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Microcantilever studies of angular field dependence of vortex dynamics in $Bi_2Sr_2CaCu_2O_{8-x}$

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Using a nanogram-sized single crystal of $Bi_2Sr_2CaCu_2O_{8-x}$ attached to a microcantilever we demonstrate in a direct way that in magnetic fields nearly parallel to the *ab* plane the magnetic field penetrates the sample in the form of Josephson vortices rather than in the form of a tilted vortex lattice. We further investigate the relation between the Josephson vortices and the pancake vortices generated by the perpendicular field component.

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Much progress has been made in the understanding of the phase diagram of layered superconductors with very weak interlayer coupling such as $Bi_2Sr_2CaCu_2O_{8-x}$ (BSCCO). In a magnetic field perpendicular to the Cu-O planes, vortex lines are viewed as stacks of pancake vortices that are weakly coupled via Josephson and magnetic interactions in adjacent layers. Depending on the relative strength of the two interactions we expect different scenarios for the melting and decoupling transitions. With stronger Josephson coupling, pancake vortices may remain coupled below the melting transition. However, for the case with stronger magnetic coupling, a ''sublimation'' transition is predicted in which the three-dimensional vortex lattice dissociates into independent two-dimensional pancake vortices at the melting transition.[1]

The study of vortex structures and melting transitions in magnetic fields canted with respect to the *c* axis has received mostly theoretical consideration.[2–4] A rich variety of vortex configurations has been proposed to take into account the finite angle between the applied field and the crystal *c* axis, as well as the layered structure, each derived in a different regime of the parameters. In particular, an interesting structure has been proposed for the case of predominantly magnetic coupling between the layers.[5] In this case the in-plane magnetic field interacts with the pancake vortices only through the Josephson interaction, while the alignment of the pancakes is determined by the magnetic coupling. Since this implies that a rigid tilt of the vortex lattice costs magnetic energy, it would be more favorable for the magnetic field to penetrate into the superconductor in the form of Josephson vortices between the layers. The consequence of the above considerations is a lattice of pancake vortices that coexists with a lattice of Josephson vortices. Depending on the angle, one lattice will be more dilute than the other.

The melting of the vortex lattice in BSCCO single crystals in a tilted magnetic field was studied recently by Schmidt *et al.*[6] using local Hall probe measurements with an active area of 80×80 μm^2. They found agreement with published results by defining an effective melting field, i.e., the perpendicular component of the magnetic field. The most striking evidence that the thermodynamics follows the perpendicular component was the observation that the entropy jump at the transition is insensitive to the presence of the in-plane field. This result was not obtained, however, at large angles where the field orientation is close to the *ab* plane. Contrary to the results of Schmidt *et al.*, Ooi *et al.*,[7] also using local magnetization measurements, though with an active sample area 3 times smaller, found that the simple perpendicular-component scaling ceases to work at much higher angles (as measured from the *c* axis), thus invoking a new temperature-dependent formula to scale the angle-dependent location of the first-order transition peak.

In this paper we present results on magnetomechanical measurements of a nanogram-sized BSCCO single crystal in a tilted magnetic field as a function of temperature, employing a microcantilever device. The size of the crystal was chosen to be smaller than the active area of previously reported local measurements,[6–8] while in this experiment the measurement itself is inherently global. Choosing nominal magnetic fields above the first-order transition,[9] we observe a flat dissipation and a resonant frequency of the device very close to the normal-state value. Tilting the sample with respect to the magnetic field reduces the perpendicular component of the field and the sample appears to undergo a melting transition at a perpendicular component that is very close to the values published in the literature for similar crystals. At nearly parallel field we observe oscillations corresponding to single Josephson vortices as they move into and out of the sample. This demonstrates that even a small in-plane field does not cant the vortex lattice but rather penetrates the superconductor in the form of Josephson vortices.

A split-coil magnet was used to allow a variation of the angle between the plane of the sample and field with a resolution of 0.05°. Samples were mounted on a silicon-nitride cantilever with length, width, and thickness of 210, 50, and 0.51 μm, respectively. The cantilevers were made at the Stanford Nanofabrication Facility employing standard micromachining techniques. Figure 1 shows a schematic of the sample mounted on the cantilever, as well as the configuration of the cantilever, sample, and magnetic field direction.

