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Effect of a Magnetic Field on Transport Properties in Multifilamentary Bi-2223 Tape

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We have measured the transport critical current I_c at 1 μV/cm and the exponent n of the power-law characterstics ($E \sim I^n$) of multifilament Bi-2223/Ag tape at 77 K and under external magnetic fields up to 300 G applied perpendicular to the tape plane. The field dependence of the transport critical current I_c is found to obey an exponential model. The structural quality, which is determined by effective grain connections and pinning centers, is rapidly degraded with magnetic field above 100 G.

High-T_c superconductors (HTSC) have the large residual resistivities over a wide interval of temperatures below the superconducting transition temperature T_c if a magnetic field B is applied. Abrikosv vortices penetrate these HTSC at even rather weak fields and can move and dissipate energy under the action of a Lorentz force [1]. In conventional superconductors and in HTSC at sufficiently low temperature, these vortices are pinned by pinning centers like material inhomogeneities as long as the current density J is below a critical value J_c. However, in HTSC at higher temperature, vortices may be depined by thermal activation [2]. This leads to a finite resistivity $\rho \propto \exp(-U/kT)$ and to flux creep with a pinning potential $U(T, B, J)$. To achieve maximum currents without dissipation, we have to maximize not only the pinning force which a pin can exert on vortices, but also the pinning potential.

Recent progress in manufacturing multifilamentary silver-sheathed $Bi_2Sr_2Ca_2Cu_3O_y$ (Bi-2223) superconducting tapes has resulted in relatively long wires with improved electrical and mechanical characteristics [3-5]. Such wires have been used in fabrication of prototype devices, including transformers, motors, generators, and superconducting magnetic energy storage systems. Factors which limit the current-carrying capability of HTSC tapes are the sensitivity of their critical current density and pinning potential to magnetic fields.

In this paper, we present some experimental results on the critical current I_c and the exponent n which are obtained from $I - E$ curves of a multifilament Bi-2223/Ag tape. We focus on the relationship between the critical current I_c at 1 μV/cm characterizing the current-carrying capability and the exponent n in the power-law $I - E$ characteristics reflecting the pinning potential.

The multifilamentary Bi-2223/Ag tape has a rectangular cross section of width $w = 3$ mm and thickness $t = 0.2$ mm. It is specified for a critical current of 50 A at 77 K in the absence of a magnetic field. In order to apply a magnetic field, we placed the sample between two long racetrack magnet coils, which produce a uniform magnetic field perpendicular to the tape plane. The measurements were carried out with the four probe method. The average electric field along the tape is calculated as $E = V/l$ where l is the length between tapes for the voltage measurement. In our measurement, l is 19 cm and the length between two current leads is 20 cm. The $I - V$ curves of the sample were measured in the presence of a perpendicular magnetic field up to 300 G. Throughout the measurement, the sample was immersed in liquid nitrogen (77 K).

Figure 1 shows typical $I - E$ curves measured in the presence of the indicated external field directed perpendicular to the tape plane. All the curves are well fitted by a power law $E = E_0(I/I_c)^n$, where I_c is the critical current related to an average field criterion $E_0 = 1$ μV/cm. Therefore, we obtained the critical current I_c and the exponent n by using the criterion $E_0 = 1$ μV/cm and fitting with $E \sim I^n$ in external magnetic fields, respectively.

Figure 2 shows the critical current I_c as a function of the external applied field B. In the absence of an external field, the critical current I_{c0} at 77 K is measured to be about 57 A. We have employed two models to describe our experimental data. The first one is Kim-Anderson model [6,7] in which the critical current I_c is given by

$$\frac{I_c(B)}{I_{c0}} = \frac{1}{1 + B/B_0} \quad (1)$$

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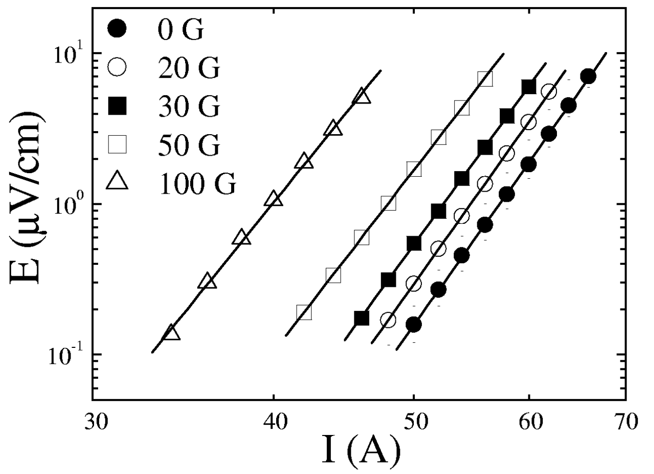

Fig. 1. Logarithmic plot of the characteristic $E(I)$ at T = 77 K under several external magnetic fields. The lines are fits to the power law $E = E_0(I/I_c)^n$.

