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Voltage–current characteristics in *c*-axis-oriented $Bi_{1.8}Pb_{0.4}Sr_2Ca_2Cu_3O$/Ag tapes

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Abstract. Detailed measurements of the voltage–current (V–I) characteristics for *c*-axis-oriented $Bi_{1.8}Pb_{0.4}Sr_2Ca_2Cu_3O_y$ (Bi(2:2:2:3))/Ag tapes have been performed in a low-magnetic-field range. The results show that the V–I curves are determined by a thermally activated flux creep process and possess a power-law behaviour. The activation energy U_J derived from the V–I curves was found to follow a $(1-T/T_c)^n/H^{0.15}$ functional relationship, n being 0.37 for $H \parallel ab$ and 0.57 for $H \parallel c$. In contrast with the $(1-T/T_c)^{3/2}/H$ theoretical prediction, this result shows very weak field and temperature dependences of U_J in the low-field region. A small negative curvature of $\log V$ versus $\log I$ plots near the temperature T_m at which the V–I curves change from being strictly linear to being nonlinear can also be found. This observation was tested using vortex glass (VG) or collective pinning (CP) models. The results showed that the VG or CP descriptions fail probably because of the high current density used in the measurement. We think that the negative curvature can be interpreted from the possible existence of the crossover from flux creep to flux flow.

1. Introduction

The static and dynamic properties of vortices in the mixed state of high-T_c superconductors (HTCSs) have received considerable attention [1], driven by both scientific and practical interest. Among the many new and interesting experimental findings, the occurrence of the 'irreversibility line' [2] and the pronounced broadening of the resistive transition [3] in a magnetic field are two of the most important. Many theoretical models to explain these experimental facts have been proposed in terms of giant flux creep [4], flux lattice melting [5], vortex glass (VG) [6] or Bose glass [7], flux motion [8], fluctuations [9] and Josephson coupling [10], but none of these approaches along has been completely successful. The measurements of the voltage–current (V–I) curves have frequently been used to examine the theoretical approaches. Conventionally, the Anderson–Kim [11] flux creep model gives V–I characteristics of the type $V \propto \sinh(I/I_0)$ and predicts a positive curvature on a $\ln V$ versus $\ln I$ plot. As pointed out by Dew-Hughes [12], this model predicts $I \propto \ln V$ for the activation energy $U \gg k_BT$ and $I \propto V$ for $U \ll k_BT$. Zeldov *et al* [13], however, observed a power-law variation in the V–I curves. By assuming that the activation energy has the form $U(T,H,J) = U_J(T,H)\ln(J_0/J)$, where J_0 is the current for which U approaches zero, this power-law behaviour can be well accounted for in the framework of the thermally activated flux-creep model. However, Koch *et al* [14] found a transition in the $\log V$ versus $\log I$ curves from positive to negative curvature as the temperature decreases. This observation was claimed to be strong evidence for the existence of the transition from vortex liquid to VG because a negative curvature is only expected by the VG [6] or collective pinning (CP) [15–17] theories. In these theories, V–I curves follow the functional relationship $V = A\exp[-(B/J)^{\mu}]$, where A and B are current-independent constants and μ is a universal constant. On the other hand, several workers have argued [18, 19] that the observed change in the $\log V$ versus $\log I$ curves can also be interpreted within the framework of the flux-creep theory [11]. Up to now, most experimental data reported were obtained from YBa_2Cu_3O and $Bi_2Sr_2CaCu_2O$ superconductors [20]. On the practical side, the Bi(2:2:2:3) material is the most promising because of the higher $T_c(= 110$ K) and because it contains no rare earth element. The studies on Bi(2:2:2:3)/Ag tapes are of important significance for applications such as superconducting magnets. In this paper, a series of measurements of the V–I curves for a c-axis-oriented Bi(2:2:2:3)/Ag tape are presented. The results seem to support the dissipation mechanism of thermally activated flux motion.

2. Experiment

The c-axis-textured tapes with the nominal composition $Bi_{1.8}Pb_{0.4}Sr_2Ca_2Cu_3O$ were fabricated by a method following the powder-in-tube technique. The Ag-sheathed sample (length, 15 mm; width, 8 mm) had an overall thickness of 80 μm, with an oxide core of 40–50 μm. The x-ray diffraction pattern for the tape showed that the superconductor was composed of an almost pure Bi(2:2:2:3) phase [21], having a preferential grain orientation with the c axis perpendicular to the film plane. The details of the preparation process have been reported elsewhere [21]. The critical current density of the sample used in this study was about 2.25×10^4 A cm^{-2}. The V–I curves were measured by the DC four-probe technique and recorded through an x–y recorder with a sensitivity of 5 μV cm^{-1}. The magnetic field was applied perpendicular ($H \parallel c$) and parallel ($H \parallel ab$) to the tape surface and always normal to the current direction. The temperature was measured with a calibrated copper–constantan thermocouple.

