LA-UR-04-5539

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Submitted to: Ultrafast Phenomena XLV

Los Alamos

NATIONAL LABORATORY

Dynamic coupling-decoupling crossover in the current-driven vortex-state in $Tl_2Ba_2CaCu_2O_8$ studied using terahertz time-domain spectroscopy

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Abstract: Employing terahertz time-domain spectroscopy in transmission, we have measured the Josephson plasma resonance in $Tl_2Ba_2CaCu_2O_8$ high-T_c thin films, and studied the current-driven coupling-decoupling crossover in the driven vortex lattice.

1. Introduction

The properties of driven periodic structures subject to quenched disorder, including charge-density waves, Wigner crystals and vortex lattices, have become one of the central issues in the phenomenology of nonequilibrium statistical mechanics [1–4]. In the context of the vortex lattice, Koshelev and Vinokur predicted the driven system to undergo a dynamic phase transition at some threshold current between the fluid-like and crystal-like moving states [2]. In other words, an applied current puts forth a scenario where a pinned vortex lattice flows plastically at first as some vortices are depinned, and then becomes more ordered at higher applied currents as more vortices are depinned, possibly forming a moving ordered vortex lattice. Thus, beyond some critical value a dynamic phase transition may occur to a more ordered state, characterized by a change from incoherent to coherent vortex motion.

The *c*-axis correlations of pancake vortices in a highly anisotropic high-T_c superconductor are directly related to the interlayer phase coherence, $\langle\cos\varphi_{n,n+1}\rangle$, in the vortex state [5]. $\varphi_{n,n+1}(\mathbf{r},B)$ is the phase difference between layer n and $n+1$, $\mathbf{r}$ is the in-plane coordinate, and B is the magnetic field. When the pancake vortices form straight lines perpendicular to the layers, $\varphi_{n,n+1}(\mathbf{r},B)$ vanishes and the average of the cosine of the phase difference $\langle\cos\varphi_{n,n+1}\rangle = 1$. However, when the pancake vortices are misaligned along the direction perpendicular to the layers, a nonzero phase difference is induced, which results in the reduction of $\langle\cos\varphi_{n,n+1}\rangle$ from unity. Interlayer correlations of pancakes in a driven vortex system in highly anisotropic layered superconductors were studied by Aranson *et al.* by numerical simulations of the time-dependent Ginzburg-Landau-Lawrence-Doniach equations in a model of two coupled layers [1,2]. The authors calculated the average of the cosine of the phase difference, $W_c = \langle\cos\varphi_{12}\rangle$, as a function of the electric field E along the layers produced by the intralayer current. The authors found a decrease of W_c at low electric fields (currents) in the plastic flow regime accompanied by an increase of W_c at higher electric fields (currents) as smectic flow replaces plastic flow. The rate of increase becomes stronger as the anisotropy decreases because the vortex system approaches the case of an isotropic superconductor where a dynamic transition should occur at some critical value of the current. The authors concluded that a dynamic coupling-decoupling crossover takes place regarding the interlayer pancake ordering, while a change of intralayer ordering with current can be described as a dynamic melting transition.

Here we use the c-axis Josephson plasma resonance (JPR) [6], which is one of the most powerful experimental probes for probing the interlayer phase coherence and c-axis ordering of pancake vortices in highly anisotropic layered superconductors. The JPR is a Cooper pair charge oscillation mode perpendicular to the CuO_2 layers. In zero magnetic field the JPR is a direct probe of the Josephson coupling between the layers. In this case the JPR frequency is given as $\omega_0(T) = c/[\lambda_c(T)\sqrt{\varepsilon_\infty}] = c/[\gamma\lambda_{ab}(T)\sqrt{\varepsilon_\infty}]$. Here, λ_c and λ_{ab} are the London penetration depths along the c-axis and ab-plane, respectively. γ is the anisotropy parameter, c is the speed of light, and ε_∞ is the high-frequency dielectric constant along the c-axis. In the presence of a c-axis magnetic field B, the JPR can be written as [5]

$$\omega_p^2(B,T) = \omega_0^2(T)W_c,\quad W_c = \left\langle\cos\left[\varphi_{n,n+1}(\mathrm{r},B)\right]\right\rangle. \qquad (1)$$