The fundamental frequency of the bare cantilever was f_0 $\sim$10 kHz, yielding a spring constant $k\sim0.02$ N/m. The quality factor Q of the bare cantilever was measured to be 1.8×10^4 at room temperature and 8.0×10^4 at 4 K. Single crystals of BSCCO were grown by a directional solidification method[10] and their T_c was measured by superconducting

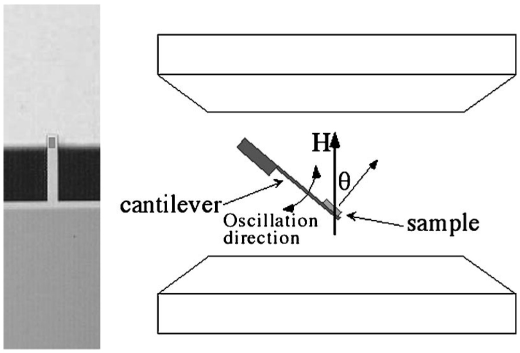

FIG. 1. Schematic of the experimental geometry. Theta (θ) is the angle between the field and the normal to the sample (and to the cantilever). At left is a top view of the silicon-nitride cantilever with the sample outlined on its surface near the tip.

quantum interference device (SQUID) magnetometry. A slightly underdoped crystal with T_c of about 87.5 K was used. The crystal's dimensions were $40\times20\times1$ μm^3 and the sample was glued with a thin layer of epoxy to the cantilever with the c axis perpendicular to the cantilever surface. Though placing the sample on the cantilever changed its natural frequency to $\sim$6500 Hz according to the additional mass (of sample and epoxy), less than 20% degradation in the Q of the system was observed due to the gluing process.

The cantilever displacement was determined interferometrically using a fiber interferometer. In such a device,[11] light from a diode laser travels down a fiber situated just above the surface of the cantilever. Light that bounces off the cleaved end of the fiber interferes with light that exits the fiber, reflects off the cantilever, and then reenters the fiber. The interferometric signal allows the determination of the distance between the fiber end and the cantilever with subangstrom resolution for small measurement bandwidths.

The experimental procedure consisted of the measurement of the resonant frequency of the cantilever-sample system as a function of temperature, magnetic field strength, and magnetic field angle. A self-oscillation drive system was designed to maintain the cantilever vibration at a fixed amplitude. In this system, the thermal noise vibration signal from the cantilever is amplified and shifted in phase, and then sent to a piezoactuator that drives the cantilever. Because of the high quality factor of these micromachined cantilevers, the thermal noise induces motion predominantly at the resonant frequency, and therefore, the self-oscillation drive constantly maintains the system at this resonant frequency. The frequency is measured concurrently with the amplitude of the drive signal necessary to sustain a constant oscillation amplitude. The amplitude of the drive signal is inversely proportional to the Q of the system and is hence a measure of the relative dissipation.

The gross behavior of the system of BSCCO crystal and cantilever in perpendicular (field aligned with the c axis and cantilever normal) and parallel (field aligned with the ab plane and long axis of the cantilever) field is depicted in Fig. 2. Here we plot the resonant frequency of the system and its measured dissipation as a function of magnetic field for both orientations. In a perpendicular field the dissipation is flat

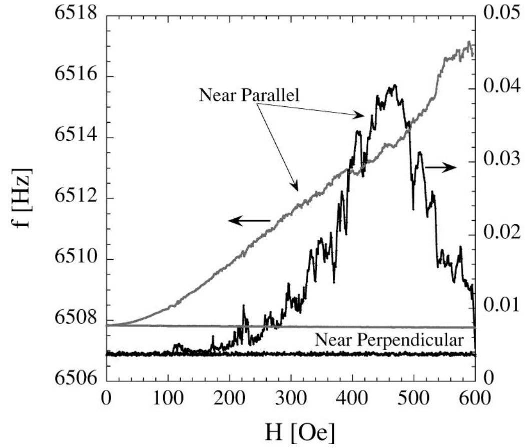

FIG. 2. Resonant frequency and dissipation vs magnetic field ($T=80$ K) for field orientations parallel and perpendicular to the cantilever's long direction and simultaneously the sample's ab plane.

and translates to a Q of the combined system of $\sim4.0\times10^4$ at $T\sim T_c$. The frequency of the system changes by less than 0.01% of the fundamental frequency at $H=0$ in this field range. The near-parallel behavior is very different, showing an increase in the system's frequency (i.e., restoring force) with increasing field; the dissipation peaks at $\sim$450 Oe in this particular example. The meaning of the specific location of the peak will be discussed later.

