Step-wise Behavior of Vortex-Lattice Melting Transition in Tilted Magnetic Fields in Single Crystals Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

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The vortex lattice melting transition in single crystals Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ was studied by the in-plane resistivity measurements in magnetic fields tilted away from the c-axis to the ab-plane. In order to avoid the surface barrier effect which hinders the melting transition in the conventional transport measurements, we used the Corbino geometry of electric contacts. For the first time, the complete $H^c - H^{ab}$ phase diagram of the melting-transition in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ is obtained. The c-axis melting field component $H^c_{\text{melt}}$ exhibits the novel, step-wise dependence on the in-plane magnetic fields $H^{ab}$ which is discussed on the basis of the crossing vortex lattice structure. The sharp change of resistance behavior observed near the ab-plane suggests transformation from first-order to second-order phase transition.

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After discovery of high temperature superconductors, the phase diagram of the vortex state has been reconsidered because the novel vortex phases and phase transitions have been recognized [1]. Among them, the most intriguing phenomena is the first-order vortex-lattice melting transition (hereafter VLMT) [2, 3]. However, despite a lot of experimental and theoretical efforts, the nature of this phenomenon is not completely understood yet. In particular, it is not clear what happens with melting transition in highly anisotropic systems such as Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ if magnetic field is tilted away from the c-axis, especially close to the ab-plane.

In contrast to melting transition in YBa$_2$Cu$_3$O$_{7-\delta}$ [1] described well by the anisotropic 3D Ginzburg-Landau (GL) theory [4], it was noticed [5] that VLMT in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ obeys neither 3DGL nor 2D GL scaling. Later, Oii et al. [6] found that the c-axis melting field component $H^c_{\text{melt}}$ depends linearly on the in-plane magnetic field $H^{ab}$ in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. The authors explained the observed behavior through suppression of the Josephson coupling by the in-plane magnetic fields. They concluded that the anisotropy increases with $H^{ab}$ and should become infinite in a certain magnetic field at which the decoupling of the vortex lattice occurs. On the other hand, Koshelev [7] interpreted the linear dependence of $H^c_{\text{melt}}$ on $H^{ab}$ as an indication of the crossing lattice of Josephson vortices (JVs) and pancake vortex stacks (PVSs). According to this model, the linear dependence $H^c_{\text{melt}}(H^{ab})$ breaks down and transforms into plateau as soon as the JV cores overlap. Such plateau-like behavior was observed recently [8, 9], but there is still a question about the underlying mechanisms governing the melting transition in the tilted magnetic fields. In this regard, it is challenging to investigate what happens to the melting transition in much higher in-plane magnetic fields.

Here, we have investigated the melting transition using the in-plane resistivity measurements in the oblique magnetic fields in the whole angular range and found the dramatic new features, beyond pre-existing experimental data and theoretical models. The $H^c - H^{ab}$ phase diagram of melting transition exhibits the peculiar step-wise behavior. Besides, the transformation from the first-order to the second-order phase transition near ab-plane is indicated.

It is worth to note that the novel experimental findings were obtained essentially by using the unconventional Corbino geometry of electric contacts in the resistivity measurements. As it is known well, the transport measurements in the conventional four probe strip geometry in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ [2, 3] do not probe the true bulk properties of superconductor because surface barriers short-cut the current path and, as a consequence, the currents flow only near the sample edges. Therefore, the features of VLMT are also strongly hindered in resistivity measurements in the platelet samples. In order to avoid the smearing effect of VLMT and the nonlinear behavior in the vortex liquid phase due to surface barriers [10] we have used the Corbino electric contact geometry at which currents flow radially, far from the edges of sample (see inset of Fig. 1). Such experimental set-up considerably improved quality of resistivity data compared with conventional technique.

