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Vortex phase transitions in $Bi_2Sr_2CaCu_2O_{8+x}$ probed by nonlinear AC magnetic response

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Abstract. Local nonlinear AC magnetic measurements were employed in the study of the vortex phase diagram in $Bi_2Sr_2CaCu_2O_{8+x}$. The melting and the Bragg-Glass to Vortex-Glass (solid-solid) transitions are manifested by a sharp peak and a sharp drop in the third harmonic response, respectively. The peak at the solid-liquid transition signifies the hysteretic nature of the first-order melting transition. The disappearance of the nonlinear response in the vicinity of the solid-solid phase transition line suggests the existence of an intermediate soft lattice vortex state in-between the ordered and disordered vortex phases.

The vortex phase diagram in $Bi_2Sr_2CaCu_2O_{8+x}$ has been extensively studied using various experimental techniques, including both DC and AC magnetic measurements [1-8]. Three major vortex phases have been identified: a quasi-ordered solid (Bragg glass) at low temperatures and low fields, transforming into a disordered solid (vortex glass) at high fields, and to a liquid phase at high temperatures [8-13]. In DC magnetic measurements the melting and the solid-solid order-disorder transitions are manifested by a step in the reversible magnetization, and by a second magnetization peak (SMP), respectively [6, 8]. In linear AC magnetic measurements these transitions are manifested by a decrease or an increase in the screening current, respectively. It has been recently shown that AC measurements may indicate a solid-solid transition where DC measurements exhibit a melting transition [2], demonstrating that both the solid-solid and the melting transition lines are two segments of the same continuous order-disorder transition line [2, 3, 8].

In the present work we examine the signature of the vortex order-disorder transition in the *nonlinear* AC magnetic response. We focus on the third harmonic in the AC magnetic response, which dominates over the higher harmonics, and measure it locally as a function of the field at different temperatures. Non-linear magnetic measurements have been successfully employed in various studies of superconductors such as vortex dynamics [14-17], the irreversibility line [18], and the peak effect [19, 20]. Our results in $Bi_2Sr_2CaCu_2O_{8+x}$ show that the nonlinear AC magnetic response can also serve as an effective tool in the investigation of the vortex phase diagram, and may provide further information not readily observed in the DC or the linear AC measurements.

Measurements were performed on a 1590 X 750 X 50 μm^3 optimally doped $Bi_2Sr_2CaCu_2O_{8+x}$ crystal with $T_c \approx 92$ K, employing an array of 11 micro-Hall probes. The Hall sensors with an active

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area of 30 X 30 μm^2 were fabricated from 2DEG GaAs/AlGaAs heterostructure. Both the AC and DC fields were parallel to the crystallographic c - axis of the $Bi_2Sr_2CaCu_2O_{8+x}$ crystal. The AC response was measured between 20 and 92 K with DC fields up to 1 T and AC fields with amplitude between 0.35 and 1.1 G and frequencies between 1 and 970 Hz.

Figure 1 shows the third harmonic voltage $|V_3(H)|$ of the AC magnetic response as a function of the external DC field, H, measured at 36 K by a Hall sensor located at 150 μm from the sample long edge. The signals measured at other locations show similar behavior but of smaller amplitude. The voltage $|V_3(H)|$ is proportional to the third harmonic component of the oscillating magnetic induction,$|B_3(H)|$. The figure presents data for two frequencies of the applied AC magnetic field, 1 Hz and 37 Hz, with the same amplitude of 0.7 G. Usually, $|V_3(H)|$ exhibits a single broad peak, reflecting two competing processes: increase of the penetration depth of the AC field and decrease in the persistent current with the external field [21]. Figure 1, however, shows a new feature, namely a sharp drop around 360 G, indicating a dominant linear magnetic response in this field regime. The nonlinear response increases gradually at higher fields as shown in the inset to figure 1. We note that the field range in which the sudden decrease of $|V_3(H)|$ is observed, overlaps with that of the vortex solid-solid transition as measured by DC magnetic techniques [22]. The field of this sudden decrease in the third harmonics (black arrow on the figure) does not depend on the frequency in the measured range 1 - 970 Hz. The other harmonics (*i.e.* the second, fourth, fifth etc.) are at least an order of magnitude smaller than the third harmonic, therefore the drop in the third harmonic clearly indicates vanishing of the nonlinear response. We conclude from the data that the solid-solid transition is signified by a sharp drop in the non-linear magnetic response. One may ascribe this drop to a decrease in the AC penetration depth due to the increase in the persistent current associated with the transformation of the vortex lattice into the disordered phase. However, in this case, the decrease in the third harmonics signal should depend strongly on the location of the probe, being negligible closer to the sample edge. Experimentally, all the micro Hall probes show a similar drop at the same field range. We therefore propose that the decrease of the nonlinear signal close to the solid-solid transition inductions implies a new phenomenon, namely the existence of an intermediate soft lattice vortex state in-between the ordered and disordered vortex phases.

