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Pinning effect on fluctuation conductivity in a superconducting untwinned $YBa_2Cu_3O_{7-\delta}$ single crystal with columnar defects

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The effect of columnar defects on the critical dynamics of a superconducting untwinned $YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystal has been investigated. The columnar defects are produced by Sn ion irradiation of which dose corresponds to a matching field of 1 T. The in-plane longitudinal resistivity of the irradiated YBCO crystal has been measured as a function of magnetic field H and temperature T. The extracted fluctuation conductivities are enhanced by the strong pinnings and do not exhibit the same three-dimensional (3D) XY scaling behavior as for the unirradiated YBCO single crystal; particularly at the magnetic field values near the matching field of 1 T, the fluctuation conductivities show a clear deviation from the critical dynamics. At higher magnetic fields, however, the signature of the 3D-XY scaling appears. [S0163-1829(98)03313-X]

In high-T_c superconductors, short coherence length and high transition temperature enhance fluctuation effects. Near the critical temperature, the large fluctuation provides an opportunity to observe critical fluctuations and universality class that cannot be explained by mean-field theory with Gaussian corrections. The critical fluctuation effects have been observed in several measurements.[1–9] The universality class[10] that describes the critical fluctuations has been consistent with a three-dimensional (3D) XY critical model that yields the exponent for the correlation length $\nu \approx 0.669$ and the dynamic critical exponent of $z \approx 1.5$ in the presence of magnetic field. Thus the critical behavior governed by the 3D-XY critical exponents would be similar to superfluid ^{4}He. However the contribution of vortex fluctuation on the 3D-XY scaling and its applicability in mixed state have not been systematically studied to date.[10]

The major role of columnar defects has been known to provide a stronger pinning of vortex than pointlike defects. The strong pinning effectively reduces vortex motions that would affect fluctuation conductivity. Note that the effect of disorderlike point defects has been reported to be irrelevant on static critical behavior.[11,12] The effect of the strong pinning of vortices on the critical dynamics has not been yet verified in detail.

In this paper, we report on the in-plane longitudinal resistivity of an untwinned $YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystal with columnar defects. We have discussed the effect of pinning vortices on the fluctuation conductivity near the critical temperature in the presence of magnetic field and compared the scaling behavior of the fluctuation conductivity of the irradiated YBCO crystal with the unirradiated YBCO crystal in the framework of the 3D-XY model.

The untwinned single crystal of YBCO was naturally grown in a yttria-stabilized zirconia crucible by using a flux method described in detail elsewhere.[13] The as-grown crystal was oxygenated at 500 °C for 2 weeks in flowing O_2. A transition width (10 to 90%) of 0.25 K was measured with a Quantum Design superconducting quantum interference device magnetometer. The crystal was cleaved to a typical rectangular shape ($0.5\times0.2\ \mathrm{mm}^2\times25\ \mu\mathrm{m}$) for resistivity measurement.

Contacts for attaching gold wires were made by evaporating gold onto the crystals and heating them at 500 °C for 3 h in flowing O_2. All the contact resistances were less than 1 Ω. The longitudinal resistivity was measured with a 4-terminal method at a frequency of 37.8 Hz and a current density of 2 A/cm^2 was used. Zero resistance temperature ($\equiv T_{c0}$) was 93.4 K. The T_{c0} and resistivity $\rho_{bb}(T,H)$ were almost the same as those of the detwinned YBCO crystal reported in Ref. 5.

The sample was then irradiated at 0 °C by 740 MeV Sn ions, which were produced at the Argonne Tandem Linear Accelerator System at the Argonne National Laboratory. The irradiation dose of 5×10^{10} ions/cm^2 was chosen to an equivalent matching field B_ϕ of 1 T. The irradiation was aligned parallel to the c axis of YBCO and with $\pm5°$ planar splay. A representative cross-sectional TEM (transmission electron microscopy) image similar to one in Ref. 14 shows