The in-plane resistivity measurements were performed for two as-grown single crystals [11] Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ with transition temperature $T_c = 90.3$ K and $T_c = 90.0$ K for samples #S1 and #S2, respectively. The diameters of the Corbino discs were $D = 1.9$ mm for #S1 and 2.7 mm for #S2, while the thickness was $t \approx 20$ $\mu$m for both samples. The resistance was measured by two pairs of electric contacts using the ac lock-in method at a low frequency of 37 Hz. They agree with each other in a geometrical configuration error of about 5%. The measurements of resistance were carried out as a function of the magnetic field $H$ at its different orientation $\theta$ with respect to the c-axis at various temperatures. The magnetic field was rotated by using 70 kOe split coil with fine goniometer with angular resolution of 0.001°.
The magnetic field dependence of the resistance at different orientations, which was measured at a particular temperature of 85.2 K, is shown in Fig. 1. The steep resistance drop attributed to VLMT [16,17] is clearly detected even in oblique magnetic fields and, surprisingly, changes only weakly up to $\theta = 89.86^\circ$. We should emphasize that the step height of the resistance anomaly practically remains the same and sharply separates the vortex solid and vortex liquid phases. As far as we know, the VLMT has never been found so close to the $ab$-plane. However, as the angle $\theta$ exceeds the critical value, only $0.14^\circ$ away from the $ab$-plane, the resistance level of the kink suddenly begins to decrease, while the sharpness of the anomaly gets even stronger. Then, the kink feature finally vanishes in the instrumental noise, and qualitatively new, smooth dependence $R(H)$ sets in. Instead of the quadratic field dependence of the resistance, found in the vortex liquid phase, $R(H)$ follows essentially the non-power law in the narrow angle region near the $ab$-plane. In addition, it is remarkable that the Ohmic response of the resistance observed in the vortex liquid state at angles $\theta < 89.96^\circ$ is replaced by the non-Ohmic behavior (see inset of Fig. 1). This peculiar resistance behavior may indicate the novel vortex phase in magnetic fields parallel to the $ab$-plane and the change of character of phase transition from first-order to second-order. Such experimental finding could be related to the scenario proposed earlier [18], which suggests transformation from the first-order vortex lattice melting transition into the second-order vortex-lattice — vortex-smectic phase transition in magnetic fields near the $ab$-plane.

Using the resistance data obtained at two temperatures of 85.2 K and 65 K for the sample #S1, the VLMT phase diagram is constructed in the $H^c$-$H^{ab}$ plane (Fig. 2). The melting transition was defined by the resistance criterion $R = 10^{-6}$ $\Omega$ in the whole angular range. The in-plane field dependence of the $c$-axis melting field component $H^{c\_melt}$ exhibits a very intriguing step-wise behavior (see inset in Fig. 2(b)). $H^c$ decreases linearly with the in-plane magnetic field $H^{ab}$. Then, the linear dependence is abruptly terminated at field $H^{ab(1)}$ and transforms into plateau which continues to the field $H^{ab(2)}$ where, surprisingly, the $c$-axis component of the
melting field $H_{\text{melt}}$ starts to decrease again. This finding is beyond the pre-existing experimental data and theoretical models. Finally, in the in-plane magnetic field above $H_{\text{melt}}^{ab(3)}$, the transition field $H_{\text{melt}}^{c}$ exhibits the second weak in-plane field dependence without the resistance kink anomaly (this region is indicated by filled symbols in Fig. 2). The almost identical step-wise behavior of the melting transition is found also in the sample #S2 as shown in the inset of Fig. 2b at somewhat lower temperature of 62 K.

The observed in-plane field dependence of the melting transition is in the strong contrast with the 2D scaling ruled only by the out-of-plane magnetic field component. The inset in Fig. 2b demonstrates also the essential discrepancy between our data and the fitting curve based on the 3D scaling

$$H_{\text{melt}}^{c}(\theta) = H_{\text{melt}}^{c}(0)/(\cos^2 \theta - \gamma^{-2} \sin^2 \theta)^{1/2},$$

where $H_{\text{melt}}^{c}(0)$ is the melting field for $\theta = 0^\circ$ and $\gamma = 300$ is chosen as the anisotropy parameter. Furthermore, the second decrease of the field dependence $H_{\text{melt}}^{c}(H_{\text{melt}}^{ab})$ after plateau can not be explained in the frame of the phenomenological concept of “decoupled” vortex state proposed by Ooi et al. since the latter would not be any in-plane field dependence of the melting transition above the decoupling field.