Figure 3 depicts a typical scan of frequency shift and relative dissipation of the cantilever and sample as a function of angle at $T=75$ K in a magnetic field of 160 Oe. Note that the figure is symmetric around 90° where the field is parallel to the sample's ab plane. The frequency shift measures the restoring force of the magnetomechanical system, while the

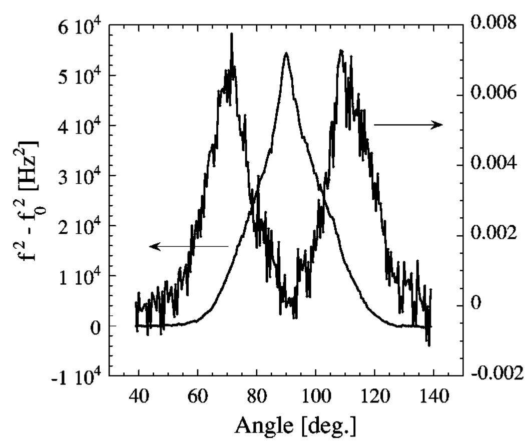

FIG. 3. Typical data from an angular scan ($T=75$ K, $H=160$ Oe). Plotted are resonant frequency and dissipation vs the angle between the crystal's c axis (as well as the cantilever surface normal) and the applied field. The resonant frequency peaks where the field is aligned with the sample's Cu-O planes, while the dissipation takes its greatest value where the normal component of the field induces a structural transition in the vortex lattice, somewhat off parallel. The curves are essentially symmetric around the parallel configuration.

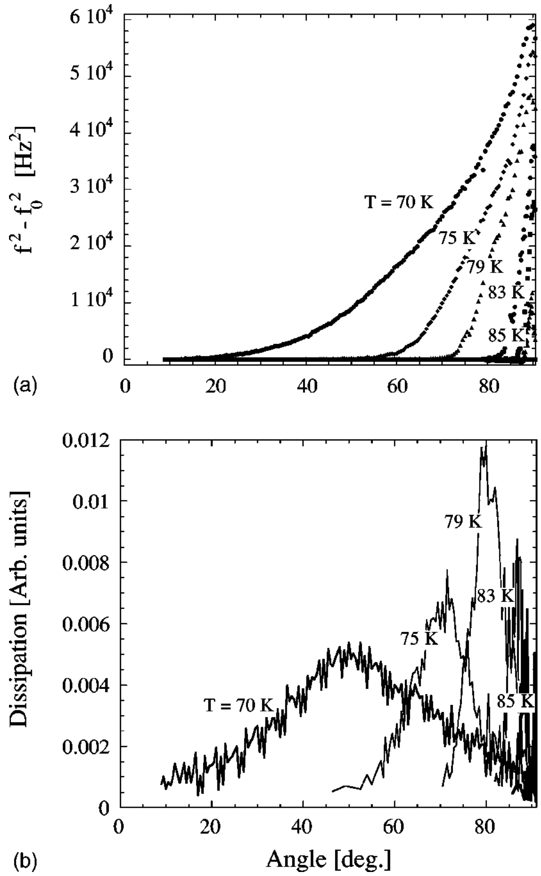

FIG. 4. Resonant frequency and dissipation as a function of angle and temperature ($H = 160$ Oe). (a) As T approaches T_c, the resonant frequency peak narrows, indicating a smaller restoring force for angles away from parallel. This is a reflection of the fact that the melting field is higher at lower temperature. (b) The position of the dissipation peak moves toward higher angles as T approaches T_c.

relative dissipation is indicative of the system's behavior as it is altered from being more dissipative (small angles) to more inductive (large angles). Such behavior is expected as dissipation can occur only in the Cu-O planes (through motion of pancake vortices). For small angles the field is almost perpendicular to the Cu-O planes and thus its normal component exceeds the melting field.[9] For angles closer to 90° the normal component of the field advances through the melting point and the dissipative motion of free vortices changes to a collective motion of the vortex lattice that provides an extra restoring force to the magnetomechanical system.

