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Pinning Effect on Critical Dynamics in $Tl_2Ba_2CaCu_2O_8$ Films Before and After Introducing Columnar Defects

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DISCLAIMER

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***Abstract* – The effect of columnar defects on the critical dynamics of superconducting $Tl_2Ba_2CaCu_2O_8$ (Tl-2212) film has been investigated. The Tl-2212 film was irradiated at 0 °C by 1.3 GeV U-ions along the normal of the film surface. The dose of 6.0×10^{10} ions/cm^2 of the U-ion irradiation corresponds to a matching field of 1.2 T. The in-plane longitudinal resistivity of the irradiated Tl-2212 has been measured as a function of magnetic field H and temperature T. The extracted fluctuation part of the conductivity $\sigma_{xx}(T, H)$ of the unirradiated sample exhibits 3D-XY scaling behavior that reveals dynamic critical exponent $z = 1.8 \pm 0.1$ and static critical exponent $\nu \approx 1.338$. The results indicate that the weak interlayer coupling along the c-axis of Tl-2212 significantly influences static critical exponent ν and does not change dynamical critical exponent. After the irradiation, the fluctuation conductivities are enhanced by the strong pinnings and do not exhibit the same 3D-XY scaling behavior as for the unirradiated Tl-2212. Particularly at the low magnetic field values near the matching field of 1.2 T, the fluctuation conductivities show a clear deviation from the critical dynamics, suggesting that the pinning effect on the critical dynamics is significant.**

I. INTRODUCTION

High-T_c superconductors have short coherence lengths and high transition temperatures that introduce appreciable fluctuation effects and scaling behaviors near critical temperature. The fluctuation effects play an important role in superconducting phase transition because mean field theory with Gaussian corrections does not provide an appropriate description. The fluctuation of order parameter and vector potential has been widely studied to understand the nature of the superconducting phase transition of high-T_c superconductors at zero and non-zero magnetic fields [1]; magnetization, conductivity, and specific-heat measurements.

There is a growing body of experimental evidence [2]-[10] that 3D-XY scaling model fits better. The fluctuation effects that are observed in several measurements have been consistent with three-dimensional XY (3D-XY) critical behavior for $YBa_2Cu_3O_{7-\delta}$ (YBCO). The universality class [11] where the critical fluctuations belong has been the same as that of superfluid ^{4}He for YBCO single crystal [6] : 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. As for $Tl_2Ba_2CaCu_2O_8$ (Tl-2212) which is more anisotropic along c-axis than YBCO, however, the 3D-XY model has not been applied and the critical exponents are unknown yet.

Another issue of how the critical dynamics is affected by strong pinning of vortex has been discussed [12], [13]. For YBCO, the strong pinning due to columnar defects effectively reduces vortex motions that influence not only the fluctuation conductivity but also its critical dynamics. The degree of the influence due to columnar defects in Tl-2212 would be different because of the larger anisotropy.

This paper reports the longitudinal resistivity of Tl-2212 film before and after U ion irradidation of a matching field 1.2 T. Near critical temperature, the scaling behavior of the fluctuation conductivity before and after irradiation is compared in the frame work of 3D-XY model. We have discussed the applicability of 3D-XY model as well as the effect of pinning vortices on fluctuation conductivity and critical dynamics in Tl-2212 film before and after the irradiation.

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II. EXPERIMENTAL

The Tl-2212 epitaxial film used in this study was prepared at Superconductor Technologies Inc. [14], which was 500 nm thick. The sample was grown by excimer laser ablation with a post-deposition anneal on substrate of $LaAlO_3$. Film was patterned using standard photolithography for resistivity measurement. Its zero-resistance temperature T_{c0} was 102 K in zero field. The longitudinal resistivity was measured with a 4-terminal method upon applying magnetic field (0 - 9 T) parallel to the c-axis of Tl-2212 film. The sample was then irradiated at 0°C by 1.3 GeV U-ion ions, which was produced at the Argonne Tandem Linear Accelerator System at the Argonne National Laboratory. The irradiation dose of 6.0 x 10^{10} ions/cm^2 was chosen to an equivalent matching field B_ϕ of 1.2 T. The irradiation was aligned parallel to the c-axis of Tl-2212 film. A representative cross-sectional TEM (transmission electron microscopy) image in [15] indicates that columnar tracks are formed throughout the Tl-2212 film thickness of 500 nm. X-ray diffraction spectra show that the film is epitaxially grown with c-axis perpendicular to the substrate surface. SEM picture shows that the sample surface is smooth.

