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2016 J. Phys.: Conf. Ser. 667 012007

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# Tilted vortex lattice in irradiate $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ single crystals

J Mirkovic<sup>1,2</sup>, I Kakeya<sup>3</sup>, S Savel'ev<sup>4</sup>, T Kashiwagi<sup>2</sup>, B Markovic<sup>5</sup>, K Kadowaki<sup>2</sup>

<sup>1</sup> Faculty of Science, University of Montenegro, G. Washington str. bb, Podgorica, and Centre for Ecotoxicological Research of Montenegro, 81000 Podgorica, Montenegro

<sup>2</sup> Division of Materials Science, Faculty of Pure and Applied Sciences, University of Tsukuba, Tennodai, Tsukuba, Ibaraki 305-8573, Japan

<sup>3</sup> Department of Electronic Science and Engineering, Kyoto University, Nishikyo-ku, Kyoto 615-8510, Japan

<sup>4</sup> Department of Physics, Loughborough University, Loughborough, LE11 3TU, UK

<sup>5</sup> Faculty of Electrical Engineering, University of Montenegro, G. Washington str. bb, and Centre for Ecotoxicological Research of Montenegro, 81000 Podgorica, Montenegro

E-mail: jovan.mirkovic@prona.org

**Abstract.** In order to enlighten the structure of vortex matter in irradiated layered  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  single crystals, the interaction of Josephson vortices and pancake vortices in was investigated by means of the local ac-magnetic permeability measurements by using the miniature local coils, while vortex matter in pristine crystals was studied by in-plane resistivity measurements. The transition anomaly, separating the strong pinning phase and the weak pinning vortex phase was found by both techniques deep in the vortex solid phase solid near ab-plane, indicating crossover from the vortex chains + lattice phase to tilted vortex chains phase. While the columnar defects affect strongly the first-order vortex-lattice melting transition, the magnetic permeability anomaly, associated with the crossover from vortex chains + lattice phase to tilted lattice, is surprisingly still clear, deep in the vortex solid phase. However, the stronger columnar defects eventually affect the crossover anomaly that it disappears too.

## 1. Introduction

Vortex matter in layered superconductors, such as  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  single crystals, differs from vortex lattices in moderately anisotropic superconductors, such as  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ . In tilted magnetic fields,  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  samples have two types of vortices: the c-axis component  $H_c$  of the magnetic field produces (2D) pancake vortices (PVs) [1], while the in-plane field component  $H_{ab}$  generates Josephson vortices (JV) between the  $\text{CuO}_2$  planes [2,3]. Interacting crossing PV and JV lattices have been studied theoretically [3]-[7] and recently were observed by using Lorentz microscopy [8,9], scanning Hall probe microscopy [10], and magneto-optical imaging [11]. There are two reasons of this surge of the interest to vortex matter and in particular crossing vortex lattice in layered superconductors. First, crossing vortex lattices exhibit non-trivial and fascinating dynamical behavior (see, e.g., [12,13]) which allows us to manipulate [14]-[18] one vortex lattice via another one (or in more general interacting nanoparticles), as well as non-standard thermodynamic properties [19-25]. For instance, in contrast to the Ginzburg-Landau (GL) approach, the first-order melting transition line (the boundary separating the vortex-solid and vortex-liquid phases) exhibits a 'step-wise' shape [19] (i.e., approximately linear decay interrupted by two flat-plateau) if plotted in the  $H_c$ - $H_{ab}$  plane.

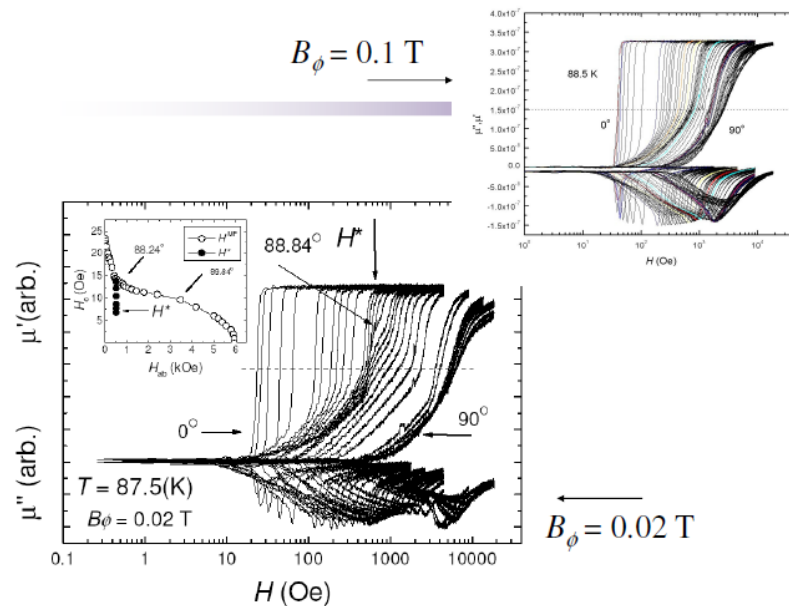


Namely, the  $c$ -axis component  $H_{\text{trans}}$  of magnetic field at the phase transition decays linearly when increasing  $H_{\text{ab}}$ , followed by a plateau. A similar stepwise shape of the phase boundary was observed [26] at a much lower temperature, where disorder plays an essential role and the transition is smooth, in contrast to first-order. Thus, this suggests that the shape of the transition line is controlled by general thermodynamic properties, rather than the precise statistical features of the vortex-solid-phase, including vortex-glass, Bragg-glass, or Bose-glass. The second reason of huge interest to vortex phase diagram in Bi-compounds is related to possible application of this material for superconducting THz electronics [27-38].

