

## Melting of regular and decoupled vortex lattices in BSCCO crystals

M. Konczykowski<sup>a</sup>, C. J. van der Beek<sup>a</sup>, M.V. Indenbom<sup>a,b</sup>, E. Zeldov<sup>c</sup>

<sup>a</sup>Laboratoire des Solides Irradiés, Ecole Polytechnique, 91128 Palaiseau, France

<sup>b</sup>Institute of Solid State Physics, 142432 Chernogolovka, Moscow District, Russia

<sup>c</sup>Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot, Israel

The angular dependence of the first-order phase transition (FOT) in the vortex lattice in  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  crystals was investigated by a low frequency AC shielding technique (with the AC field  $\parallel c$ ), in which the static-field component parallel to  $c$ - ( $H_{\perp}$ ) was varied with the in-plane field  $H_{\parallel}$  held constant. The linear decrease of the FOT field  $H_{\perp}^{\text{FOT}}$  with increasing  $H_{\parallel}$  ends at a temperature-dependent critical value of  $H_{\parallel}$ . A new transition, marked by the abrupt drop of the  $ab$ -plane shielding current, appears at this point. We draw a new phase diagram with  $H_{\parallel}$  and  $H_{\perp}$  field components as coordinates; this features at least two distinct regions in the vortex solid phase, that are determined by the different interplay between the pancake vortex- and Josephson vortex lattice.

The use of the AC shielding technique for the identification of the first order transition (FOT) of the vortex lattice [1] has allowed for the exploration of the phase diagram of  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$  (BSCCO) crystals in oblique fields. Early experiments have demonstrated that for large in-plane fields  $H_{\parallel}$ , the FOT occurs at a slightly lower value of the perpendicular ( $\parallel c$ ) field  $H_{\perp}$  than predicted for either a purely 2D pancake vortex lattice, or for a highly anisotropic 3D vortex system[2]. The linear dependence of the  $c$ -axis component of the FOT field  $H_{\perp}^{\text{FOT}}$  on  $H_{\parallel}$  suggests that this is due to the partial suppression of  $c$ -axis phase coherence by  $H_{\parallel}$ , and that an inclined field in fact penetrates as a combined lattice of pancakes and Josephson vortices [3]. Here, we present new measurements of the FOT in elevated parallel fields; the fact that one is dealing with a combined lattice inspired us to use the more straightforward experimental configuration in which  $H_{\perp}$  and  $H_{\parallel}$ , and therefore the density of pancake vortices and Josephson vortices, are varied independently by simultaneous rotation of the magnet and adjustment of the total field magnitude.

We have selected two BSCCO samples, cut from larger optimally and oxygen overdoped single crystals. After the samples' homogeneity was checked using magneto-optical imaging of the flux penetration, a miniature ( $80 \times 80 \times 80 \mu\text{m}^3$  active

volume) InSb Hall sensor was placed in the center of the sample top surface. The crystal together with the Hall sensor were placed in the centre of an excitation coil generating the low-frequency AC magnetic field, mounted on the cold-finger of a pumped  $\text{LN}_2$  dewar, and placed between the poles of a rotatable electromagnet. In this set-up the AC excitation field, of amplitude  $h_{ac}$  and frequency  $f$ , was always oriented along the crystal

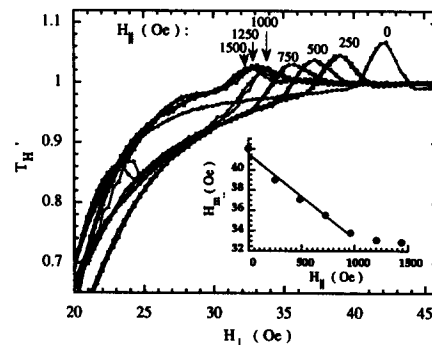


Figure 1. The  $c$ -axis field dependence of the in-phase transmittivity ( $h_{ac} = 1 \text{ Oe}$ ,  $f = 7.75 \text{ Hz}$ ) of the optimally doped sample at  $T = 84 \text{ K}$  and various  $ab$ -plane fields. The paramagnetic peak identifies the jump in the magnetization curve associated with the FOT.

