Local Permeability Studies of Vortex States in $Bi_2Sr_2CaCu_2O_{8+y}$ under Tilted Fields

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Abstract

AC local permeability is measured for a strongly anisotropic superconductor $Bi_2Sr_2CaCu_2O_{8+y}$ under tilted fields. In addition to the peak in local permeability at the vortex-lattice melting transition, step-like change accompanied by hysteresis is observed under large and nearly constant in-plane field. This anomaly naturally extrapolates to the novel peak effect reported by Ooi *et al*. [1] at low temperatures under tilted fields. This observation indicates that the vortex solid phase in the crossing-lattices state changes into a new state with less shielding in the presence of dense Josephson vortices before melting into vortex liquid.

Key words: $Bi_2Sr_2CaCu_2O_{8+y}$; local permeability; crossing-lattices

1. Introduction

In an anisotropic superconductor $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO), vortices generated by tilted fields form two orthogonal lattices of pancake and Josephson vortices, called crossing lattices [2]. Owing to the attractive interactions between these two vortex lattices, characteristic vortex chain structure is realized as was first shown by Bitter decoration [3]. More complicated transitions between various forms of ground states are predicted [4]. Some of the transitions between ground states in the crossing-lattices state have been reported by anomalies in the irreversible magnetization [1] and direct observations by scanning Hall probe microscopy [5]. The response of vortices in a superconductor is well characterized by the local AC permeability (μ) measurements. At the vortex-lattice melting field, the real part of μ shows a sharp peak [6]. We apply local permeability measurements using a miniature-Hall probe to explore the phase diagram and the nature of ground states of vortex solid under tilted fields. In addition to the vortex-lattice melting transition, we find a clear step in the real part of μ at fields with almost constant in-plane component.

2. Experiments

Crystals used in the present experiments are grown by the floating-zone method and they are annealed to be optimally doped with $T_c = 89$ K. We use a miniature Hall probe with an active area of 25×25 μm^2 fabricated from GaAs/AlGaAs hetero structure. The crystal is mounted directly on the Hall probe and AC magnetic permeability μ ($= \mu' + i\mu''$) is measured by applying AC magnetic field parallel to the c-axis with a small coil mounted near the sample. The AC field amplitude and the frequency are 1 Oe and 7 Hz, respectively. Static magnetic field up to 20 kOe is applied by a superconducting magnet at an angle θ from the c-axis, and the field dependence of μ is measured. The angle of the sample is changed using sample rotator around the horizontal axis with a resolution better than 0.01°. Here we only concentrate on the behavior of the real part of the permeability, μ'.

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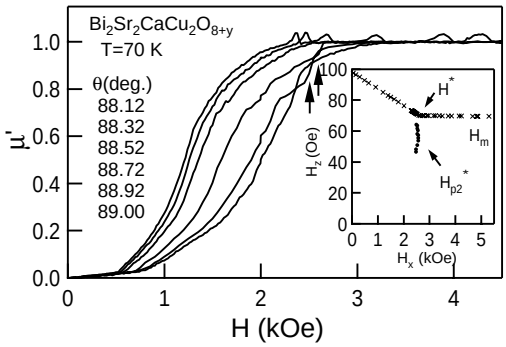

Fig. 1. μ'-H curves for various angles at T=70 K. Above $\theta = 88.7°$, μ' shows a step-like increase at H^*_{p2} (arrows). The inset shows the location of H_m and H^*_{p2} in H_x-H_z plane.

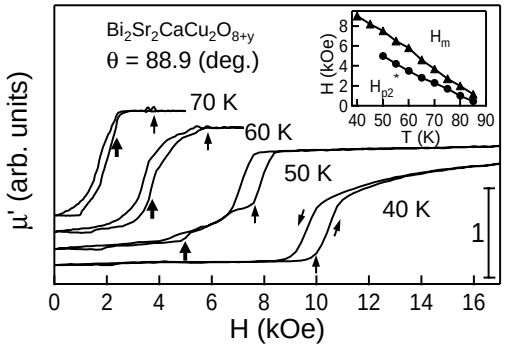

Fig. 2. $\mu' - H$ curves for various temperatures at θ= 88.9°. At higher temperatures, μ' shows step-like increase at H^*_{p2} (thick arrows) and peak at H_m (thin arrows). The inset shows temperature dependence of H^*_{p2} and H_m .

3. Results and Discussion

Figure 1 shows angular dependence of the real part of AC local permeability, μ', as functions of magnetic field at $T = 70$ K. At lower angles, μ' increases above H_{c1}, approaches to unity at the irreversibility field, and then shows a peak at the vortex-lattice melting field (H_m). At angles close to 88.7°, μ' starts to show an additional step-like feature at H^*_{p2} below H_m. As the angle is further increased, the step-like feature stays at a nearly constant field while H_m increases steadily. The inset for Fig. 1 shows the location of the anomalies in H_x-H_z plane. The c-axis component of H_m shows linear H_x dependence followed by another linear dependence above the break point H^*. The step-like feature at H^*_{p2} forms a nearly vertical line. Similar phase diagrams are also reported in BSCCO under tilted fields by Ooi *et al*. [1] and by Konczykowsky *et al*. [7] from local magnetization and local permeability measurements, respectively. Within the resolution of our measurements, the lower angle part of H^*_p in [1] at low temperatures is not observed. Our recent Hall probe measurements suggests that the lower and the higher angle part of H^*_p have different origins [8].

Figure 2 shows temperature dependence μ'-H curves only in the positive field region for cycling the magnetic field. Below 55 K, the peak in μ' turns into another step-like feature. Namely, there appear two step-like features as a function of H. At lower temperatures the step at H^*_{p2} becomes weaker. At 40 K, the only visible structure in the μ'-H curve is the steep increase around $H = 10$ kOe. Inset shows the temperature dependence of the anomalies in μ'-H curves. Obviously, the feature at H^*_{p2} is no longer visible below 50 K in the present measurement, and the steep increase of μ' at 40 K is a trace of the vortex-lattice melting transition. Considering the similarity between the H-T phase diagram determined by the anomalies in the M-H curves under tilted field for overdoped BSCCO [1], the transition into the new vortex solid phase above H^*_{p2} seems to be universal for anisotropic superconductors. The hysteresis seen in μ'-H curves in Fig. 2 can be explained by a small irreversible component of c-axis magnetization. Actually, when the width of the hysteresis is converted to the c-axis component of magnetization, it only amounts to 15 G at 40 K.

Step-like increase in μ' at H^*_{p2} indicates that the shielding capability is suppressed above this field. This change is consistent with the sudden suppression of the irreversible magnetization above H^*_{p2} at lower temperatures as observed in DC magnetization measurements under tilted fields [8].

In summary, we have observed a step-like increase in AC permeability under tilted fields in BSCCO for broad temperature range. The anomaly marks a transition in the vortex solid phase into a new state with suppressed shielding.

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