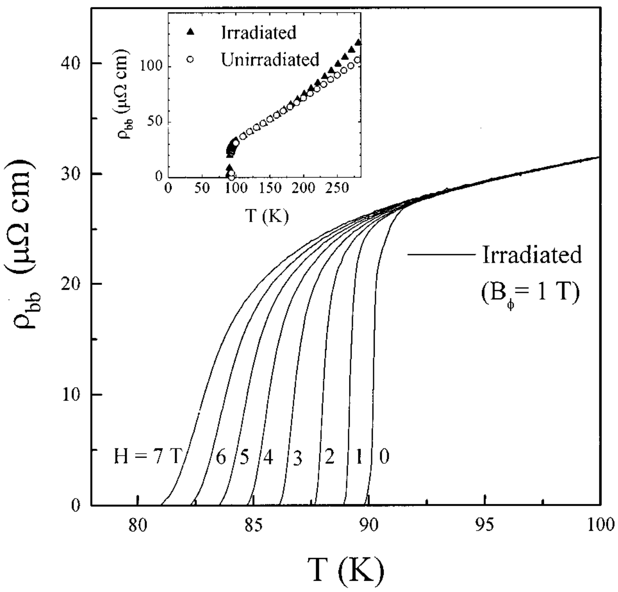

FIG. 1. Longitudinal resistivity $\rho_{bb}(T,H)$ along b axis for the irradiated untwinned single crystal of $YBa_2Cu_3O_{7-\delta}$ in magnetic field values $0 \leqslant H \leqslant 7$ T with 1 T interval. The magnetic field was applied parallel to the c axis of the sample. The crystal was irradiated by an Sn ion beam that was aligned parallel to the c axis. The irradiation dose corresponds to the matching field B_ϕ of 1 T. The inset shows the resistivities at zero magnetic field where the open circle symbols are before the irradiation and the filled triangles after the irradiation.

that columnar tracks with a splay configuration of $\Theta = \pm 5°$ are formed throughout the crystal thickness of 25 μm.

Figure 1 shows the longitudinal resistivities $\rho_{bb}(T,H)$ of the irradiated YBCO at magnetic field values $0 \leqslant H \leqslant 7$ T with a 1 T interval. The magnetic field was applied parallel to the c axis of sample. Zero resistance temperature T_{c0} in zero magnetic field was lowered to 89.8 K from 93.4 K after the irradiation. The resistivities of the irradiated sample near T_{c0} are almost the same as the values before the irradiation. Normal-state resistivity of the irradiated one is slightly curved up over 175 K, as shown in the inset of Fig. 1.

Figure 2 shows the resistive transitions of a YBCO crystal before and after the irradiation as a function of reduced temperature T/T_c for magnetic fields of 1 and 2 T where T_c is defined as a temperature where $d\rho_{bb}/dT$ is a maximum. The onset temperature of ρ_{bb} in each magnetic field is enhanced due to vortex pinning and the kink structures shown in the unirradiated sample near melting transition temperatures disappear after irradiation, consistent with Ref. 15. All of the resistivity data used for studying fluctuation conductivity were taken above the resistive transition temperature at each magnetic field value and should be Ohmic behavior.[16]

Fluctuation conductivity $\sigma^*_{bb}(T,H)$ was obtained by background subtraction from the resistivity $\rho_{bb}(T,H)$. The longitudinal conductivity σ_{bb} can be expressed as $\sigma^*_{bb} + \sigma_{BG}$ where σ^*_{bb} and σ_{BG} are, respectively, the fluctuation and the background conductivity. The σ_{BG} is simply one over the background resistivity. Since the resistivity of the irradiated sample was not linear with temperature above 175 K, as shown in the inset of Fig. 1, the background subtraction for fluctuation conductivity cannot be done with the same way

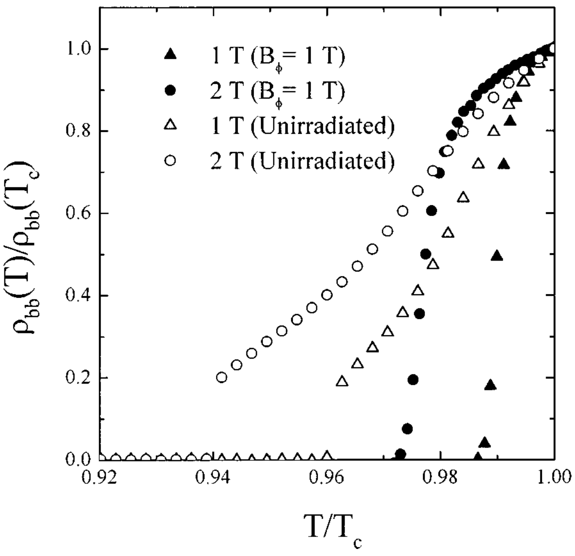

FIG. 2. $\rho_{bb}(T,H)/\rho_{bb}(T_c,H)$ vs T/T_c in magnetic field values of 1 and 2 T with $H \| c$ axis. T_c is defined as a temperature where $d\rho_{bb}/dT$ is a maximum. The open symbols are before the irradiation and the filled ones after the irradiation. At each magnetic field, the onset temperature of ρ_{bb} is enhanced after the irradiation.