Fig. 1 shows the longitudinal resistivity $\rho_{xx}(T, H)$ of unirradiated Tl-2212 film for several values of applied magnetic field with H parallel to c-axis. Zero resistance temperature at zero magnetic field (≡ T_{c0}) is 102 K. The resistive transition temperature (10 to 90 %) is about 3 K. The inset of Fig. 1 shows that zero field resistivity is linear for T > 220 K. The resistivity curve extrapolates to non-zero value at zero temperature, indicating that some random disorder exist. Note that the random disorder has been reported to be irrelevant on static critical behavior [16], [17]. The zero resistance temperature is very much decreased upon applying magnetic field, compared with that of YBCO.

Fig. 2 shows the longitudinal resistivity $\rho_{xx}(T, H)$ of irradiated Tl-2212 film at several values of applied magnetic field with H parallel to c-axis. After the irradiation T_{c0} was lowered to 99.3 K from 102 K at zero magnetic field. Over the transition temperature, the resistivity after irradiation is slightly increased and its general shape is close to one before the irradiation. Normal state resistivity of the irradiated one is shown in the inset of Fig. 2. 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.

Fig. 3 displays the resistive transitions of Tl-2212 film before and after irradiation vs reduced temperature T/T_{c0} for 1 and 4 T. The resistivity is plotted in log scale. T_{c0} is defined as a temperature where ρ_{xx} at zero magnetic field is zero. Symbols are after irradiation and lines before irradiation. The onset temperature in each magnetic field is increased due to strong pinning of vortex. The resistivity is decreased due to vortex pinning enhancement by columnar defects.

In order to investigate the enhancement of fluctuation conductivity due to vortex pinning, fluctuation conductivity $\sigma^*_{xx}(T, H)$ was obtained by background subtraction from resistivity $\rho_{xx}(T, H)$. Longitudinal conductivity σ_{xx} can be expressed as $\sigma^*_{xx} + \sigma_{B.G}$ where σ^*_{xx} and $\sigma_{B.G}$ are respectively fluctuation and background conductivity. The $\sigma_{B.G}$ is one

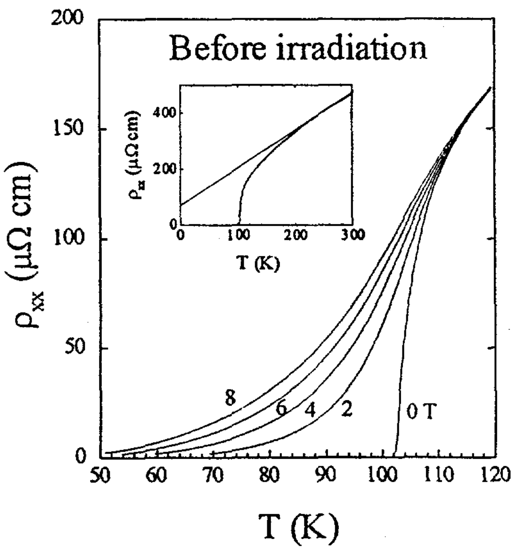

Fig. 1. Longitudinal resistivity $\rho_{xx}(T, H)$ for the unirradiated film of $Tl_2Ba_2CaCu_2O_8$ at H = 0, 2, 4, 6, and 8 T. The magnetic field was applied parallel to the c-axis of the sample. The inset shows a normal state resistivity curve. The linear line is a background resistivity.

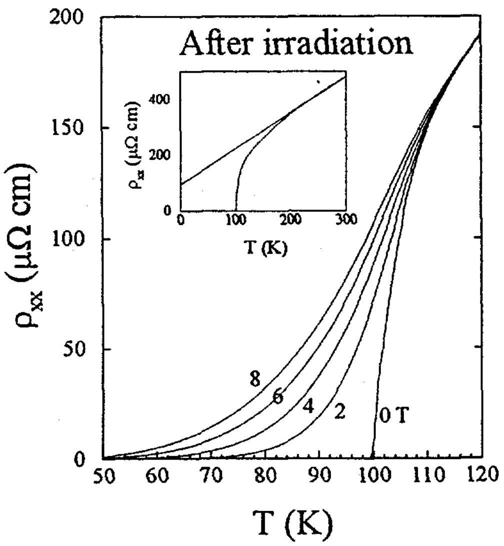

Fig. 2. Longitudinal resistivity $\rho_{xx}(T, H)$ for the irradiated film of $Tl_2Ba_2CaCu_2O_8$ at H = 0, 2, 4, 6, and 8 T. The magnetic field was applied parallel to the c-axis of the sample. The inset shows a normal state resistivity curve. The linear line is a background resistivity.

