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The non-linear dynamics of vortices subjected to correlated and random pinning disorders in a quasi-2D superconductor

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Abstract. Understanding the dynamics of vortex matter subjected to random and correlated pinning disorders in layered superconductors remains a topic of considerable interest. The dynamical behavior of vortices in these systems shows a rich variety of effects due to many competing interactions. Here, we study the ac response of as-grown as well as heavy-ion-irradiated $Tl_2Ba_2CaCu_2O_8$ (Tl-2212) thin films by using a micro Hall-probe susceptometer. We find that the dynamics of vortices in the high-temperature, low-field regime of the H–T phase diagram investigated here depends on the nature of pinning defects. While the decay of screening currents $J(t)$ indicates a glassy behavior in both types of samples, the nature of the glassy phase is different in the two cases. Samples with columnar defects show distinct signature of a Bose glass in the measurement of $J(t)$ and the angular dependence of the irreversibility field (B_{irr}).

Keywords. Vortices; quasi-2D superconductor; correlated pinning; non-linear dynamics.

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1. Introduction

The dynamics of vortices subjected to correlated pinning disorder in epitaxial thin films of $Tl_2Ba_2CaCu_2O_8$ (Tl-2212) superconductor has been studied extensively using resistivity $\rho(T)$ and critical current density (J_c) measurements [1,2]. While these dc measurements have contributed immensely to our understanding of the dynamics of the two-dimensional (2D) vortices subjected to correlated pinning disorder, there are many aspects of vortex motion, which cannot be resolved using the dc techniques. The elastic response of the flux line lattice and the temporal evolution of the mixed state when a perturbation is applied, are some examples of this. The time dependence of the mixed state parameters can be studied effectively using ac susceptibility techniques. In this paper, we report measurements of the ac response of Tl-2212 epitaxial films in their virgin state and after irradiating them with 250 MeV Ag ions. We observe that the low-field, high-temperature response of vortices in this layered superconductor depends sensitively on the dimensionality of the pinning defects.

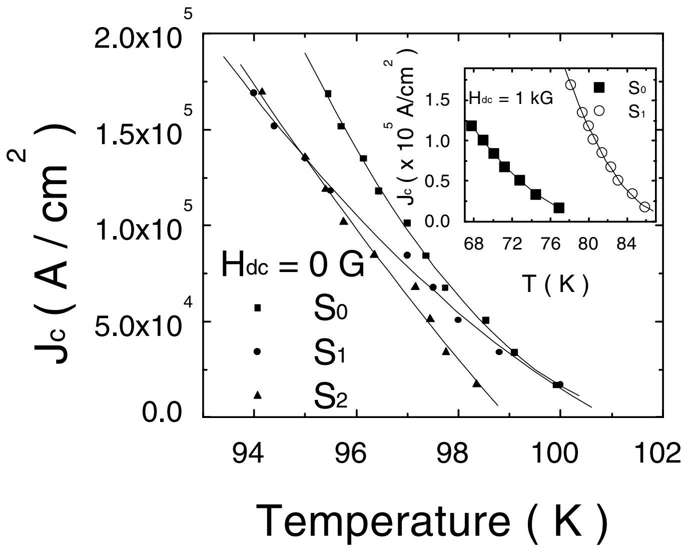

Figure 1. Temperature dependence of zero-field J_c of samples S_0, S_1 and S_2. Inset shows temperature dependence of J_c for samples S_0 and S_1 at 1 kG dc field.

2. Experimental details

Details of preparation of Tl-2212 thin films on (100) $LaAlO_3$ substrates are described elsewhere [3]. We have used $\sim 1\ \mu$m thick films for the ac susceptibility measurements. Columnar defects (CDs) were produced in two films by irradiation with 250 MeV Ag ions in a direction parallel to the c-axis at the doses of 1×10^{10} ions/cm^2 and 5×10^{10} ions/cm^2, which correspond to the matching fields $B_\phi (= n_\phi \times \phi_0$, where n_ϕ is the density of defects present in the system and ϕ_0, the flux quantum) of 2 kG and 10 kG, respectively. The unirradiated sample, and the samples irradiated at 2 kG and 10 kG dose are referred to as S_0, S_1 and S_2, respectively in the subsequent discussion. The ac susceptibility measurements were carried out using a local Hall-probe based susceptometer consisting of a GaAs/GaAlAs Hall sensor of effective area $25 \times 25\ \mu$m^2. Details of this ac susceptometer are described elsewhere [4]. The real and imaginary parts (χ' and χ'') of the ac susceptibility are calculated from the in-phase (T'_H) and out-of-phase (T''_H) components of the fundamental and third harmonic ($|T_{H3}|$) transmittivities [4]. From the measurements of ac response as a function of drive-field amplitude, we have calculated the critical current density (J_c) of the pristine and irradiated samples.

