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Microwave vortex dynamics in Tl-2212 thin films

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Abstract

We present measurements of the effective surface impedance changes due to a static magnetic field, $\Delta Z(H,T) = \Delta R(H,T) + \mathrm{i}\Delta X(H,T)$, in a Tl-2212 thin film with $T_c > 103$ K, grown on a CeO_2 buffered sapphire substrate. Measurements were performed through a dielectric resonator operating at 47.7 GHz, for temperatures 60 K $\leqslant T < T_c$ and magnetic fields $\mu_0 H \leqslant 0.8$ T. We observe exceptionally large field induced variations and pronounced super-linear field dependencies in both $\Delta R(H)$ and $\Delta X(H)$ with $\Delta X(H) > \Delta R(H)$ in almost the whole (H,T) range explored. A careful analysis of the data allows for an interpretation of these results as dominated by vortex dynamics. In the intermediate-to-high field range we extract the main vortex parameters by resorting to standard high frequency model and by taking into proper account the creep contribution. The pinning constant shows a marked decrease with the field which can be interpreted in terms of flux lines softening associated to an incipient layer decoupling. Small vortex viscosity, by an order of magnitude lower than in Y-123 are found. Some speculations about these findings are provided.

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Keywords: $Tl_2Ba_2CaCu_2O_8$+x; Surface impedance; Pinning

1. Introduction

The softness of the fluxon system in high-T_c superconductors (HTS), favoured by anisotropy, small coherence length and large penetration length, makes it strongly susceptible to disorder induced by both thermal effects and order parameter inhomogeneities. An extreme limit of fluxon line softening shows up in layered compounds, where vortex lines leave place to 2D segments (pancakes) moving independently. Consequently, the (H,T) plane is populated by very heterogenous vortex matter phases differing under many aspects, among which pinning mechanisms are of particular interest.

Vortex motion induced by a transport current is the main source of power dissipation. It is influenced by the nature of pinning and of the vortex system, which together determine the vortex mobility [1]. Moreover, the vortex motion dissipation involves quasiparticle (QP) excitations, whose density of states can be both bound inside or extending outside the vortex cores (as in nodal superconductors). In this sense the vortex motion can indirectly probe the electronic state inside vortices [2].

In these respects the microwave response is a powerful probe: the small amplitude of the vortex oscillations induced at microwave frequencies reduces the effects of the complex interaction between vortices in the dynamic behavior. The simple, single-vortex elastic regime is often excited by microwaves, which is represented by the so-called pinning constant k_p. The power dissipation is represented through the vortex viscosity η, which is linked to the vortex core properties in terms of QP density of states and lifetime. Additional extrinsic effects that might arise from grain boundaries and, in general, weak-links, are often identified by their peculiar magnetic field dependence.

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Within standard Abrikosov vortex dynamics, the microwave response has been modeled by many authors [3–5]. According to Brandt's approach [5], in the limit of negligible QP conductivity with respect to superfluid conductivity ($\sigma_1 \ll \sigma_2$, i.e. $T \lesssim 0.98T_c$) the following expression can be written down:

$$\tilde{\rho} = \rho_{vm} + i\frac{1}{\sigma_2} = \rho_{ff}\frac{\epsilon' + i\omega\bar{\tau}}{1 + i\omega\bar{\tau}} + i\frac{1}{\sigma_2} \quad (1)$$

where the second equality defines the vortex motion resistivity ρ_{vm} and $\rho_{ff} = \Phi_0 B/\eta$ is the flux flow resistivity, $\bar{\tau} = \frac{\tau\tau_r}{\tau+\tau_r}$, where $\tau = \eta/k_p$ is the depinning characteristic time and $\tau_r = \tau e^{U/K_B T}$ is the creep relaxation time in the linear regime [5]. Finally, U is the pinning potential barrier height and $\epsilon' = \frac{\tau}{\tau+\tau_r}$ is a dimensionless creep parameter. In the limit of no creep $U \to \infty$, $\epsilon' \to 0$, $\bar{\tau} \to \tau$ and ρ_{vm} in Eq. (1) reverts to the simpler Gittleman–Rosenblum (GR) expression [3]. By increasing the excitation frequency, one spans from a pinning to a dissipation dominated dynamics which, for sufficiently high frequencies, becomes pure flux flow. The crossover is given by the characteristic (de)pinning angular frequency $\omega_p = k_p/\eta = 1/\tau$. It is however worth noting that the above described model does not apply in full to the case of large creep rates (e.g., when T approaches T_c), so that an estimate of the creep factor ϵ' is necessary in the analysis of the data.