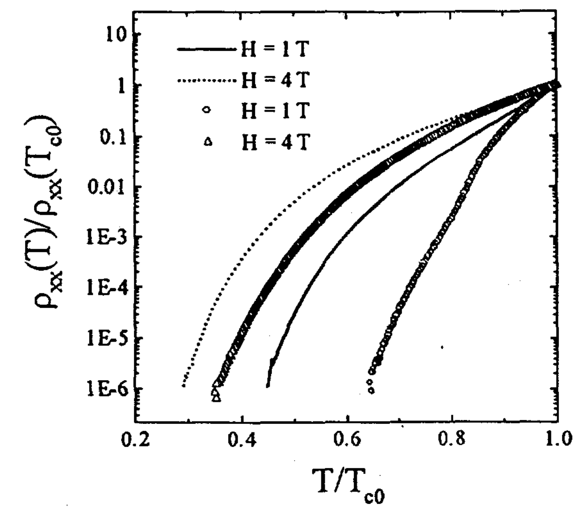

Fig. 3. $\rho_{xx}(T, H)/\rho_{xx}(T_{c0}, H)$ vs T/T_{c0} in magnetic field values of 1 and 4 T with H // c-axis. T_{c0} is defined as a temperature where ρ_{xx} at zero magnetic field is zero. The curves are before the irradiation and the symbols after the irradiation. At each magnetic field, the onset temperature of ρ_{xx} is enhanced after the irradiation.

over the background resistivity $\rho_{B.G}(T)$. A linear resistivity fit for unirradiated Tl-2212 film is used for the background resistivity above 220 K. By subtracting $\sigma_{B.G}$ from σ_{xx}, the fluctuation conductivity σ^*_{xx} was obtained. Since the resistivity of the irradiated sample was curved below 220 K, a linear resistivity fit over $220 \le T \le 300$ K was chosen. Note that a polynomial fit $a + bT + cT^2$ or a linear fit near transition temperature display qualitatively the same scaling behavior of fluctuation conductivity as for the linear-with-T resistivity fit above 220 K [12].

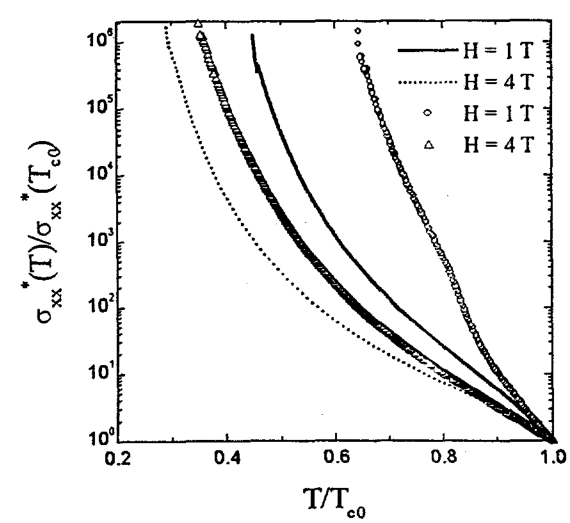

Fig. 4. $\sigma^*_{xx}(T)/\sigma^*_{xx}(T_{c0})$ vs T/T_{c0} at H = 1 and 4 T before and after irradiation. The fluctuation conductivity is enhanced by columnar defects. The curves are before the irradiation and the symbols after the irradiation.

To compare pinning effect on fluctuation conductivity, the fluctuation conductivity and temperature are respectively normalized with the values at zero resistance temperature T_{c0}. $\sigma^*_{xx}(T)/\sigma^*_{xx}(T_{c0})$ vs T/T_{c0} for H = 1 and 4 T are displayed in Fig. 4. Fig. 4 reveals that vortex pinning due to columnar defects enhances the fluctuation conductivity. Note that the inherent random disorder in film such as point defects, grain boundary, and dislocation provides weaker pinning effect than columnar defect in film [13]. For other fields up to 9 T, the similar enhancement of fluctuation conductivity as in Fig. 4 is observed.

Before irradiation, the fluctuation conductivity of Tl-2212 film obeys 3D-XY scaling behavior shown in Fig. 5 ; $\sigma^* \sim H^{-(2+z-d)/2} F(t/H^{1/2\nu})$ where dynamic critical exponent z = 1.8 ± 0.1, static critical exponent ν = 1.338, dimension d = 3, F is a scaling function, and $t \equiv 1 - T/T_{c0}$. Fitting process is described elsewhere [6], [12]. Surprisingly the static critical exponent ν is two times larger than for YBCO, whereas the dynamic critical exponent z is almost the same as for YBCO, indicating that coherence length ratio $\xi(T)/\xi(0)$ in Tl-2212 increases faster as temperature reaches T_c and the universality class determined by the dynamical critical exponent is similar to one for YBCO film. For a note, in YBCO film, the pinning due to the inherent random disorder increases the dynamic critical exponent z to 1.86 ± 0.1 from the value of 1.5 that is for YBCO single crystal. The value of the static critical exponent ν, however, is not changed by the inherent disorder in YBCO film.