Here $\langle\cos\varphi_{n,n+1}\rangle$ is the local thermal and disorder average of the cosine of the gauge-invariant phase difference between adjacent layers n and $n+1$. Thus, the JPR probes the value of W_c, which is directly related to the correlations of pancake vortices along the c-axis.

2. Results and Discussion

Here we present the first studies of the current-driven vortex state in a high-T_c superconductor, $Tl_2Ba_2CaCu_2O_{8+\delta}$ (Tl-2212), by directly probing the interlayer phase coherence with the JPR, and measured employing THz-TDS in transmission. The growth process of Tl-2212, the experimental setup are discussed in Ref. 6. All experiments were performed in field-cooled mode.

In Fig. 1 we show the interlayer phase coherence factor, $W_c = \omega_p^2(B = 2.5\,\mathrm{kG}, T, I)/\omega_0^2(0, 10\,\mathrm{K}, 0)$, as a function of current in the ab-plane at 10, 60, 80, and 90 K in a 2.5 kG c-axis applied magnetic field. We see three different types of behavior of $W_c(I)$ with increasing current: a) at low currents W_c decreases with I, i.e. plastic flow regime; b) rapid increase of W_c with I as smectic flow is established above the threshold current; and c) slower increase of W_c with I. Next we compare our experimental data with theoretical simulations for W_c at 80 and 90 K. We note that in a magnetic field of 2.5 kG and at temperatures 80 and 90 K the current-driven vortex state corresponds to the liquid vortex state [7]. We associate the pronounced increase in $<\cos\varphi_{n,n+1}>$ at 80 and 90 K with a

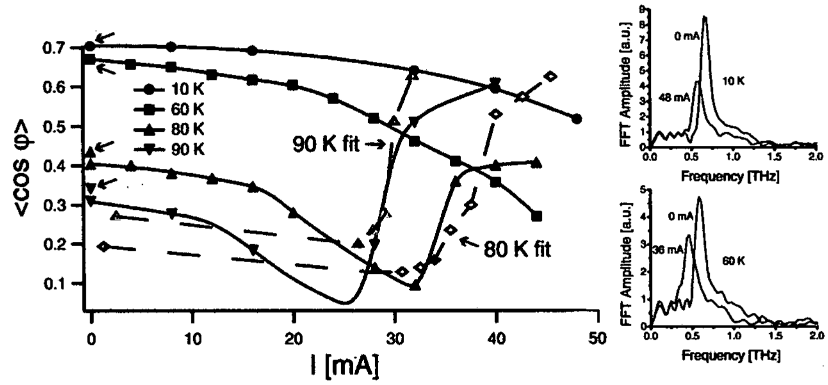

Fig. 1. Interlayer phase coherence factor $<\cos\varphi_{n,n+1}>$ versus applied *ab*-plane current in Tl-2212 in 2.5 kG *c*-axis magnetic field. The solid lines are guides for the eye. The arrows at 0 mA indicates the value of $<\cos\varphi_{n,n+1}>$ for each temperature after the current has been switched off. The shown fits for 80 and 90 K are obtained from simulations using I_c = 24 mA. The two right figures illustrates the effect of the current on the JPR.

dynamic phase transition as predicted by Koshelev and Vinokur [2], where a crossover from coupled to decoupled liquid vortex state occurs. We conclude that there is qualitative good agreement between the experimental and theoretical results. The minor discrepancy between the experimental and theoretical results in the regime of small currents (from 0 to 20 mA) can be attributed to the fact that thermal fluctuations were neglected in the simulations. These fluctuations will possibly enhance the vertical alignment in the small current regime.

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