In the following, we focus on the Tl-2212 compound, which has received little attention with respect to other cuprates such as YBCO and BSCCO. Moreover, it has an intermediate anisotropy between the more isotropic Y-123 and the strongly layered Bi-2212, so that its vortex phase properties can be a bridge between the almost rigid, rod like fluxons in Y-123 and the pancake behavior of Bi-2212 fluxons.

2. Experimental results and discussion

Measurements are performed on a Tl-2212 thin film square sample, 10 mm wide and $d = 240$ nm thick. It was grown c-axis-oriented (i.e. with the film c-axis parallel to the substrate normal) on CeO_2-buffered sapphire (0.44 mm thickness) by conventional two step method [6]. The critical temperature, estimated from the microwave response, was $T_c > 103$ K. The inductively measured critical current density is $J_c(77\text{ K}) = 0.5\text{ MA/cm}^2$. A solid/liquid nitrogen cryostat provides temperatures down to 60 K. A conventional electromagnet generates magnetic fields $\mu_0 H \leqslant 0.8$ T, applied perpendicular to the sample surface (i.e. parallel to the sample c-axis). The microwave response is determined by means of a cylindrical sapphire resonator using the TE_{011} mode with the surface perturbation method, at a resonating frequency $\omega/(2\pi) \approx 47.7$ GHz. The resonator unloaded quality factor Q_u and ω are determined by a Lorentz fit of the measured microwave power reflected by the resonator as a function of frequency [7]. Their field induced changes yield the field changes of the effective surface impedance $\Delta Z(H) = Z(H) - Z(0) = \Delta R(H) + i\Delta X(H)$ according to

$$\Delta Z(H) = G_s\left(\Delta\frac{1}{Q_u(H)} - 2i\frac{\Delta\omega(H)}{\omega}\right) \quad (2)$$

where G_s is a geometric factor of the resonator.

In the spirit of extracting as much information as possible from the raw data, we first report and discuss the measured Q_u against H (upper panel of Fig. 1), at selected temperatures.

As it can be seen, Q_u quickly decreases even by applying small magnetic fields. This clearly indicates a large magnetoresistance, whose magnitude can be better appreciated by comparison with similar measurements performed on a typical Y-123 film. Indeed, the Y-123 data (shown in the lower panel of Fig. 1 at the same reduced temperatures of the preceding set) show a much smaller field induced decrease of Q_u [8]. Following conventional approaches [9], it is possible to estimate the vortex viscosity η, for which we find values fully consistent with the literature [9]. The comparison brings into light a peculiar feature of the measurements on Tl-2212: since the magnetoresistance is upper bounded by the free flux flow resistivity ρ_{ff}, the large magnetoresistance in Tl-2212 determines a peculiarly high ρ_{ff} or, equivalently, a small η. This result arises directly from the raw data.

A second feature that is apparent in the comparison presented in Fig. 1 is the characteristic curvature of the $Q_u(H)$ curves in Tl-2212, which yields additional information on

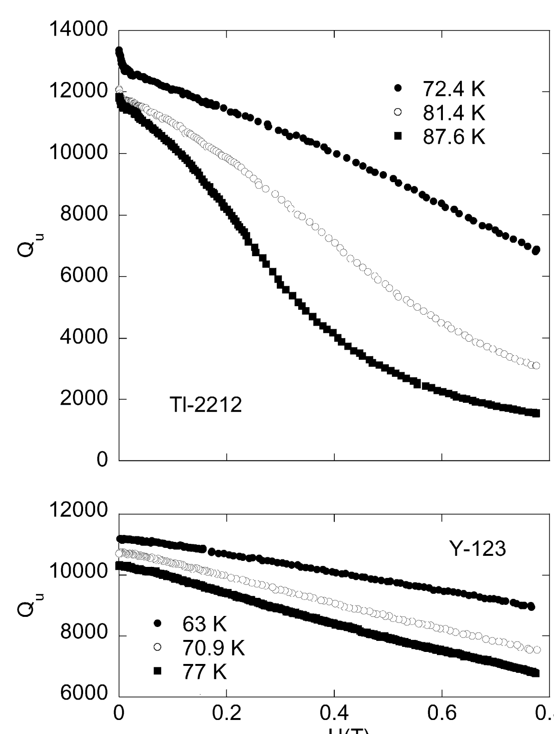

Fig. 1. *Upper panel*: Q_u *vs.* H at selected temperatures for Tl-2212. *Lower panel*: analogous measurements on Y-123, reported for same values of reduced temperatures T/T_c.