for the unirradiated YBCO (Ref. 5). So two ways of background subtraction were tested in order to see how much the fluctuation conductivity depends upon the ways; a linear resistivity fit over $100 \leqslant T \leqslant 150$ K and a polynomial fit $a + bT + cT^2$ over $120 \leqslant T \leqslant 280$ K are chosen. The linear resistivity fit used for the background resistivity was $\rho_{BG} = -4.2$ ($\mu\Omega$ cm)+35.8 T ($\mu\Omega$ cm/K). The polynomial fit was $\rho_{BG} = 14$ ($\mu\Omega$ cm)+8.9×10^{-2} T ($\mu\Omega$ cm/K) +9.5×10^{-4} T^2 ($\mu\Omega$ cm/K^2). By subtracting σ_{BG} from σ_{bb}, the fluctuation conductivity σ^*_{bb} was obtained. The both fluctuation conductivities obtained from the above methods show a similar behavior to each other that will be described below. Note that the background resistivity of the irradiated sample near T_{c0} was almost the same as that of the unirradiated one as shown in Fig. 1.

The extracted fluctuation conductivity $\sigma^*_{bb}(T)$ and the temperature were normalized in order to see the change in the fluctuation conductivities after the irradiation of $B_\phi = 1$ T. $\sigma^*_{bb}(T)/\sigma^*_{bb}(T_c)$ for $H = 1$ T and 2 T vs T/T_c are displayed in Fig. 3. The filled symbols denote the fluctuation conductivity obtained from the linear fit of the background resistivity, and the lines are obtained from the polynomial fit. The data show that below T_c the fluctuation conductivity σ^*_{bb} after the irradiation are enhanced due to strong pinning and that this enhancement is not critically dependent on how the background subtraction is made. For higher magnetic fields $3 \leqslant H \leqslant 7$ T was also seen the enhancement of the fluctuation conductivity. This enhancement of the fluctuation conductivity could be conjectured from two facts; near T_{c0} the background conductivity is not much changed even after irradiation, whereas the total conductivity $\sigma_{bb}(T,H)$ in the mixed state is enhanced due to the pinning.

Before the irradiation, the fluctuation conductivity showed the 3D-XY scaling behavior as reported for the unirradiated YBCO single crystal in Ref. 5; $\sigma^* \sim H^{-(2+z-d)/2} F(t/H^{1/2\nu})$ where a dynamic critical exponent

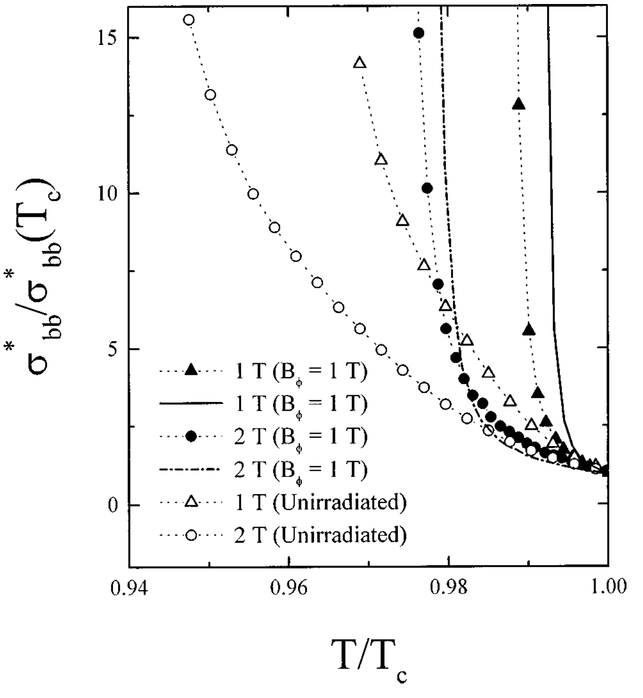

FIG. 3. $\sigma^*_{bb}(T)/\sigma^*_{bb}(T_c)$ vs T/T_c for magnetic fields of 1 and 2 T. Fluctuation conductivities $\sigma^*_{bb}(T,H)$ are enhanced after the irradiation of $B_\phi = 1$ T. The filled symbols and the curves without symbols are after the irradiation and obtained, respectively, by the linear resistivity fit and by the polynomial fit. The open symbols are before the irradiation.