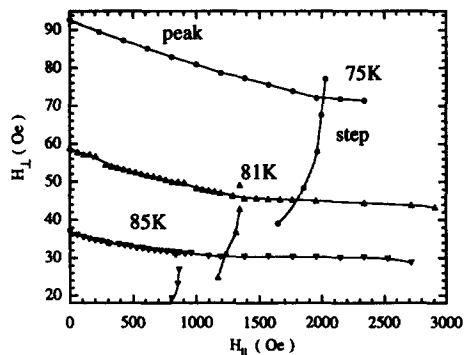


Figure 2. Two field component phase diagram of the vortex lattice of BSCCO crystals, inferred from transmittivity measurements at various temperatures.

$c$ -axis while the orientation and magnitude of the DC magnetic field were independently controlled by a computer system.

Two types of isothermal field-sweeps have been realized. First,  $H_{\perp}$  was varied with  $H_{\parallel}$  held fixed; second,  $H_{\parallel}$  was varied at fixed  $H_{\perp}$ . The angular resolution of  $10^{-3}$  degree allowed scans of  $H_{\perp}$  in the range of 0 - 100 Oe on a  $H_{\parallel}$ -background of several kOe. The fundamental and third harmonic component of the AC magnetic induction were measured by two lock-in amplifiers. Typical variations of the normalized in-phase transmittivity  $T'_H$  are presented in Fig. 1.  $T'_H$  is defined as  $(V' - V'_0)/(V'_{\infty} - V'_0)$ , where  $V'$ ,  $V'_{\infty}$ ,  $V'_0$  denote the RMS in-phase AC Hall voltage, its value when shielding can be neglected, and its value at full shielding. We identify  $H_{\perp}^{FOT}$  by the paramagnetic peak in  $T'_H$ , where this exceeds 1. This marks the step in the DC-magnetisation curve [1,4]. The application of a moderate in-plane field  $\sim 50$  G yields a smaller  $T'_H$  for  $H_{\perp} < H_{\perp}^{FOT}$ , i.e. an enhancement of the shielding current. The linear decrease of  $H_{\perp}^{FOT}$  as function of  $H_{\parallel}$  is consistent with earlier results [2].

The novel result is the end of this decrease at high in-plane field. In the optimally doped sample, we observe the paramagnetic peak in  $T'_H$  at the same  $H_{\perp}$  for all values of  $H_{\parallel} > 1$  kOe. A new feature appears in the  $T'_H$  curves recorded with  $H_{\parallel}$  slightly below 1 kOe: there is an additional

$T'_H$ -minimum in the region of partial shielding ( $0 < T'_H < 1$ ). The position of this minimum is independent of  $h_{ac}$  and  $f$ , which indicates that a transformation of the vortex lattice takes place at this point. Other field scans in which  $H_{\parallel}$  field was swept with  $H_{\perp}$  held constant showed a step-like drop of the shielding current at this new transition. Remarkably, the drop in the shielding current at this transition corresponds exactly to its enhancement observed after the initial application of a moderate in-plane field  $\sim 50$  G. Using alternative  $H_{\perp}$  and  $H_{\parallel}$  scans we determine a two-field component phase diagram of the vortex lattice in oblique fields shown in Fig. 2.

Three hypothetical transition lines can be drawn on the diagram presented in Fig. 2. In a highly anisotropic superconductor such as BSCCO, an oblique vortex lattice is expected to decompose into two superposed lattices of pancake vortices in the  $\text{CuO}_2$  double layers and Josephson vortices between layers. The enhancement of the shielding current by a moderate  $ab$ -plane field may be considered the result of this decomposition. The melting line of the vortex lattice along the  $c$ -axis is expected to decrease with increasing  $H_{\parallel}$  because of the introduction of Josephson vortices between the layers. This decrease saturates at high  $H_{\parallel}$  when the cores of the Josephson vortices overlap, or when the lattice of Josephson vortices melts. Using a realistic value of the anisotropy factor  $\gamma$ , the line corresponding to Josephson core overlap should be located at a much higher value of  $H_{\parallel}$ , of the order of 1 T [3]. The invariance of the  $H_{\perp}^{FOT}$  at high  $H_{\parallel}$  indicates a uniform field distribution in the  $ab$ -direction, which is equivalent to the suppression of Josephson coupling. Thus the quasi-vertical lines in Fig. 2 mark the crossover from the Josephson coupled regime to a regime where the planes are decoupled by the in-plane field.

## REFERENCES

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