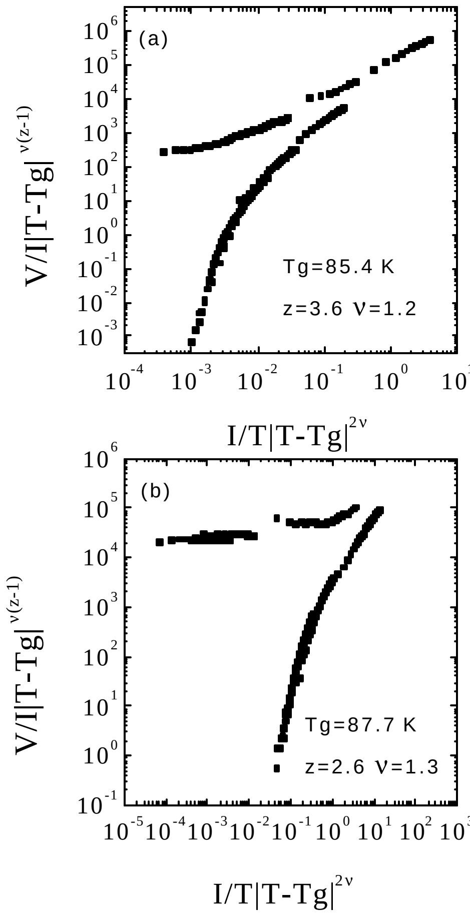


**Figure 2.** The scaling collapse of the I-V curves for (a) $S_2$ and (b) $S_1$, using the experimental values of *Tg*, *z* and $\nu$.

## 3. Results and Discussion

Figure 1 shows a log-log plot of the *I-V* curves for the two YBCO films. These curves are isotherms displaying the common critical VG behavior, crossing over from a positive curvature above *Tg* to a negative curvature below *Tg*. Using the method proposed by Zhao et al. [18] we fitted every curve to a second order polynomial of the form $\log V = a_0 + a_1 \log I + a_2 \log^2 I$ .

The coefficient $a_2$ determines the curvature, and we obtained the *Tg* values by interpolating the curve for $a_2 = 0$. According to Fisher et al. [7] the *E-J* curves follow a power-law relation at *Tg*: $E(J, T = Tg) \propto J^{z+1/2}$, where *z* is the dynamical exponent. This way, the slope of the power-law characteristic at *Tg* provides a measure of *z*.

Near the phase transition the electric field exhibits a scaling dependence on *J* according to $\frac{E}{J|T-Tg|^{\nu(z-1)}} = F_{\pm}\left[\frac{J}{T|T-Tg|^{2\nu}}\right]$ where $\nu$ is the static exponent and $F_{\pm}$ is a scaling function. $\nu$ is related with a linear resistivity above *Tg* in the small current regime. In our case $\nu$ was found to be 1.3(1) for $S_1$ and 1.2(1) for $S_2$. Therefore the VG model predicts that the *I-V* curves will collapse onto a single scaling function with two branches when each isotherm is plotted as $\frac{V}{I|T-Tg|^{\nu(z-1)}}$ versus $\frac{I}{T|T-Tg|^{2\nu}}$.

In figure 2 we can observe that this scaling is clearly defined for both samples, using our experimental values of *Tg*, *z* and $\nu$. These values are shown in Table I.

**Table 1.** Critical temperature (*Tc*), glass temperature (*Tg*) and scaling indexes *z* and $\nu$ for the YBCO films investigated. Typical error bars are ± 0.1 K for *Tc* and *Tg*, and ± 0.1 for z and $\nu$.

| Sample | *Tc* (K) | *Tg* (K) | *z* | $\nu$ |
|---|---|---|---|---|
| $S_1$ | 89.5 | 87.7 | 2.6 | 1.3 |
| $S_2$ | 89.2 | 85.4 | 3.6 | 1.2 |

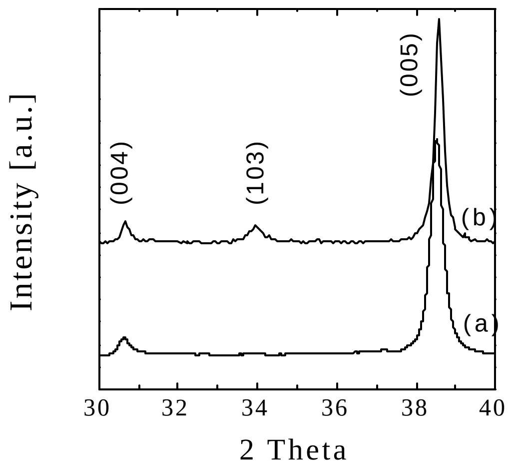


**Figure 3.** X-ray diffractogram in the 30°- 40° region for (a) $S_2$ and (b) $S_1$. The (103) peak is clearly observed in $S_1$, but absent in $S_2$.

