# Phase diagram in highly anisotropic layered superconductors: crossing lattice melting transitions

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**Abstract**

Recently, the crossing vortex lattice state in highly layered superconductors such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ has been explored both theoretically and experimentally by intensive studies in magnetic fields parallel to the superconducting $CuO_2$ plane. We discuss to establish the vortex phase diagram obtained by the novel ac-miniature coil measurement with emphasis on the spatial symmetry breaking.

*Key words:* superconductivity; vortex phase diagram; crossing vortex lattice; broken symmetry ; novel phase transition

## 1. Introduction

There has been much interest in the vortex state in highly layered superconductors, since it has been recognized that the novel vortex state may be realized in a field rotated to superconducting *ab*-plane from *c*-axis[1][2]. This is due to the fact that the superconducting state has a so pronounced layered structure that the supercondcuting system undergoes a broken symmetry, *i.e.*, the crystallographic *c*-direction is no longer equivalent to the *ab*-direction. This spatial symmetry breaking leads to a dramatic consequence that the scaling law is no longer valid in such a superconductor.

We have reported evidence obtained resistivity measurement in a special Corbino electrode configuration before[3]. Although this technique is unique to avoid edge pinning effect and has revealed qualitatively different and new results from prevailing data obtained by a conventional four probe technique, it cannot approach to the vortex solid phase because of zero resistivity. We have developed a new technique to probe even solid vortex phase by simple ac-mutual inductance measurement using a set of miniature coils. One is used for driving small ac-magnetic field to generate purturbation to the vortex system, and another one is grued on another side of the sample surface for detecting the transmitted ac-response. This simple device is superior to the conventional ac-susceptibility technique, where the sample is in general set inside the measuring coils. First of all, this technique provides a constant sensitivity for all field direction even for a field parallel to the *ab*-direction, since the coils are fixed to the sample. Secondly, the size of the coil is typically less that 0.5 mm and sufficiently smaller than that of the sample (∼5 mm) so that the edge current effect can be neglected. Thirdly, the sensitivity is sufficiently high to detect minute change of transmitted ac-response, since the filling factor for the detection coil is high.

## 2. Experimental Results

In Fig. 1 we demonstrate sensitivity of our technique by presenting a vortex phase transition. The effect is so subtle that it cannot be observed in other measurements previously. When a constant magnetic field below the melting field is set and rotated slowly, the

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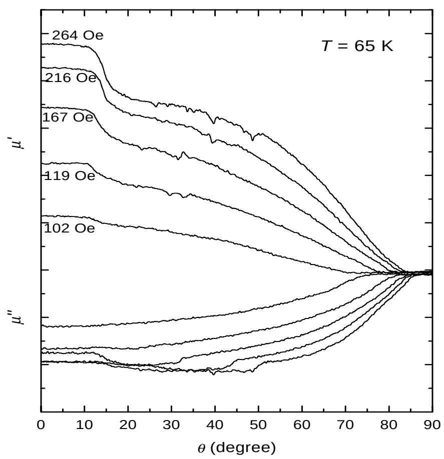


Fig. 1. The real($\mu'$) and inaginary($\mu''$) part of the ac-response as a function of $\theta$ in a constant low magnetic field region.

real part of the response($\mu'$) shows a sudden drop at $\sim 15 \pm 2^\circ$ from the $c$-axis, indicating an abrupt onset of pinning phenomenon. Since this effect disappears above the melting field, this response occurs only inside the vortex solid state. Considering the good agreement of the angle we found and small angle neutron experiment indicated loosing the hexagonal diffraction pattern from the Abrikosov vortex lattice image[5][4], we attribute this phenomenon is due to the structural change of the tilted vortex lattice to the crossing vortex lattice of the pancake and the Josephson vortex lattices. Although this phenomenon has been suggested theoretically[1], such a direct result has never been found in the previous measurements.

When magnetuic field is further tilted toward the $ab$-plane, the ac-response shows a dramatic behavior. With increasing magnetic field a peak followed by a sharp rise in $\mu'$ appears and eventually reaches a flat level, corresponding to the one in the normal state, as seen in Fig. 2(a). This happens in the intermediate angular range of $\sim 15^\circ < \theta < \sim 83^\circ$ in the whole temperature region. Corresponding to the sharp dip and rise of $\mu'$, $\mu''$ shows a broad peak with a sharp spike-like peak at the higher field side, indicating occurence of the peak effect, as seen in Fig. 2(b). With further rotation of the angle, the sharp rise becomes independent of the angle any more, then a new dramatic sharp increase of $\mu'$ encounters again. In accordance with this new rise of $\mu'$, $\mu''$ again shows a sharp peak, corresponding to the second peak effect. This effect can be interpreted as a peak effect right below the first order pancake lattice melting transition. This continues to exist up to $\sim 89.5^\circ$. Above this angle and within $\pm 0.4^\circ$ from the

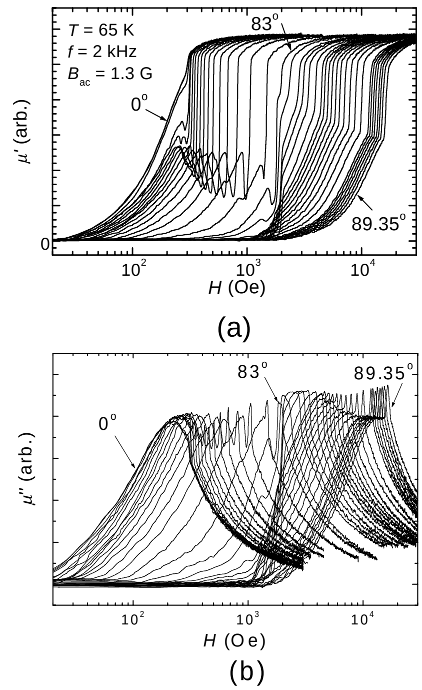


Fig. 2. The reral($\mu'$) and imaginary($\mu''$) parts of the ac-response taken with field sweep mode.

$ab$-plane, the first order nature of the transition is lost, perhaps, changing the character to the second order-like phase transition. In this narrow angle region we believe that the crossing lattice essentially disappears and the Josephson vortex state may fully be realized.

## 3. Conclusion

We have found a clear evidence of the phase transition at $\sim 15^\circ \pm 2^\circ$ from the tilted Avrikosov vortex lattice state to the crossing lattice state. Furthermore, the first-order pancake lattice melting transition continues up to $89.5^\circ$ and it suddenly disappears, while the first order phase transition in the vortex solid phase was found to be independent of the angle of the applied field.

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