The first theoretical explanation of the unusual linear dependence $H_{\text{melt}}^{c}(H_{\text{melt}}^{ab})$ was given by Koshelev who analyzed the crossing vortex lattice with interaction between pancake vortices (PVS) and JVs. Using the general thermodynamical equality of the free energies of vortex solid and vortex liquid phases at the melting transition, Koshelev obtained the linear dependence of the c-axis melting field component:

$$H_{\text{melt}}^{c}(H_{\text{melt}}^{ab}) = H_{\text{melt}}^{c}(0) - 4\pi \varepsilon J H_{\text{melt}}^{ab} / (\Delta B \Phi_0),$$

where $\varepsilon J$ is the energy of a JV in the presence of PV lattice, $\Delta B$ is the jump of the magnetic induction at the melting point, and $\Phi_0$ is the quantum of the magnetic flux. In general, the energy of JV contains both, the self energy of JV, $\varepsilon^{self} J$ (eq. (3) in Fig. 2b), and the interaction energy $E_{PJ}$ of PVS with currents generated by JV, i.e. $\varepsilon J = \varepsilon^{self} J - E_{PJ}$. The self energy contribution elevates the free energy of vortex solid phase and reduces the stability of the vortex crystal, while the second term acts in the opposite way, through decreasing of the free energy. The latter, interaction term, $E_{PJ}$, was omitted in the analysis of the melting transition for the case of a dense PV lattice. Figure 2b shows the fitting curve (dashed line) obtained from the equation (8) of Reference with rather high value of anisotropy parameter $\gamma = 1500$ (the lower values of $\gamma$ give even stronger discrepancy with experimental data), the in-plane penetration depth $\lambda = 2000/\sqrt{1 - T/T_c}$ Å, the interlayer distance $s = 15$ Å, and $\Delta B = 0.85$ Oe. It is easy to see that the above mentioned model qualitatively describes our experimental data but the calculated average slope ($dH_{\text{melt}}^{c}/dH_{\text{melt}}^{ab} \approx 0.025$) as well as the expected breaking field ($H_{\text{melt}}^{ab(1)} \approx 7$ kOe) appeared to be several times higher than our experimental values ($dH_{\text{melt}}^{c}/dH_{\text{melt}}^{ab} \approx 0.01$, $H_{\text{melt}}^{ab(1)} \approx 2.5$ kOe).

On the other hand, in the experimentally studied magnetic field range and for the more realistic value of the anisotropic parameter $\gamma \approx 300$, the size of the non-linear JV core $\lambda J = \gamma s$ is about the same distance as the distance between pancakes vortices, $a_p$. In such a case, according to Koshelev, the interaction between PVSs and currents generated by JVs becomes important, and it is necessary to consider also the energy $E_{PJ}$. Due to Lorentz force, PVs shift from their equilibrium positions (Fig. 3a) reducing the free energy of the solid phase. Thus, the vortex crystal is stabilized and the c-axis melting field component decreases more slowly with the in-plane magnetic field. Therefore, the transformation of the linear dependence $H_{\text{melt}}^{c}(H_{\text{melt}}^{ab})$ into plateau could be related not to the overlapping of the JV cores, but to the compensation of the self energy of JVs by their interaction energy with PVs. The rough calculations, taking into account the pinning of PVs born by the interaction with currents of JVs, improve the correlation between model and experimental data (Fig. 2b (solid line)). The fitting curve was obtained under assumption that the pinning term is suppressed logarithmically by the in-plane field similar to the self-energy of Josephson vortex. Nevertheless, this term decreases faster in higher in-plane fields due to diminishing of currents generated by JVs, when the distance $b_J$ between JVs along the c-axis approaches $2s$. This means that the mentioned compensation can be destroyed in the field close to $\Phi_0/b JA_J = \Phi_0/2\sqrt{3}\gamma s^2$ ($A_J$ is the distance between JVs in a layer) and the new decay of the c-axis melting field component could follow again; for $\gamma = 300$, $\Phi_0/2\sqrt{3}\gamma s^2 \approx 9$ kOe, which is close to the observed value $H_{\text{melt}}^{ab(2)}$ at $T = 65$ K. Next, we point out that the disap-
pearance of the kink anomaly at the field $H^{ab(3)}$ could indicate the so-called "lock-in" transition [22] above which the observed behavior could be related to the melting of JV lattice via the second-order phase transition [18,23].