3. Results and discussion

A series of V–I curves in a low-magnetic-field range have been measured by a pulsed-current method to reduce the heating effect. Figure 1 shows a set of these measured curves for a magnetic field of 1000 G applied perpendicular to the tape plane ($H \parallel c$). The data were taken at 1 K intervals from 79.5 to 98.5 K, omitting 85.5 K. The temperatures for the other three curves are labelled in figure 1(a). In figure 1(a) they are plotted on linear axes and in figure 1(b) on log–log axes. The appearance of the curves in figure 1(a) changes dramatically at 97.5 K and below this temperature they show increasing upward curvature. What appears to happen at this temperature, denoted by T_m, is that the curves change from being strictly linear, to being affine, i.e. they do not go through the origin but develop a positive intercept on the current axis. The behaviour at the other fields is similar T_m was found to decrease as the magnetic field increases. The field dependences of T_m are shown in figure 2 for $H \parallel c$ and $H \parallel ab$. It is evident that T_m is much lower for $H \parallel c$ than for $H \parallel ab$. The strictly linear V–I curves above T_m are expected from both free flux flow [22] and thermally activated flux flow (TAFF) [12] models in a mixed state. The comparison with the results of the resistive transition [23] seems to support a TAFF-like behaviour. As the temperature decreases, figure 1(b) indicates a negative curvature for all measured V–I curves below T_m in the log–log plot. This behaviour can be accounted for

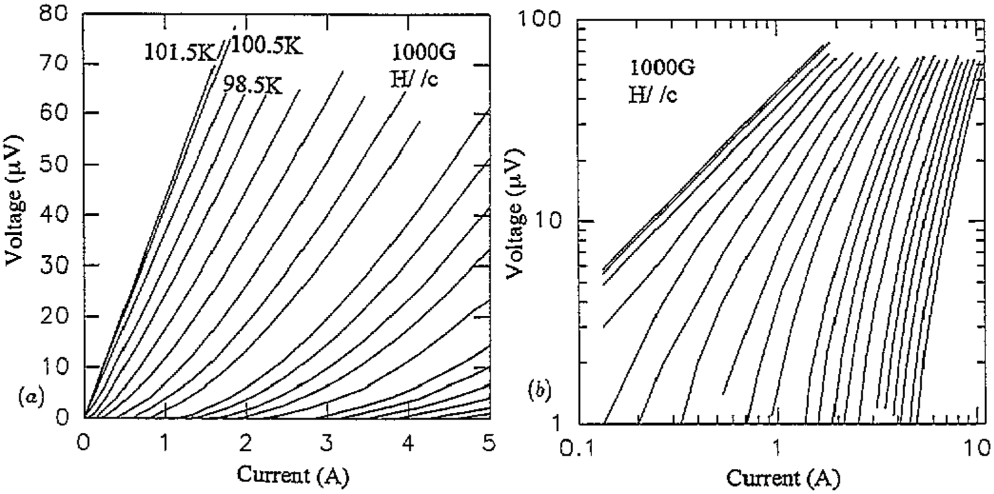

Figure 1. (a) Measured V–I characteristics for various temperatures at 1000 G applied perpendicular to the tape surface, plotted on linear axes. Except for those labelled in the figure, the curves were taken at 1 K intervals from 79.5 to 98.5 K, omitting 85.5 K. (b) Measured V–I characteristics for various temperatures at 1000 G applied perpendicular to the tape surface, plotted on log–log axes.

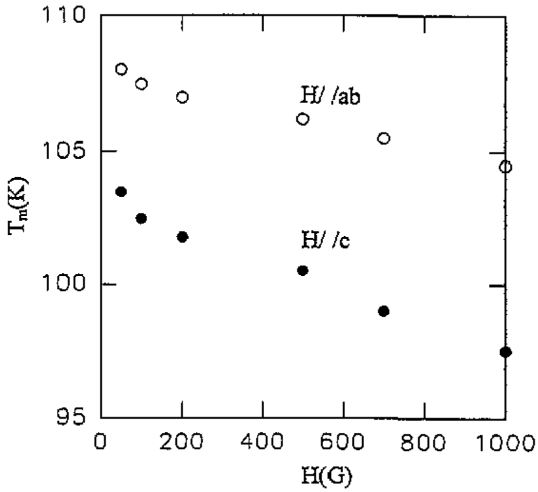

Figure 2. Field dependence of the temperature at which the V–I curves change from being strictly linear to being affine.