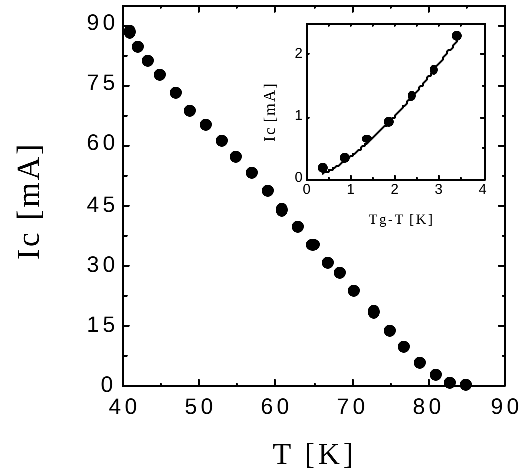


**Figure 4.** Critical current (*Ic*) vs. temperature for sample $S_2$. The inset shows the behavior near *Tg*. The solid line corresponds to a fitting of the type $Ic \propto (Tg - T)^d$, with $d$= 1.48 ± 0.06.

The resistivity transition for both samples is approximately 3 K broad, indicating the presence of structural defects in the films [19]. In figure 3 we can observe the existence of the (103) peak in the x-ray diffractogram of $S_1$. For $S_2$ this peak is absent, and only the (00l) peaks characteristic of the c-axis preferential growth are present. The (103) peak is associated with a misalignment in the film (c axis tilted by ± 45° respect to the substrate surface normal). Grains with this alignment produce structural defects in the sample. This non-optimum structural property of $S_1$ is responsible of a wider distribution of pinning centers through this sample.

In reference 20 the scaling of the *E-J* curves was theoretically examined for YBCO thin films assuming a magnetic field of 4 T. Different spreads of pinning forces were assumed. In that case the *Tg* values increased, *z* values decreased and $\nu$ values increased with broadening of the distribution of flux-pinning strength. Samples with such inhomogeneous pinning distribution contain regions with a very low local *Jc* [21].

According to our results shown in Table 1, the *Tg* value is about 3 K higher for $S_1$, the sample with poorer structural properties. Also, the z value decreased from 3.6 for $S_2$ to 2.6 for $S_1$. Therefore the sample with a wider inhomogeneous pinning center distribution has a larger *Tg* and smaller *z*. The tendency of our experimental results for *Tg* and *z* coincide with calculations of reference 20. However, even for $S_2$ the *z* value is small in comparison with similar measurements (*z* = 4.4, Wang et al. [14]), indicating still the existence of a wide pinning center distribution. The $\nu$ values for both films are the same within the error margins, in correspondence with similar reports [22].

Figure 4 shows the critical current vs. temperature characteristic for sample $S_2$. A linear dependence is clearly observed over a wide range of temperature.

Near *Tg* (inset of figure 4) the behavior is nonlinear, and in general can be expressed as a power law $Ic \propto (Tg - T)^d$, with $d$= 1.48 ± 0.06. For sample $S_1$ the *Ic* dependence on temperature is similar, with $d$= 1.51 ± 0.06. In other works it has been reported that the static critical index $\nu$ is closely related with the critical current dependence on temperature, so in our measurements we obtained similar $\nu$ values, and corresponding similar exponents for the *Ic* dependence on *T* [23].

**Conclusions**

A current-induced vortex glass transition is clearly appreciated, in our *I-V* measurements even at zero magnetic field. This work emphasizes that the VG transition is not universal for different films, and the scaling exponents (*Tg*, *z*, $\nu$) depend on the amount and kind of inhomogeneities of the films. Particularly we observed that *Tg* increases and z decreases for the film with poorer structural properties. In our case the additional defects are associated with the existence of the misalignment (103) peak in the x-ray diffractogram. The critical current dependence on temperature is linear over a wide range of temperature. Near *Tg* the behavior is nonlinear, and in general can be expressed as a power law.

**Acknowledgements**

We thank the technical support given by Wilian Cauich, Oscar Ceh, Fabio Chalé, Fidel Gamboa, Oswaldo Gómez, Mario Herrera, Victor Rejón, Felipe Caballero, and Roberto Sánchez. Secretary assistance from C. Simón and L. Pinelo is fully acknowledged.

Partial financial support from CONACYT is also acknowledged. M. Acosta thanks a scholarship from Secretaría de Relaciones Exteriores (México).

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