Finally, we note that the unusual step-wise behavior of the melting transition seems to be induced by the second-order phase transition in magnetic fields and currents of JV, depends on the distance $|b_J|$ between JVs along the $c$-axis should have discrete values $b_J = ks$, where $k$ is an integer. The structural transitions could explain the sharpness of dependence $\delta F_{\text{melt}}(H^{ab})$ at points $H^{ab(1)}$ and $H^{ab(2)}$ since the interaction between PVS and JVs is sensitive to the change of JV lattice parameters $b_J$ and $a_J$. Interestingly, the ratio of the magnetic fields where last two structural transitions happen (from the lattice 1 to 2 and from 2 to 3 in Fig. 3b) is 25/9, being close to the experimentally observed value $H^{ab(2)}/H^{ab(3)} \approx 3-4$ at all temperatures.

In summary, we present for the first time the complete $H^{ab} - H^{ab}$ phase diagram of VLMT in the single crystals Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. In strong contrast to the conventional superconductors and YBa$_2$Cu$_3$O$_{7-\delta}$, we observe the step-wise behavior of the melting transition, which reflects the layer structure of the system and could be related to interaction between pancake vortices and Josephson vortex lattice. The resistivity behavior indicates that melting transition changes its character from first-order to second-order phase transition in magnetic fields applied very close to the $ab$-plane.

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[19] We emphasize that our experimental results agree well to ac magnetization measurements over the common measured interval (for $H^{ab} < H^{ab(2)}$ compare [10] and [1]). However, in contrast to ac and dc magnetization technique [6,8,11,25], the resistance measurements with Corbino geometry do not lose sensitivity for fields aligned near the $ab$-plane, and thus, make it possible to get the complete $H^{ab} - H^{ab}$ phase diagram in the whole angular range.

[20] The general thermodynamical equation at the melting transition is: $F^{c}_c(B^{c}_0 + \delta B^{c}_0) + \delta F_c = F^{t}_c(B^{t}_0 + \delta B^{t}_0) + \delta F_t$, where $F^{c}_c$ and $F^{t}_c$ are the free energies of the vortex solid and vortex liquid states for the $c$-axis magnetic field, respectively, $B^{c}_0$ is the melting field in $H^{ab} = 0$, $\delta B^{c}_0$ is the shift of the $c$-axis melting field induced by $H^{ab}$, while $\delta F_c$ and $\delta F_t$ are the contributions to the free energies born by the in-plane magnetic field. Expanding $F^{c}_c$ and $F^{t}_c$ with respect to $\delta B^{c}_m$, one gets $B^{c}_m = B^{t}_0 - 4\pi(\delta F_c - \delta F_t)/\Delta B$. In the case of crossing lattice, $\delta F_c = (B^{ab})^2/8\pi - \epsilon_1 B^{ab}/\Phi_0$, i.e. it consists of the magnetic energy and the energy of JVs in the presence of PV lattice. Taking into account that Josephson coupling is suppressed in the vortex liquid state ($\delta F_t \approx (B^{ab})^2/8\pi$), and neglecting the difference between magnetic induction and external magnetic field, we obtain the equation as presented in the text.

[21] The pinning contribution to the free energy of the vortex solid phase is obtained from the condition that the gain of energy $E(x)$, born by interaction between PVS and currents of JV, depends on the distance $x$ between PVS and JV: the maximum of $E(x)$ corresponds to PVS placed on the center of JV. For the PV lattice with the intervortex distance $a_p = \sqrt{2\Phi_0/\sqrt{3}H^c}$, the pinning energy $E_p x$ per unit length of JV can be evaluated as $E_p x = (E(0) - E(a_p/2))a_p \approx AE_x a_p/\lambda^3$, where $E_x = E(0)$ is defined by eq. (9) in [3], and $A$ is the coefficient close to unity (we used $A = 0.5$). The corresponding contribution to the slope $dH^{ab}_m/dH^{ab}$ is $4\pi AE_x a_p^2/(\Phi_0 \lambda^3)$.

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