[24] from the VG transition at T_m. However, for the present sample, a more careful analysis is clearly needed because of the existence of the silver sheath. The resistivity of the silver is 10^{-1}–10^{-2} $\mu\Omega$ cm at 77 K [25]. For our sample's dimension, the resistance R_{sl} of the silver sheath would be a few tens of microhms, having the same order of the resistance related to the V–I curves. To derive the true V–I curves from the measured curves, it is first necessary to know the temperature dependence of the silver sheath's resistance R_{sl}-T. Because the normal resistivity of the Bi(2223) superconductor is of the order of 150 $\mu\Omega$ cm [26] which is about three orders higher than that of the silver, R_{sl}-T of the tape can be

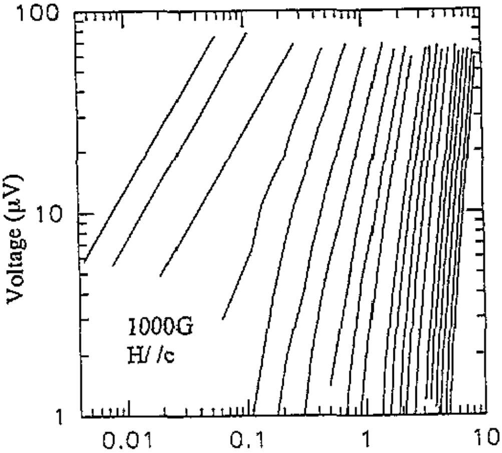

Figure 3. The log–log plot of the corrected V–I_s characteristics for various temperatures at 1000 G applied perpendicular to the tape surface. The curves were taken for the same temperatures as figure 1.

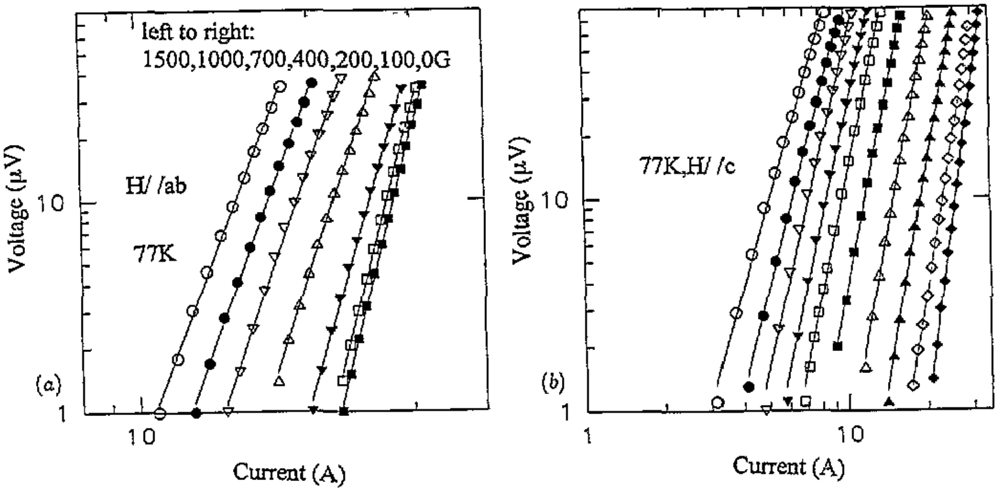

Figure 4. (a) The log–log plot of the corrected V–I_s characteristics at 77 K for various fields applied parallel to the tape surface. (b) The log–log plot of the corrected V–I_s characteristics at 77 K for various fields applied perpendicular to the tape surface.

obtained from the measurement above T_c. In the present tape, we had

$$R_{sl} = 0.69T - 25.3\ \mu\Omega \tag{1}$$

if T is expressed in kelvins.

On the assumption that equation (1) is also effective for the temperature below T_c, the real current I_s flowing through the oxide is

$$I_s = I_m - V/R_{sl} \tag{2}$$

where I_m is the measured overall current.

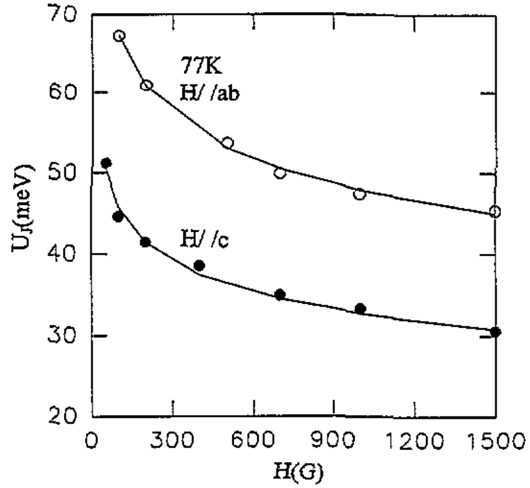

Figure 5. Field dependence of the activation energy derived from the V–I_s curves at 77 K: ○, $H \parallel ab$; ●, $H \parallel c$.