3. Results and discussion

Figure 1 shows the temperature dependence of J_c for the three samples. This is derived from the isothermal measurements of T'_H and T''_H as a function of ac field amplitude (h_m). J_c is related to h_m as $h_m = 0.97 J_c d$, where d is the thickness of the film [5]. Although

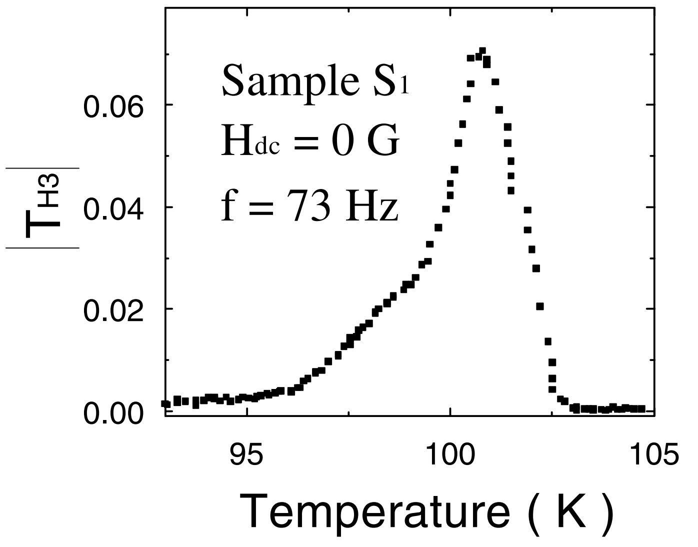

Figure 2. Temperature dependence of $|T_{H3}|$ for sample S_1 in zero dc field.

zero-field J_c of the sample S_0 has higher value than the samples having columnar defects, J_c of the latter samples is considerably higher in the presence of a static magnetic field aligned parallel to the CDs. Inset of figure 1 shows the temperature dependence of J_c at 1 kG dc field for samples S_0 and S_1. The enhancement in J_c is attributed to localization of flux lines at the columnar defects.

In figure 2, we show the third harmonic susceptibility ($|T_{H3}|$) of sample S_1 in zero-dc field. The appearance of $|T_{H3}|$ is a signature of non-linear screening response to the ac field. The temperature at which $|T_{H3}|$ is detectable on cooling is identified as the irreversibility temperature [6]. Figure 3 shows the irreversibility line (IRL) for all the three samples. The irreversibility field (B_{irr}) of the irradiated samples varies as $e^{-\alpha T}$ with $\alpha = 0.16$ for $B \leq B_\phi$, and above B_ϕ, it increases linearly with the decreasing temperature. The abrupt change in slope of IRL at $B = B_\phi$ in sample S_1 is evident in the inset of figure 3. The discontinuity in IRL at $B = B_\phi$ signals a change in pinning mechanism from a Bose glass-type regime to the regime of collective pinning of many vortices by a single columnar pin.

As evident from figure 4, T'_H shows a minimum when the external magnetic field becomes parallel to the defects, and the angular width and depth of this minimum increase on lowering the temperature. The minimum in T'_H is a clear indication of a line-like nature of the vortices in this range of temperature and field strength. Since $|T_{H3}|$ at these temperatures and fields is non-zero, we conclude that the minimum seen in figure 4 is a signature of the correlations between pancake vortices along the field direction in the vortex solid phase [7]. Since a totally decoupled ensemble of pancake vortices would not show any angular selectivity, it can be concluded that the dissipative excitations in this range of temperature and field strength are half-loops comprising of many pancake vortices.

