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Observation of vortex-glass-to-liquid transition in the high-T_c superconductor $Bi_2Sr_2Ca_2Cu_3O_{10}$

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We report a series of measurements of I-V curves for a c-axis-oriented $Bi_2Sr_2Ca_2Cu_3O_{10}$/Ag tape immersed in liquid oxygen. By applying the critical scaling analysis to the I-V characteristics measured in various magnetic fields, a vortex-glass–liquid phase-transition line was identified in the mixed state of this system for $H \leqslant 1.2$ T, with critical exponents $\nu = 1.25 \pm 0.15$ and $z = 8.5 \pm 1.5$. We also show that this transition boundary in the H-T plane defines the upper limit of useful current carrying capacities for the $Bi_2Sr_2Ca_2Cu_3O_{10}$/Ag tapes at a given temperature and magnetic field.

The behavior of high-T_c superconductors in a magnetic field, particularly the magnetic vortex phase diagram, has received considerable attention, driven by purely scientific interests as well as practical needs.[1–7] One of the most important and also controversial issues is whether the onset of the resistive transition in a magnetic field is due to the vortex-glass-to-liquid phase transition in a weak-pinning regime, or related to the conventional vortex depinning process.[1] In the vortex-glass model, a second-order phase transition is suggested at transition temperature T_g, between a vortex liquid and a vortex-glass phase. Associated with this transition, there exists a diverging correlation length given by $\xi_g \sim |1 - T/T_g(H)|^{-\nu}$, and a diverging correlation time $\tau \sim \xi_g^z$, where ν and z are the static and the dynamic critical exponents, respectively. By means of the general argument of critical phenomena, the vortex-glass model made several predictions about the character of the resistive transition as a function of temperature, magnetic field, and current density for a three-dimensional (3D) type-II superconductor within the critical regime of T_g. One of them is the scaling behavior of electric field as a function of current density (E-J curve). By defining $\tilde{E} = (E/J)|1 - T/T_g(H)|^{\nu(1-z)}$ and $\tilde{J} = (J/T)|1 - T/T_g(H)|^{-2\nu}$, all scaled E-J curves within the critical region should collapse into two universal curves $\tilde{E}_{\pm}$, with universal critical exponents ν and z, and a proper value of $T_g(H)$. Many groups have observed this scaling behavior in $YBa_2Cu_3O_7$ (YBCO) (Refs. 4–6) and $Bi_2Sr_2CaCu_2O_8$ [Bi(2:2:1:2] (Ref. 7) superconductors. However, there has been no convincing experimental evidence for such a phase transition in $Bi_2Sr_2Ca_2Cu_3O_{10}$ [Bi(2:2:2:3)] system.[8] The experimental difficulties involved in the study of the Bi(2:2:2:3) system are a lack of available single crystals and high-quality films. On the practical side, an enormous amount of effort has been devoted to the development of Bi(2:2:2:3)/Ag composite tapes and wires for large-scale applications. Unfortunately, the critical current density (J_c) of the Bi(2:2:2:3)/Ag tapes is disappointingly low at elevated temperatures, e.g., $T > 50$ K, in moderate magnetic fields.[9,10] In order to clarify the nature of the onset of the resistive transition of Bi(2:2:2:3) in magnetic fields (e.g., the vortex-glass–liquid transition), and to discern the J_c limiting factors for this material, we made detailed measurements of I-V characteristics of a c-axis-oriented Bi(2:2:2:3) tape at temperatures from ~54 to ~90 K by immersing the specimen in liquid oxygen. We found excellent scaling behavior for all the measured E-J curves within the critical region for $H \leqslant 1.2$ T. Thus, a vortex-glass–liquid phase transition was clearly identified in Bi(2:2:2:3). In addition, we show that this transition boundary defines the upper limit of useful current carrying capacities for the Bi(2:2:2:3)/Ag tapes at a given temperature and magnetic field. The observation of this phase-transition line in a Bi(2:2:2:3)/Ag tape confirms the earlier conjecture that the dissipation in such a tape originates from the vortex motion *within* the grains at elevated temperature for fields greater than that which is sufficient to destroy the weakly coupled regions.[10]

The highly c-axis-textured Bi(2:2:2:3) tapes (~5 mm wide) used in this study were made by a conventional powder-in-tube method.[11] The Bi(2:2:2:3) core was ~60 μm in thickness and sheathed in an ~30 μm thick silver jacket. The lengths of the specimens were ~40 mm with the central 10 mm used for the voltage leads. The measurements were performed by immersing the specimen holder in liquid oxygen at reduced pressures. The sample temperature was monitored by an in-field calibrated thermometer mounted on the specimen holder, and controlled within ± 0.1 K by regulating the vapor pressure above the liquid and using a heater. The voltage from the sample was continuously measured by using a Keithley 1801 preamplifier and a 2001 multimeter from 10^{-3} down to 10^{-10} V, which corresponds to electric field E from 10^{-1} to 10^{-8} V/m. No sample heating effect was observed at an applied current as high as 20 A. Magnetic field was applied perpendicular to the tape, and thus approximately parallel to the c axis of the Bi(2:2:2:3) platelets. Here, we only report on the results of the measurements of a