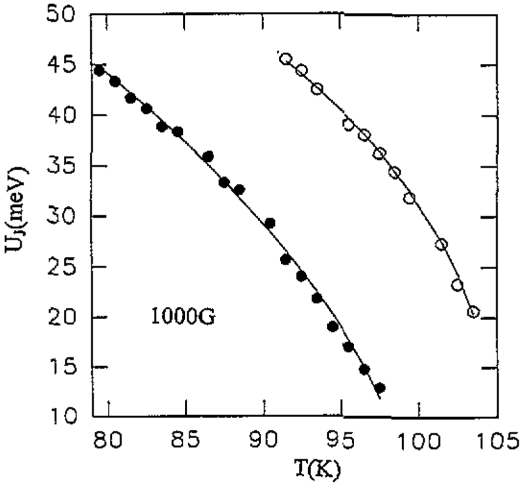

Figure 6. Temperature dependence of the activation energy derived from the V–I_s curves at 1000 G: ○, $H \parallel ab$; ●, $H \parallel c$.

By using equations (1) and (2), the true V–I_s curves of the superconductor can be derived from the measured curves. For comparison, figure 3 gives the corrected data at 1000 G for $H \parallel c$. It can be seen that after the correction the V–I_s curves in the log–log plot are nearly linear for all measured temperatures, except very near T_m. This power-law behaviour of the resistance can be interpreted in the framework of the thermally activated flux-creep model [11]. The electric field V originating from flux creep follows:

$$V = V_0 \exp(-U/k_B T). \tag{3}$$

On the assumption that the effective activation barrier grows logarithmically with decreasing current [13, 27],

$$U(H, J, T) = U_J(H, T) \ln(J_0/J) \tag{4}$$

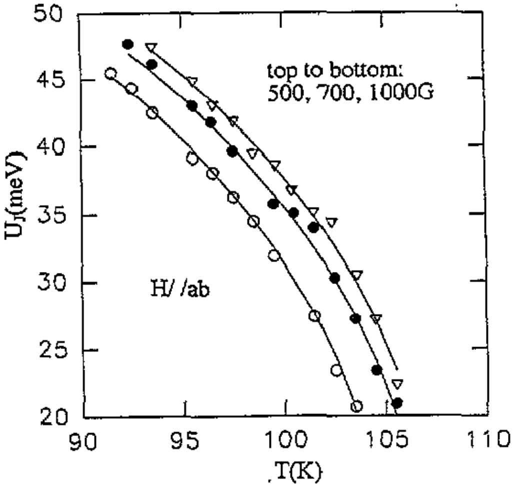

Figure 7. Temperature dependence of the activation energy derived from the V–I_s curves at several magnetic fields for $H \parallel ab$.

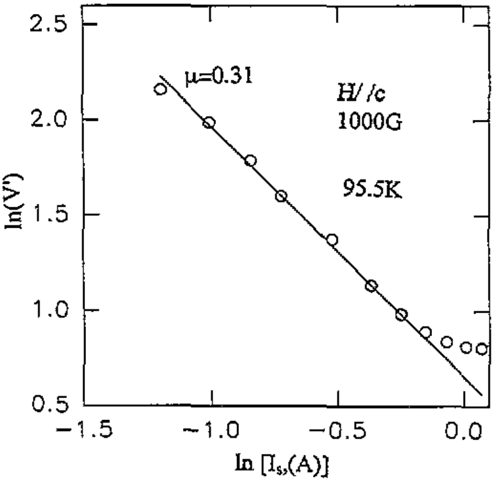

Figure 8. Test of the VG or CP models by plotting $\ln V'$ versus $\ln I_s$.

where J_0 is the 'critical current' at which U approaches zero and is generally magnetic field and temperature dependent.

Inserting equation (4) into equation (3) then gives

$$V = V_0(J/J_0)U_J/k_BT \tag{5}$$

or

$$\ln V = (U_J/k_BT)\ln I + \text{constant}. \tag{6}$$

Our experimental results are consistent with equation (6) as shown in figure 3. This power-law variation was also found for various magnetic fields. As an example, figures 4(a) and 4(b) show those curves at 77 K for $H \parallel ab$ and $H \parallel c$, respectively. From the slopes of these curves, we can derive the field and temperature dependences of the activation energy using equation (6). Figure 5 gives U_J data as a function of the magnetic field at 77 K.

