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Physica C 282–287 (1997) 2045–2046

PHYSICA C

Angular dependence of the first-order vortex-lattice phase transition in $Bi_2Sr_2CaCu_2O_8$

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The paramagnetic peak in the local ac susceptibility χ' is used to identify the first-order vortex-lattice phase transition in $Bi_2Sr_2CaCu_2O_8$ at various tilt angles θ of the dc magnetic field with respect to the c-axis. The transition field H_m follows roughly the 2D scaling function $H_{dc}\cos(\theta)$. The amplitude of the paramagnetic peak, and thus the jump in magnetization ΔB, do not depend on the tilt angle which demonstrates that the entropy jump at the transition, ΔS, is insensitive to the presence of the in-plane field.

1. INTRODUCTION

Recently local induction measurements on a BSCCO single crystal have revealed a jump in local magnetization indicative of a first order phase transition in the vortex matter [1]. In the following it has been shown, that a paramagnetic peak appears in the in-phase part of the ac- susceptibility as a result of this jump [2]. Using the Clausius-Clapeyron relations one can deduce from these measurements the entropy jump at the transition $\Delta S = -\frac{\Delta B}{4\pi}\frac{dH_m}{dT}$. This jump exhibits an anomalous temperature dependence and reaches excessively high values close to T_c (estimated to be of the order of 6 k_B per pancake vortex [2]). Due to the lack of theoretical models that could account for this and inconsistencies in torque measurements in the presence of an in-plane field, some authors suggest an artifactual origin of the observed jump in magnetization [3]. In order to test this suggestion and to get more insight into the phenomenology of the transition we have carried out a detailed study of the angular dependence of the phase transition making use of the paramagnetic peak in the in-phase ac-susceptibility. We traced the position and amplitude of this peak as a function of the tilt of the magnetic field with respect to the c-axis at various temperatures.

2. EXPERIMENTAL

A miniature InSb Hall sensor (active volume: $80\times80\times80$ μm^3) was placed on top of a BSCCO crystal of approximate dimensions $500\times500\times40$ μm^3. The sample stems from the same crystal as the piece investigated in a previous work [1]. The crystal with the Hall sensor were placed in the centre of an excitation coil providing a low frequency (7.75 Hz) ac magnetic field of 1 Oe parallel to the c-axis of the crystal. The entire set-up was placed in an electromagnet. By rotating this magnet the orientation of the external dc magnetic field H_{dc} could be varied continuously from the ab-plane to the c-axis. The inset of Fig.1 illustrates the orientations of the two fields with respect to the sample. At selected temperatures the in- and out-of-phase components of the ac magnetic induction B'_{ac} and B''_{ac} were measured as a function of the dc field amplitude for various orientations. The high sensitivity (50 mΩ/G) and low resistance of the Hall probe allowed the resolution of the ac detection to be of the order of 0.1 mG.

3. RESULTS AND DISCUSSION

Typical results of the magnetic field scans at various angles are presented in Fig.1. On decreasing H_{dc} screening sets in gradually and the ac response B'_{ac} is reduced from its full amplitude in the transparent state at high dc fields. A very well defined paramagnetic peak in B'_{ac} appears at some dc field labelled $H_m(\theta)$, which increases with tilt angle θ from the c-axis. It has been demonstrated previously that the appearance of such a paramagnetic peak indicates the existance

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PII S0921-4534(97)01114-3

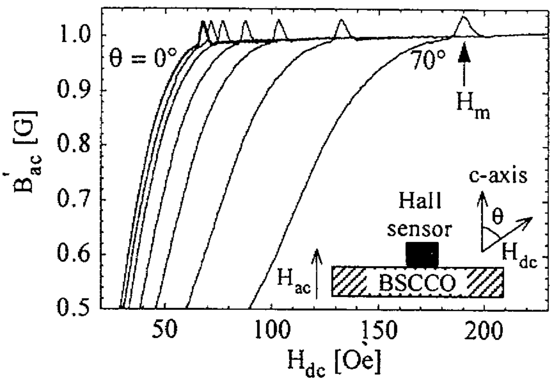

Figure 1. B'_{ac} as a function of H_{dc} for different angles between c-axis and dc-field direction, $\theta =$ 0° to 70° in 10° intervals. $T = 80$ K, $H_{ac}= 1$ Oe, f = 7.75 Hz. Inset: schematic description of the setup and the orientations of the applied fields.

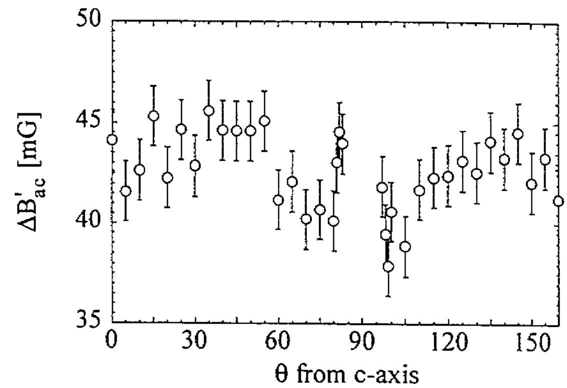

Figure 2. Peak height as a function of the applied field angle θ with respect to the c-axis at $T =$ 80 K.

of a first-order phase transition and reflects the jump in the equilibrium magnetization [2].

Position and width of the peak scale with $\cos(\theta)$ up to angles of $\theta \approx 80°$ [4]. Thus the transition is dominated by the c-axis component of H_{dc} and remains unchanged even in the presence of an important in-plane field in clear contradiction to the observation made in reference [3].

Figure 2 shows the measured peak height ΔB_{ac} as a function of angle for $T = 80$ K. Measurements at 70 K and 88 K give similar results. Within our experimental resolution the peak height (and thus the entropy jump at the transition) has a constant value up to tilt angles of 83° from the c-axis. Up to 89° the peak still remains observable, but the determination of its height becomes much more imprecise. In Fig. 2 data beyond 83° are omitted. It is remarkable however, that even at such a high tilt angle the peak is still observed, because this angle corresponds to the presence of an in-plane field of about 3 kOe for the measurement at 80 K.

In conclusion, we have demonstrated that the first order transition in the vortex lattice persists in the presence of large in-plane fields. In a wide range of angles, only the c-axis component determines the position of the transition. The independence of the amplitude of the paramagnetic peak on the direction of the dc magnetic field implies that the entropy jump at the transition is insensitive to the presence of an in-plane field and is determined only by the density of the pancake vortices.

We thank V. B. Geshkenbein for helpful discussions and are grateful to H. Motohira for providing the BSCCO crystals. This work was supported by the Israeli Ministry of Science and the Arts and the French Ministry of Research and Technology (AFIRST).

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