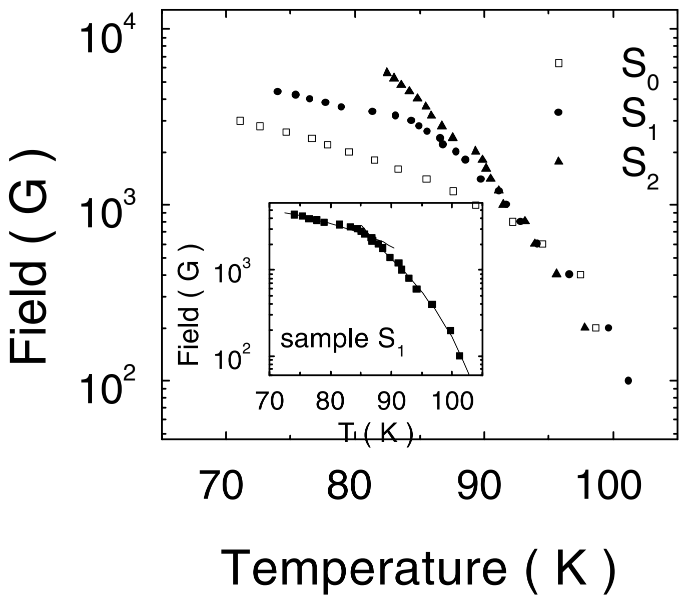

Figure 3. The IRL of S_0, S_1 and S_2 samples. Inset shows the IRL for sample S_1. The linear and exponential fits above and below B_ϕ respectively, are shown as solid lines.

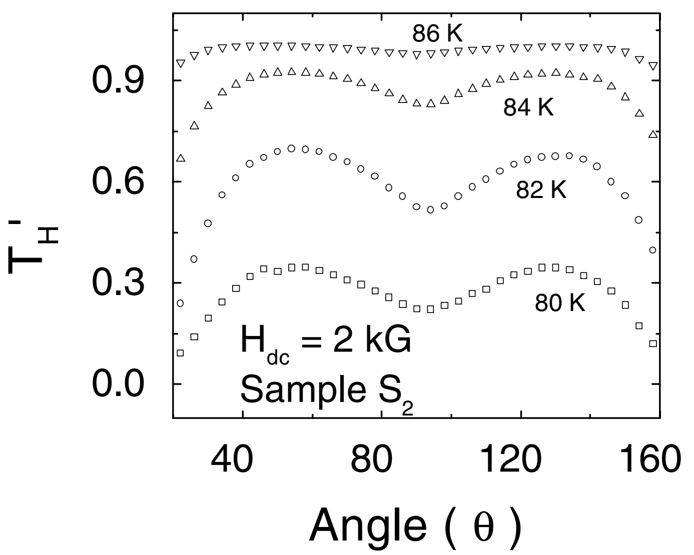

Figure 4. Angular dependence of $T'_{\rm H}$ at 2 kG dc field for sample S_2.

4. Conclusion

In summary, we have measured the ac response of $Tl_2Ba_2CaCu_2O_8$ thin epitaxial films in their pristine as well as irradiated forms using a micro Hall-probe-based ac susceptometer. We observe a significant enhancement in J_c of these films after the introduction of columnar defects. This is accompanied by a shift in IRL to higher temperatures and fields. Angular dependence of the susceptibility data shows that the vortices in irradiated samples are correlated along the field direction in the high-temperature and low-field regime investigated here.

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References

[1] R C Budhani, W L Holstein and M Suenaga, *Phys. Rev. Lett.* **72**, 566 (1994)
R C Budhani, M Suenaga and S H Liou, *Phys. Rev. Lett.* **69**, 3816 (1992)
[2] D H Kim, K E Gray, R T Kampwirth and D M Mckay, *Phys. Rev.* **B42**, 6249 (1990)
[3] W L Holstein, L A Parisi, C Wilker and R B Flippen, *Appl. Phys. Lett.* **60**, 2014 (1993)
[4] Leena K Sahoo, S Patnaik, R C Budhani and W L Holstein, *Phys. Rev.* **B63**, 214501 (2001).
[5] John R Clem and Alvaro Sanchez, *Phys. Rev.* **B50**, 9355 (1994)
[6] J Deak, M McElfresh, John R Clem, Zhidong Hao, M Konczykowski, R Muenchausen, S Foltyn and R Dye, *Phys. Rev.* **B47**, 8377 (1993)
[7] David R Nelson and V M Vinokur, *Phys. Rev.* **B48**, 13060 (1993)