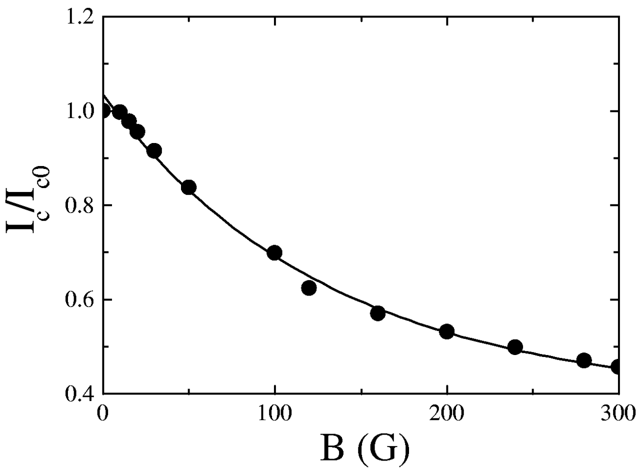

Fig. 2. Critical current divided by the critical current at $B = 0$ G, I_c/I_{c0}, versus external magnetic field B. The line is a fit to Eq. (2).

where I_{c0} is the critical current at zero field and B_0 is a characteristic field depending on the microstructure of the superconductor. The second one is the exponential model derived from the percolation theory by Doyle *et al.* [8]. According to this model, the critical current I_c is given by

$$\frac{I_c(B)}{I_{c0}} = A\left[\exp\left(-\frac{B}{B_e}\right) + \delta\right] \tag{2}$$

where B_e and δ are some phenomenlogical parameters, characterizing the weak link network and A is a constant close to unity. In this model, the parameter δ is related to the average correlation range of a grain boundary junction and is a sensitive and potentially useful indicator of the properties of the weak links. In an attempt to get a resonable model, we fitted our data to Eq. (1) and Eq. (2). As a result, we found that Eq. (2) of the exponential model described the critical current characteristics very well within our field range, as shown by the solid line in Fig. 2. For our sample, we obtain $\delta \simeq 0.59$ from the exponential model. Also, A and B_e are 0.64 and 132.3 G, respectively. The values of δ for the sintered ceramic Y-123 [8] and Tl-1223 [9] are 0.01 to 0.04, respectively, and are about one order of magnitude smaller than one for our sample. Therefore, it is clear that our sample exhibits less granularity than the sintered ceramics Y-123 and Tl-1223.

The average velocity associated with the thermally activated vortex lines is

$$v = v_0 \exp\left(-\frac{U(T,B,J)}{kT}\right) \tag{3}$$

where U is the pinning potential and the prefactor v_0 may also be a function of T, B, and J. Since $E = (1/c)Bv$, E is also exponentially dependent on $U(J)$ at given T and B. Thus, vortex creep is generally associated with a highly nonlinear $I - V$ relationship, which is dictated by the specific dependence of U on J and by the exponential dependence of E on U. The logarithmic barrier model of Zeldov *et al.* [10] assumes

$$U(J) = U_0 ln\left(-\frac{J}{J_{c0}}\right), \tag{4}$$

resulting in a power-law $I-V$ dependence, where U_0 and J_{c0} are a characteristic barrier scale and a critical current density without vortex creep, respectively. Therefore, the electric field can be described as

$$E \propto \left(-\frac{J}{J_{c0}}\right)^n \tag{5}$$

where the exponent n is given by U_0/kT. The exponent n at given temperature is reduced with the magnetic field.