This general scenario is better described in Fig. 4. Figure 4(a) shows the angular dependence of the frequency shift and Fig. 4(b) the angular dependence of the relative dissipation for temperatures in the range 70–87 K, just 0.5 K below T_c. The nominal magnetic field is 160 Oe. The increase in frequency shift with increasing angle could simply indicate that for a given temperature, above a certain angle, there is an added restoring force due to the formation of a vortex lattice. However, we also note from Fig. 2 that the equivalent measurement in a perpendicular field does not produce a similar

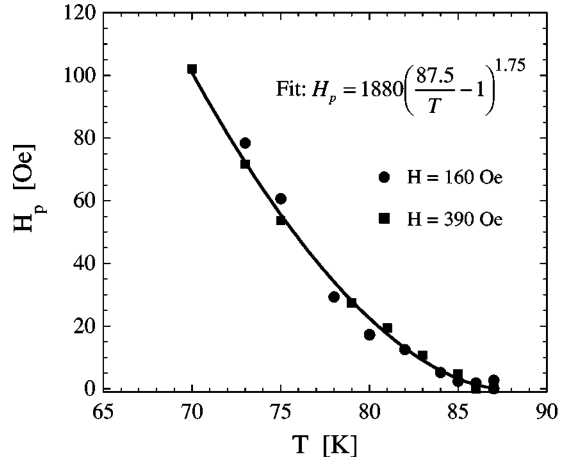

FIG. 5. Normal component of the magnetic field at the angular location of the dissipation peaks as a function of temperature. The line is a fit to a power law ($H_p \propto [T_c(0) - T_c(H)]^b$) with the best fit for an exponent of $b = 1.75$.

increase in resonant frequency. We are therefore led to conclude that there is an additional magnetomechanical coupling in the system that increases with the change of angle towards a parallel configuration. The most likely explanation is the coupling of Josephson vortices to the magnetic field, a subject that we will discuss further below.

Concentrating first on the position of the peak as a function of temperature [Fig. 4(b)] as an indication of the dissociation of the pancake vortex lattice, we show in Fig. 5 the respective perpendicular component of the magnetic field versus temperature for two different nominal magnetic fields. Fitting our data near the transition we find that $H_p \propto [T_c(0) - T_c(H)]^b$ with $b = 1.75 \pm 0.1$. Comparing our results to those of Zeldov *et al.*[9] who find an exponent closer to 1.5, we notice that our data exhibit more curvature as a function of temperature. We note that quadratic dependence is what one would expect based on a simple Lindeman criterion cal-

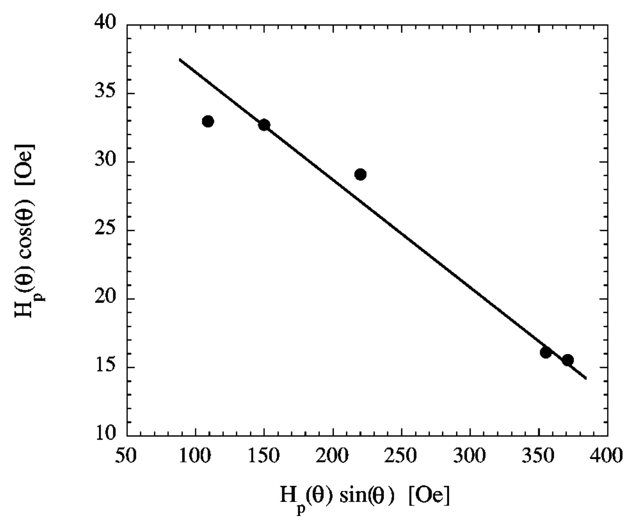

FIG. 6. Perpendicular component of field at dissipation peak location vs parallel component of same. The line is a linear fit, after the prediction of Koshelev, with a slope of -0.07 ± 0.01 (see text).

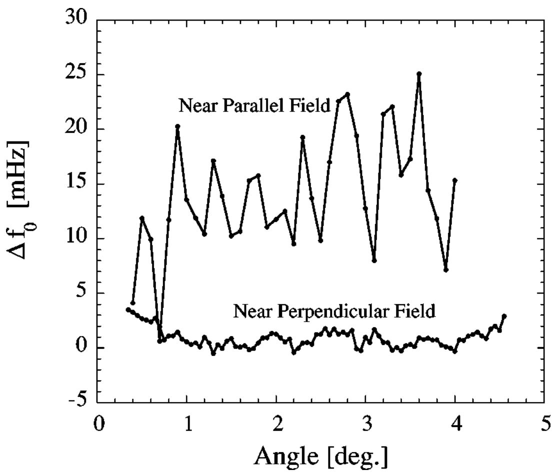

FIG. 7. Shift in resonant frequency as a function of angle (values relative) around a parallel configuration as compared to the frequency shift in a similar range around a perpendicular configuration. The scatter in the latter data is on the level of the noise of the measurement (a few mHz). These data suggest the observance of Josephson vortex motion.