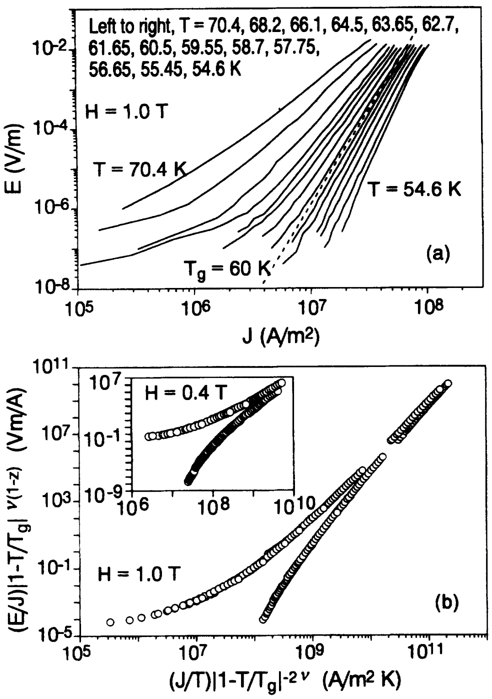

FIG. 1. (a) Electric field versus current density (E-J) curves for the Bi(2:2:2:3) tape at an applied field $H=1.0$ T for temperatures from 54.6 to 70.4 K. The temperature for T_g at this field is shown as the dotted line. (b) A scaling plot of all E-J isotherms for Bi(2:2:2:3) at $H=1.0$ and 0.4 T (inset).

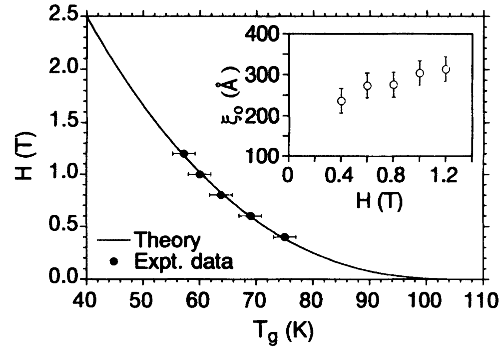

FIG. 2. The vortex-glass–liquid transition boundary line for Bi(2:2:2:3), where the solid circles represent the experimentally determined $T_g(H)$, and the solid line is a theoretical curve of $H(T_g)=H(0)(1-T_g/T_{c0})^{2.5}$. The inset shows the field dependence of the vortex-correlation length $\xi_0(H)$.

Bi(2:2:2:3)/Ag tape with $J_c \cong 2\times10^8$ A/m^2 at 77 K and zero magnetic field. We have also measured the I-V curves for a number of other specimens with J_c ranging from 1×10^8 to 4×10^8 A/m^2 at various temperatures and fields, which exhibit essentially the same resistive characteristics. It is worthwhile to point out that the Ag sheath makes negligible effect on the I-V characteristic of Bi(2:2:2:3) tape, since the resistivity of Ag sheath was found at least two orders of magnitude higher than that due to the flux motion for the entire I-V curves that we used for the scaling analysis.[12] Ag sheath should not form a parallel conduction path to share the current flow. Thus, the voltage that we measured comes directly from the flux motion.