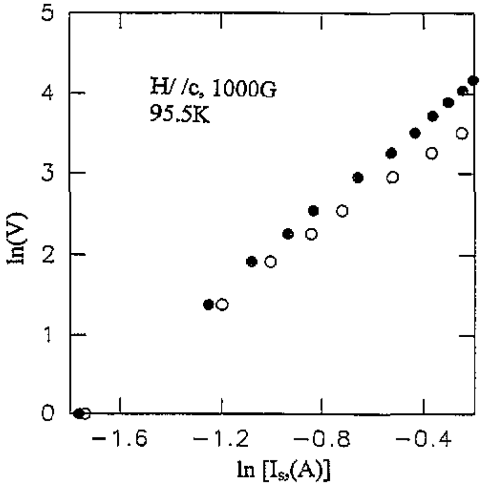

Figure 9. ln–ln plot of the V–I_s curves at 95.5 K and 1000 G for $H \parallel c$, showing a small downward curvature of ln V versus ln I_s that could result from the crossover from flux creep to flux flow.

We found that in the low-field region (below 1500 G) the field dependence of U_J follows a $H^{-0.15}$ functional relationship for both the $H \parallel c$ and the $H \parallel ab$ cases, as shown by the solid curves. Compared with the theoretical $1/H$ predictions [4, 8], this result gives a much weaker field dependence of the activation energy in the low-field regime. Similar to this, an unusual temperature dependence of U_J was also observed, shown in figure 6. Instead of an upward curvature of the U_J–T curve for high fields [13], our low-field results clearly indicate a downward curvature. Fitting the experimental data to the usual $(1 - T/T_c)^n$ form, U_J was found to follow $(1 - T/T_c)^{0.37}$ for $H \parallel ab$ and $(1 - T/T_c)^{0.57}$ for $H \parallel c$ at the field of 1000 G, shown by the solid curves in figure 6. The behaviours at other fields are very similar. As an example, figure 7 gives the U_J–T curves at fields of 500, 700 and 1000 G for $H \parallel ab$. It is apparent that all these curves have similar shapes and show a $(1 - T/T_c)^n$ functional dependence with slightly different n-values, i.e. $n = 0.37$, 0.38 and 0.36 for fields of 1000 G, 700 G and 500 G, respectively.

Finally, it is also worth pointing out that a slight downward curvature of log V versus log I_s curves can also be observed, in particular, at temperatures near T_m. However, we shall see that such a negative curvature cannot be simply attributed to VG or CP behaviours. To check the V–I relationship $V = A \exp[-(B/I)^{\mu}]$ predicted by VG or CP theories, we first define $V' = \mathrm{d}(\ln V)/\mathrm{d}I_s$. From the theoretical description, the V–I relationship can be rewritten as

$$\ln V' = \text{constant} - (\mu + 1) \ln I_s. \tag{7}$$

According to equation (7), if the VG or CP descriptions were valid, the experimental results would result in straight lines in the ln V' versus ln I_s plots in the entire current range with the slope of $\mu + 1$. As an example, figure 8 shows a ln V' versus ln I_s curve at 95.5 K and 1000 G for $H \parallel c$. One can find that equation (7) is reasonable only in the limited current region. In the low- and high-current ranges, the curve clearly deviates from the straight line. This result seems contrary to the VG or CP prediction although more data especially obtained from a single crystal or a high-quality film are needed. Also, the failure of the VG or CP description may also result from the high current density in the measurements [1]. The cause of the negative curvature is still unclear. In our opinion, the crossover from flux creep to flux flow at high current densities could be responsible for this behaviour. As considered in [18], on the assumption that the conduction channel of the flux flow is parallel to that of flux creep, then the current I_{FC} carried through flux creep should be equal to $I - V/R_{FF} - V/R_{sl}$, where R_{FF} is the resistance resulting from the flux flow. The full circles in figure 9 show the results corrected using $R_{FF} = 255\ \mu\Omega$. In comparison with uncorrected data (open circles), we can see that the small negative curvature can be corrected by consideration of the flux flow effect.

In summary, detailed measurements of the V–I curves in the low-field region have been performed. The result seems to support the flux creep dissipation mechansim with the logarithmic current dependence of activation energy. U_J derived from the experimentally measured V–I curves was found to have a much weaker field and temperature dependence in low-field regime (below 1500 G).

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