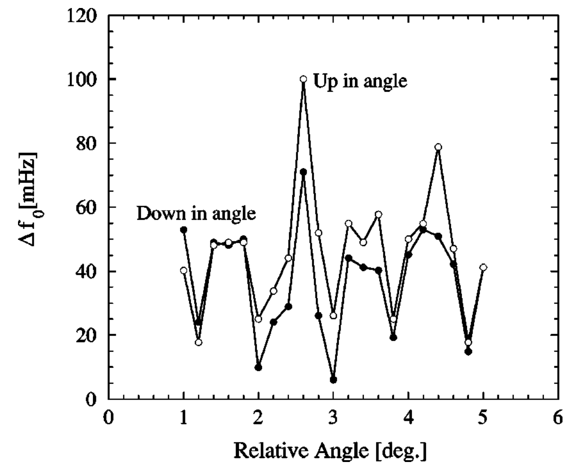

FIG. 8. Shift in resonant frequency vs angle around the parallel configuration, displaying data for a sweep up in angle as well as a sweep down. The jumps are somewhat reproducible with some hysteresis due to sample-specific vortex behavior. Analysis of the power spectrum of these data implies a periodicity corresponding to the entrance or exit of one Josephson vortex into or out of the sample.

culation as was first calculated by Houghton *et al.*[12] and that the actual exponent depends on the range of fields used in the experiment.[1] Our result is therefore in the range of melting transition exponents, $b = 1.3–2.0$, cited in previous work.[9,13,14]

One of the more interesting effects resulting from the Josephson lattice is a shift in the melting point. Assuming negligible entropic correction to the free energy of the Josephson lattice and that the dominant coupling between layers is magnetic, Koshelev[5] calculated the slope of the linear dependence of the melting fields in the perpendicular and parallel directions. Figure 6 shows typical data at $T=80$ K where the perpendicular component (i.e., along the c axis) of the field at the dissipation peak is plotted against the parallel component (i.e., along the *ab* plane).

The linear fit shown in Fig. 6 indicates a slope of -0.07 ± 0.01. This value is in agreement with measurements on BSCCO crystals performed at the same temperature ($T = 80$ K) by Ooi *et al.*[7] and is very close to the value estimated by Koshelev.[5] Note that for moderately anisotropic superconductors the perpendicular field depends quadratically on the in-plane field. Thus, the linear dependence observed here is a direct indication of crossing lattices, which should exist in highly anisotropic superconductors like BSCCO.

We finally discuss fine scans of the frequency shift near a parallel field. With the field magnitude fixed, the angle is varied around the parallel field. The data are shown in Fig. 7. Definite oscillations are observed near the parallel field and are reproducible with a period of $\sim 0.4°$ as derived from a power spectrum of the data. The reproducibility is shown in Fig. 8 where it can be seen that the peak positions do not change between a sweep up in angle (magnetic field) and a subsequent sweep down. In contrast, a similar experiment near perpendicular magnetic field shows a flat response (see Fig. 7). Knowing the area of the sample in the parallel direction and the applied magnetic field we find that the flux associated with one period is $\sim(160\ \mathrm{Oe})\times(0.4\pi/180)\times(20\ \mu\mathrm{m}^2)\approx 2.2\times 10^{-7}\ \mathrm{Oe\,cm}^2 \approx \Phi_0$, where Φ_0 is one flux quantum. This result clearly indicates that we are monitoring single Josephson vortices entering (or exiting) the sample as the angle is changed.

In conclusion, we have presented a detailed study of the low-field magnetic behavior of a nanogram-sized BSCCO single crystal while varying the direction of the sample in the applied field. Our data indicate a vortex structure consisting of two vortex lattices. A pancake vortex lattice that melts according to the perpendicular component of the magnetic field exists in the *ab* planes. A Josephson vortex lattice penetrates the material along the *ab* planes and melts at the same temperature as the pancake vortex lattice. At angles very close to parallel there exists only one row of Josephson vortices in the *ab* planes, and upon changing the angle of the magnetic field, single Josephson vortices are observed to enter or exit the sample depending on the direction of the sweep of the field.

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