$z=1.5$, dimension $d=3$, F is a scaling function, and $\nu = 0.669$. In order to study the pinning effects on the critical dynamics, the 3D-XY scaling is applied to the fluctuation conductivity of the irradiated crystal with all parameters z, d, and ν chosen to be the same values as for the unirradiated sample except zero resistance temperature T_{c0}. Figure 4 shows that in the presence of a magnetic field $1 \leqslant H \leqslant 7$ T, the fluctuation conductivity $\sigma^*_{bb}(T,H)$ of the irradiated sample do not collapse onto a function of $t/H^{1/2\nu}$ particularly near a magnetic field of 1 T, where $t \equiv 1 - T/T_{c0}$ and T_{c0} is a zero resistance temperature of 89.8 K. The fluctuation conductivities for the upper panel of Fig. 4 were extracted with the linear resistivity fit for the background subtraction. The lower panel of Fig. 4 was obtained from the polynomial fit. Both graphs show a similar result, indicating that the scaling is not sensitive to the method of background subtraction. As a magnetic field increases, however, the data begin to collapse to a single curve over a wide range of temperature, indicating a signature of the 3D-XY scaling.

The critical exponents z and ν, and the critical temperature T_{c0} have been changed to make a better collapse of fluctuation conductivities onto a single curve over a wide range of temperature and magnetic field. All attempts failed to produce a scaling. Note that the lowest Landau model did not exhibit a scaling either. The scaling in Fig. 4 was the best one among the attempts, particularly at higher magnetic field.

In summary, the columnar defects of the $YBa_2Cu_3O_{7-\delta}$ single crystal enhance the fluctuation conductivity in mixed state. The enhanced fluctuation conductivities σ^*_{bb} show a deviation from the 3D-XY scaling near the matching field of 1 T, indicating that when the number of vortices is close to that of columnar defects, the pinning effect on the critical dynamics is significant. The strong pinning influences not only on the fluctuation conductivity but also on its critical dynamics in the field regime. At the magnetic fields much higher than the matching field, however, the fluctuation conductivities show a signature of the 3D-XY scaling behavior. In the high fields the pinning effect on the critical dynamics is relatively small so that the critical dynamics approaches the universality class of superfluid ^{4}He.

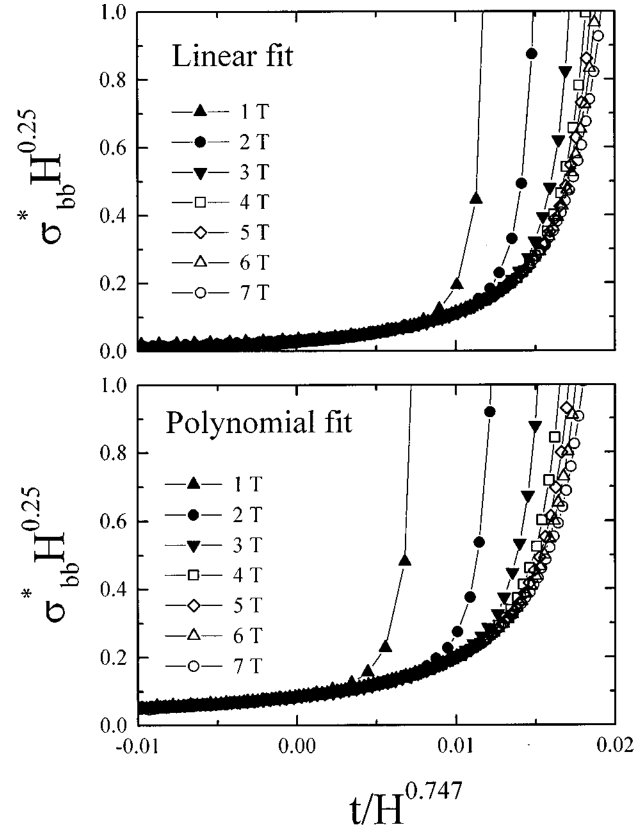

FIG. 4. $\sigma^*_{bb}H^{0.25}$ vs $t/H^{0.747}$ for the irradiated YBCO with $B_\phi = 1$ T. $t \equiv 1 - T/T_{c0}$ and T_{c0} is a zero resistance temperature of 89.8 K. The units of σ^*_{bb} and H are, respectively, $\mu\Omega^{-1}$ cm^{-1} and Tesla. The σ^*_{bb} for the upper panel is extracted by the linear-with-T resistivity fitting. The polynomial fit is used for the lower panel. These different methods for background subtraction show a similar result. At the magnetic-field values near matching field of 1 T, a deviation from 3D-XY scaling appears. At higher magnetic fields, a signature of the 3D-XY scaling is shown.

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