In Fig. 1(a), an example of the measured electric-field-versus-current-density (E-J) curves is shown for the Bi(2:2:2:3) tape at applied field $H=1.0$ T for temperatures from 54.6 to 70.4 K. Similar curves were also observed at all other applied fields, 0.4, 0.6, 0.8, and 1.2 T. These resistive characteristics for the Bi(2:2:2:3) tape were nearly identical to what was observed and used to argue for the vortex-glass-to-liquid transition in YBCO by Koch *et al.*[4] and others.[6] In order to see whether this was the case for Bi(2:2:2:3), we applied the universal scaling analysis suggested by the vortex-glass model[1] to the present data. In this model, near the phase transition, the vortex correlation length is given by $\xi_g=\xi_0(H)|1-T/T_g(H)|^{-\nu}$, where $\xi_0(H)$ is a temperature-independent constant. In a constant field, the electric field E due to the vortex motion in a 3D system near T_g follows the critical scaling relation, $E=J\xi_g^{(z-1)}\tilde{E}_\pm(x)$, where $x\equiv J\xi_g^2\phi_0/(k_BT)$, $\tilde{E}_\pm(x)$ are the universal functions for $T>T_g(\tilde{E}_+)$ and $T<T_g(\tilde{E}_-)$. ϕ_0 is the single flux quantum, and k_B is the Boltzmann constant. All scaled E-J curves in variables $\tilde{E}=(E/J)|1-T/T_g(H)|^{\nu(1-z)}$ and $\tilde{J}=(J/T)|1-T/T_g(H)|^{-2\nu}$ within the critical region should collapse into two universal curves $\tilde{E}_\pm$, with universal critical exponents ν and z, and a proper value of $T_g(H)$. In Fig. 1(b), we demonstrate such scaling behavior of all E-J isotherms for our Bi(2:2:2:3) tape taken at $H=1.0$ T, while the inset displays the same scaling for all E-J data taken at $H=0.4$ T. The value for T_g at $H=1.0$ T is 60 K, which is shown as a dotted line in Fig. 1(a). It was found that the critical exponents for the scaling functions $\tilde{E}_\pm(x)$ at $H=0.4$–1.2 T were identical, and they are $\nu=1.25\pm0.15$ and $z=8.5\pm1.5$. The excellent scaling behavior with the same critical exponents at all fields that we studied manifests that the onset of the resistive transition of Bi(2:2:2:3) in field $H\leqslant1.2$ T is indeed due to the vortex-glass–liquid transition. Our attempts to fit the I-V data to other alternative theoretical functions failed. We found that neither the flux creep theory, nor the thermally assisted flux-flow (TAFF) resistivity could reproduce our I-V characteristics at the entire field range that we measured.

For further confirmation of the vortex-glass–liquid transition in Bi(2:2:2:3), we depicted those determined $T_g(H)$ values for $H\leqslant1.2$ T in Fig. 2, together with a solid line showing the expected field dependence of $T_g(H)$, i.e., $H(T_g)=H_0(T_{c0}-T_g)^{2\nu_0}$, in the 3D XY critical regime at small fields and close to T_{c0}.[1] ν_0 is the zero-field critical exponent. In obtaining the theoretical fitting curve of $H(T_g)$, both ν_0 and H_0 were used as adjustable parameters, while T_{c0} is a fixed value being equal to the zero-field transition temperature ($=106.5$ K). A least-squares fit to our data shows $\nu_0=1.25\pm0.2$, which is identical to the derived value of ν from the E-J scaling analysis as illustrated in Fig. 2. The data of $T_g(H)$ for Bi(2:2:2:3) are surprisingly in excellent agreement with the theory, which was also previously reported for YBCO.[6] We noted that the derived value of ν_0 for Bi(2:2:2:3) was bigger than the value $\frac{2}{3}$ expected for an ideal

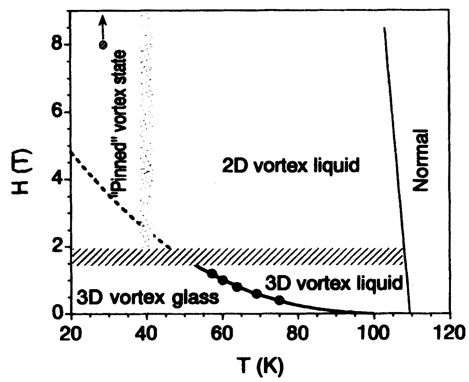

FIG. 3. The vortex phase diagram in the mixed state of Bi(2:2:2:3) superconductor. The solid line and closed circles show the true 3D vortex-glass–liquid phase transition boundary, while the dotted line shows its extrapolation. The hatched area represents the 3D to 2D vortex crossover. The data point with an attached arrow implies that it is in a "pinned" vortex state (see text), and a dotted area is a suggested "pinned" vortex state to 2D vortex liquid crossover region.

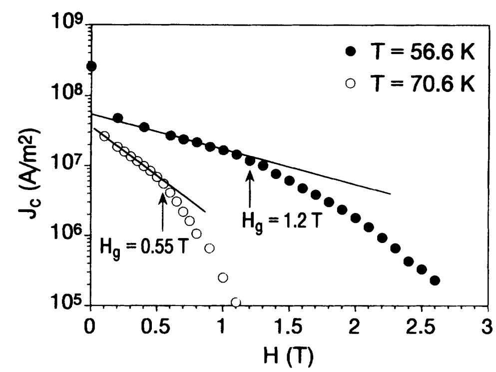

FIG. 4. The critical current densities (defined at $E_c = 10^{-6}$ V/m) for the Bi(2:2:2:3)/Ag tape plotted against the applied field at 56.6 and 70.6 K.

3D isotropic system.[1] This discrepancy could presumably be due to the high anisotropy of the Bi-based cuprates, which may not be in the same universality class as an isotropic system. The vortex-glass–liquid transition line for Bi(2:2:2:3) was found to be considerably lower than that for YBCO,[4–6] but significantly higher than that for single-crystal Bi(2:2:1:2).[7] These differences are also the reflection of the large differences in their anisotropy ratios.