In this article we report recent measurements of the vortex-solid phase diagram in  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  pristine and irradiate samples and observation of the phase boundary deep in the vortex solid phase which can be attributed to a vortex structure transition. This transition smears out for strongly irradiated samples. We discuss this transition based on the vortex phase diagram having both tilted and crossing vortex lattice structures.

## 2. Experiment

The two  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  as-grown single crystals with  $T_c = 89$  and  $88.9$  K were used. These samples had defects along  $c$ -axis introduced by heavy-ion irradiation ( ${}_{127}\text{I}_{28+}$ , 650 Mev), with doses of  $B_\phi = 0.1$  and  $0.02$  T, respectively. The vortex phases were probed via local ac mutual-inductance measurements by using a set of two miniature coils. The size of the coils was  $0.35$  mm, which was sufficiently smaller than the size of the samples ( $\sim 3\text{mm} \times 3\text{mm}$ ) in order to diminish the surface barrier.

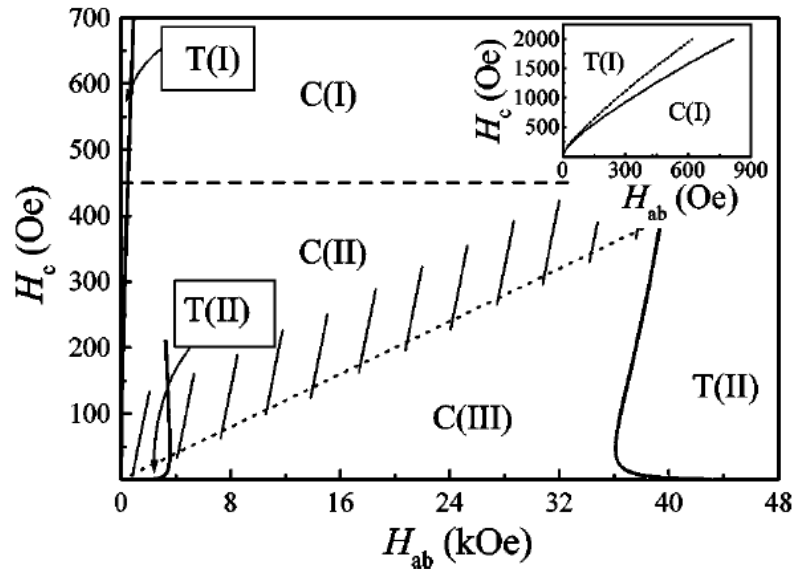


**Figure 1.** The magnetic field dependence of the real and imaginary parts of the ac-local magnetic permeability  $\mu$  for irradiated  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ , with two doses  $B_\phi = 0.1$  T (upper) and  $B_\phi = 0.02$  T (lower) with corresponding phase diagram (left).

The dc magnetic field, generated by a 70 kOe split coil magnet, was rotated with a fine angular resolution of  $0.01^\circ$ . A representative set of data (ac-local magnetic permeability versus dc magnetic field for different angles) is shown in Fig. 1. In order to construct the phase boundary, we used the voltage level of  $15\mu\text{V}$  (approximately middle point between zero and the saturation value of the real part of the permeability,  $\mu$ ).

### 3. Discussion

Comparison of the free energies of crossing and tilted vortex lattices result in a complicated picture of phase transitions between these vortex structures. The proposed phase diagram [4] is shown in Fig. 2.



**Figure 2.** The proposed phase diagram of the vortex-solid phase in the oblique magnetic fields [4].

The tilted vortex structure TI of inclined PV stacks can be replaced by the crossing lattice quite close to the  $c$  axis (see phase diagram obtained for  $\gamma = 500$ , inset in Fig. 2). The crossing lattice, which exists in a wide angular range, can have different substructures. At high enough out-of-plane fields, the “shifted” PV sublattice is realized in the crossing-lattices structure where the PVs are shifted from their equilibrium positions by currents generated by JVs.

In this substructure, the JV currents shift the PV’s mostly along the  $x$  axis. The “shifted” phase can transform into the “trapped” PV lattice CII when the energy gain related to the “crossing-lattice pinning” exceeds the energy needed for the additional shear deformation (the dashed line in Fig. 2 separating CI and CII). Around this line, the lattice CII can be changed by the tilted lattice TII with JV strings linked by PV kinks Fig. 2 bottom panel or by the crossing-lattice structure CIII at which all PV stacks are placed on a few JV’s. As one can see, the vortex phase diagram in layered superconductors is very complicated even with no disorder or pinning. Disorder can affect this by both shifting phase boundaries from their no-disorder position and smear or even destroy phase boundaries. The experiments discussed here seem to be related to phase boundary between TII and CII (or CIII) phase boundary. This boundary is defined by the condition of the balance between the free energy  $F_t$  of the tilted lattice and the free energy of the crossing lattice  $F_c$ :  $F_t(H_c, H_{ab}) = F_c(H_c, H_{ab})$ . In the presence of pinning, we have to include the term, describing the interaction of vortices with disorder, which by itself is very non-trivial procedure. In the naive approach, we could just add a term  $F_p(H_c, H_{ab}, H_T)$ , where  $H_T$  describes the dose of irradiation. One would expect the spreading  $\langle [H_{ab}^{\text{tran}}(H_c)]^2 \rangle - \langle H_{ab}^{\text{tran}}(H_c) \rangle^2$  of the phase line  $H_{ab}^{\text{tran}}(H_c)$  to be proportional to  $H_T^2$ , which is consistent with our experimental results.

In conclusion, we study the deformation of vortex matter phase diagram of irradiated  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  samples. The result is consistent with proposed earlier phase diagram for layered superconductor. However, a detailed description of disordered layered superconductors might require more detailed theoretical studies.

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