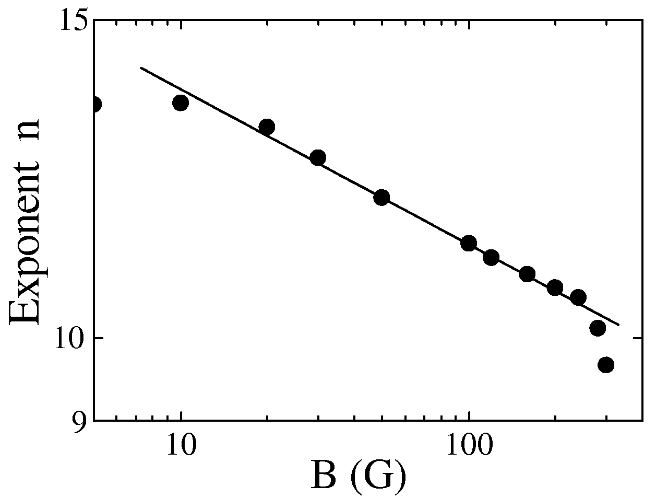

Fig. 3. Logarithmic plot of the exponent n as a function of the external magnetic field B.

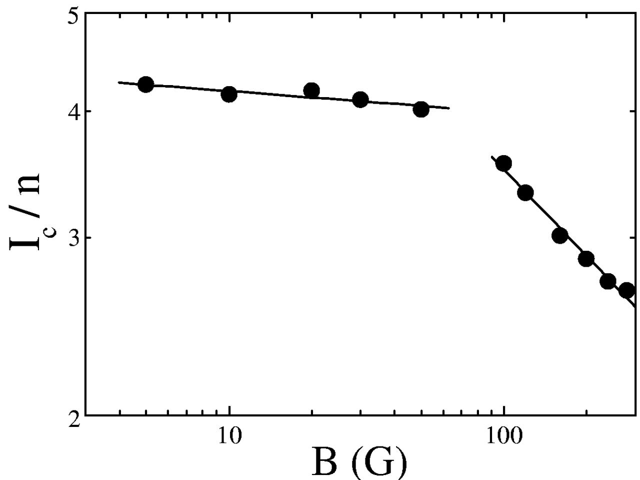

Fig. 4. Ratio of the transport critical current I_c to the exponent n as a function of the external magnetic field B. We can see easily that I_c/n is nearly independent of the external field up to 100 G. The lines are guides for the eye.

Figure 3 shows the exponent n as a function of the external applied field B. As mentioned above, the exponent n is related to the pinning potential. In general, the pinning potential is expressed by an inverse power law in the field, *i.e.*, $U \sim B^{-m}$ [11-13]. Thus, we can determine the dependence of the pinning potential on field from the log-log plot of n versus field. Figure 3 clearly shows that n is dominated by a power law in the field within the field range between 10 G and 200 G. The exponent of the power law in this field range is -0.09. The upper limit of our magnet is about 300 G, so we couldn't get data for higher fields. However, we expect that due to an increase in the interaction between vortices at higher fields, the effective pinning potential will decrease more rapidly as compared to the one at lower fields. We observed an indication of this behavior of the pinning potential near 300 G.

The energy dissipated by moving the vortex bundles through a mean distance a is equal to the energy for the pinned vortex lines [14]

$$BJ_ca = U_0N \tag{6}$$

where U_0 is the average value of the pinning potential well depth and N is the effective number of pinning centers per unit volume. In general, J_c, a, U_0, and N are temperature and magnetic field dependent. With $J_c = I_c/A$, where A is the cross section of the superconductor, it is possible to express the ratio of the critical current I_c to the exponent n as

$$\frac{I_c}{n} = \frac{kTNA}{Ba}. \tag{7}$$

The product NA is the apparent number of pinning centers per tape length. The ratio NA/a increases with the structural improvement of the tape; *i.e.*, the ratio I_c/n depends on the structural quality of sample.

In order to get the field effect on the structural quality, we plotted the ratio I_c/n as a function of the external applied field B, as shown in Fig. 4. It is clearly seen that, in the low-field range (below 100 G), I_c/n is almost field independent ($I_c/n \simeq 4.4$ A). However, I_c/n rapidly decreases with the field above 100 G. This means that above 100 G, as the field increases, the structural quality of our sample is remarkably affected by the field.

In conclusion, we have measured and compared the critical currents I_c (at 1 μV/cm) and the exponents n of multifilament Bi-2223/Ag tape at 77 K and in magnetic fields up to 300 G from $I-E$ curves. We find that the dependence of the transport critical current on an external magnetic field obeys an exponential model based on percolation theory. Also, the structural quality of our sample was easily degraded by fields above 100 G.

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