The inset of Fig. 2 shows the vortex-correlation length $\xi_0(H)$ for Bi(2:2:2:3) as a function of field. $\xi_0(H)$ is a field-dependent, but not temperature-dependent quantity. It was estimated in a twinned YBCO single crystal by Yeh *et al.*,[6] from the analysis of the asymptotic behavior of the scaling function $\tilde{E}_\pm(x)$. For YBCO, they reported that $\xi_0(H)$ was ~ 200 to ~ 800 Å at $0.1 \leq H \leq 7$ T. Using the same technique, we found that the value of ξ_0 for Bi(2:2:2:3) at $H = 1$ T was ~ 300 Å, which was rather close to that obtained for a YBCO single crystal at the same field.[6] As field increased, ξ_0 of Bi(2:2:2:3) increased slowly, which was consistent with a stronger intervortex correlation at higher fields.

At this point, it would be informative to consider how this observed segment of the transition boundary fits within the general notion of the vortex phase diagram in a highly anisotropic superconductor. In such a material, a 3D vortex solid to a 2D "pancake vortex" crossover is expected upon increasing fields due to the thermal fluctuations.[1,13] This crossover field $B_{2D\text{-}3D}$ is estimated to be $\approx \phi_0/(s\gamma)^2$, where s is the inter-CuO_2 plane separation, and γ is the anisotropy ratio. For Bi(2:2:2:3), the value of $B_{2D\text{-}3D}$ is estimated to be ~ 1.5 to 2.2 T, using $s = 1.8$ nm and $\gamma \approx 17$ to 20.[14] We represent it as the hatched area in Fig. 3. The observed 3D vortex-glass-to-liquid transition below 1.2 T is consistent with the above 2D-3D crossover argument. On the other hand, the resistive measurement of a similar tape immersed in liquid neon (27 K) revealed negative curvatures for all I-V curves obtained at fields up to 8 T.[9] This indicated that the vortex-glass-to-liquid transition (if exists at 27 K) must take place at a field greater than 8 T. Obviously, this is well above the extrapolated value of $H_g(T)$ at 27 K, from our high-temperature data. This is likely to be an indication of the crossover of a 2D vortex system above $B_{2D\text{-}3D}$ to an *incipient* 3D one when temperature is lowered,[15] as observed in a Bi(2:2:1:2) crystal by Safar *et al.*[7] and suggested by theoretical considerations.[1,13,15] This crossover is the result of the increased superconducting coupling among the 2D pancake vortices along the c axis as temperature is lowered, and thus vortex pinning is enhanced below this crossover region. In addition, this is likely driven by temperature and only weakly depends on field.[13] This crossover was found to be in a temperature range of 25–30 K for a Bi(2:2:1:2) single crystal.[7] For Bi(2:2:2:3), it probably takes place at ~ 40 K, as suggested by the present results and the earlier transport measurement of a similar tape at 27 K.[9]

The low melting field of vortex lines at elevated temperatures, as shown in Fig. 2, has immense technological implications as it defines the limiting magnetic field perpendicular to the tape surface for useful critical current densities at a given temperature. To illustrate this point, the critical current densities (defined at $E = 10^{-6}$ V/m) for the Bi(2:2:2:3)/Ag tape at 56.6 and 70.6 K were plotted as a function of field in Fig. 4. As noted previously,[9,10] after initial steep drop due to a fraction of grain boundaries, which are weakly coupled, the value of J_c exponentially decreases until the applied field reaches H_g. Beyond this point, J_c drops at a significantly higher rate than that at $H < H_g$, due to the vortex-glass-to-liquid transition. This behavior is more clearly seen for those data taken at high temperatures (e.g., at 70.6 K) than lower ones (e.g., at 56.6 K). Thus, H_g is the upper limiting field for the practically usable J_c. In order to improve this situation, the effective pinning centers, such as columnar defects,[16,17] need to be introduced in a practical way.

In conclusion, we have studied the transport properties of a c-axis-oriented Bi(2:2:2:3) superconducting tape. We found that the onset of dissipation at $H \leq 1.2$ T in this material can be well described by a second-order vortex-glass-to-liquid transition, with the critical exponents $\nu = 1.25 \pm 0.15$ and $z = 8.5 \pm 1.5$. The vortex correlation length ξ_0 for Bi(2:2:2:3) was determined to be in the order of 300 Å at 0.4 T$\leq H \leq 1.2$ T and increased slightly with increasing field.

The vortex-glass–liquid transition temperature T_g was found to be related to H, via $H(T_g) \sim (T_{c0} - T_g)^{2.5}$. We also demonstrated that critical current in Bi(2:2:2:3) at elevated temperatures was fundamentally limited by the vortex-glass–liquid transition.

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