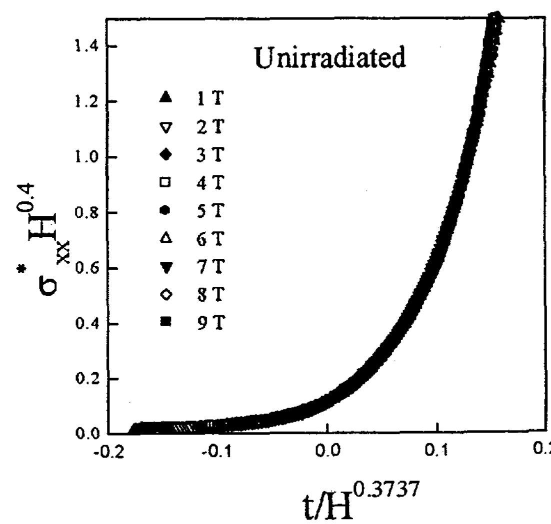

Fig. 5. $\sigma^*_{xx} H^{0.4}$ vs $t/H^{0.3737}$ for the unirradiated $Tl_2Ba_2CaCu_2O_8$ film. $t \equiv 1 - T/T_{c0}$ and T_{c0} is a zero resistance temperature of 102 K. The units of σ^*_{xx} and H are respectively $\mu\Omega^{-1}cm^{-1}$ and Tesla. The σ^*_{xx} is extracted by the linear-with-T resistivity fitting. The dynamic critical exponent z is 1.8 ± 0.1 which is the same value as for YBCO film. However, the static critical exponent ν of 1.338 is two times larger than for YBCO.

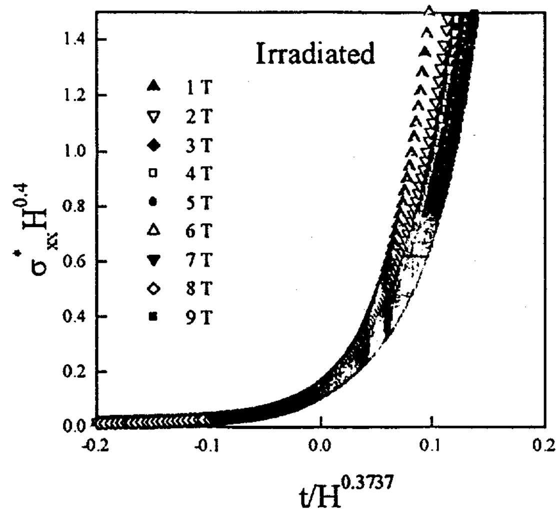

Fig. 6. $\sigma^*_{xx}H^{0.4}$ vs $t/H^{0.3737}$ for the irradiated $YBa_2Cu_3O_{7-\delta}$ film with B_ϕ = 1.2 T. $t \equiv 1 - T/T_{c0}$ and T_{c0} is a zero resistance temperature of 99.3 K. The units of σ^*_{xx} and H are respectively $\mu\Omega^{-1}cm^{-1}$ and Tesla. At low magnetic field, a clear deviation from 3D-XY scaling exists.

The 3D-XY scaling model is applied to see the strong pinning effect by columnar defects on the critical dynamics; all parameters z, d, and ν are chosen to be the same values as for the unirradiated sample except zero resistance temperature T_{c0}. Note that the data collapse as in Fig. 5 over wide temperature range could not be made by changing z and ν, as described for YBCO [12], [13]. Fig. 6 demonstrates that in the presence of magnetic fields (1 - 9 T), the fluctuation conductivity $\sigma^*_{xx}(T, H)$ of the irradiated sample do not collapse onto a function of $t/H^{1/2\nu}$ particularly at low magnetic field, where T_{c0} is a zero resistance temperature of 99.3 K. At high magnetic field, however, the data show better collapse to a curve, that is a signature of the 3D-XY scaling. This result is consistent with the data of the irradiated YBCO crystal and film [12], [13].

III. CONCLUSION

In summary, the fluctuation conductivity of the unirradiated Tl-2212 film obeys 3D-XY scaling behavior, though Tl-2212 has longer c-axis and larger anisotropy than those of YBCO. The static critical exponent ν of 1.338 is two times larger than one for YBCO. The dynamic critical exponent z of 1.8 ± 0.1 is quite similar to one (1.86 ± 0.1) for YBCO film. The results indicate that the weak interlayer coupling along the c-axis of Tl-2212 significantly influences most likely static critical exponent ν and does not change dynamical critical exponent. The columnar defects in the irradiated Tl-2212 film enhance fluctuation conductivity. As shown in the irradiated YBCO [12], [13], the enhanced fluctuation conductivity σ_{xx}^* by the columnar defects in the irradiated Tl-2212 film does not show the 3D-XY scaling particularly at low magnetic field, indicating that the pinning effect on the critical dynamics is significant. .

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