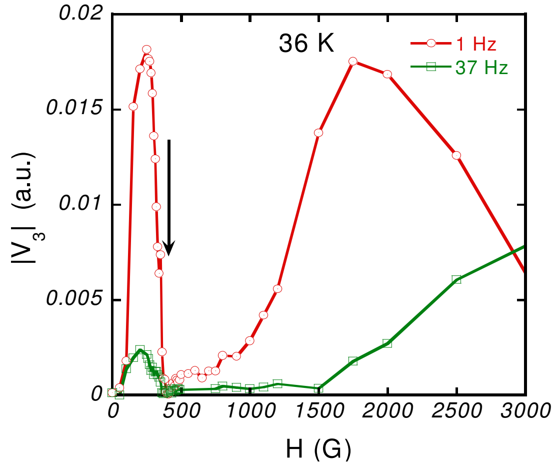


Figure 1. Absolute value of the third harmonic of the AC magnetic response measured at 36 K by Hall sensor located at 150 μm from the sample edge, the AC field amplitude is 0.7 G, and frequency 1 Hz (circles) and 37 Hz (squares). The solid lines are guide for the eye. The arrow points to the solid-solid transition.

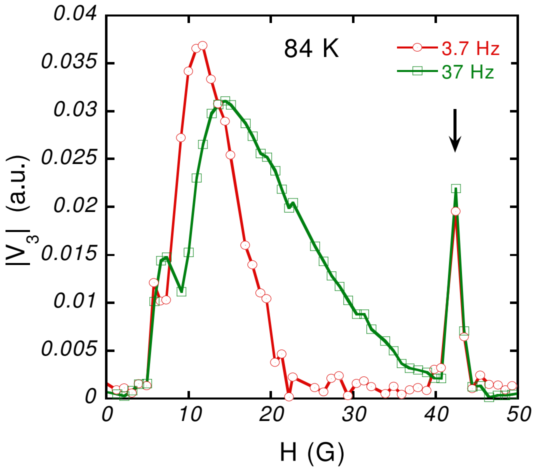
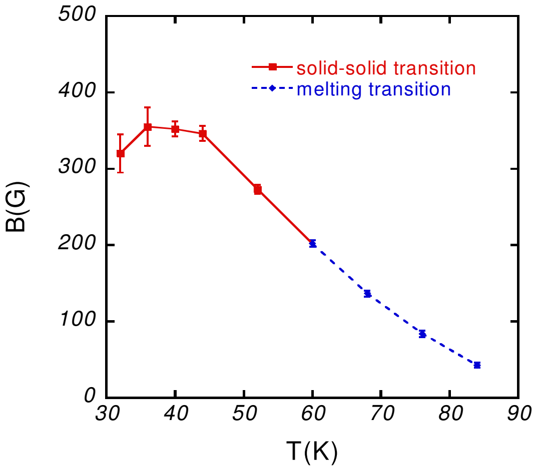


Figure 2. Third harmonic signal of the AC magnetic response measured at 84 K by a sensor close to the center of the sample. The amplitude of the AC field is 0.7 G. The circles and squares refer to data for 3.7 and 37 Hz respectively. The solid lines are guide for the eye. The narrow peak at 42.5 G indicates the melting transition.

The vortex melting transition is manifested by $|V_3(H)|$ quite differently. Figure 2 presents $|V_3(H)|$ as a function of the external DC field measured at 84 K by a probe located near the sample center. Other sensors, placed at different locations on the sample, show similar behavior but with smaller amplitude of the signal. The two data sets in figure 2 correspond to AC fields of frequencies 3.7 (open circles) and 37 Hz (open squares) and of the same amplitude of 0.7 G. Figure 2 shows that the first order melting transition is manifested by a sharp peak at 42.5 G DC field. The position of the peak in $|V_3(H)|$ is frequency and amplitude independent and it manifests the hysteretic nature of the first order melting transition. Namely, due to superheating and supercooling effects, on the ascending half cycle of the AC field the vortex solid melts at slightly higher field than on the descending half cycle. As a result, hysteresis loop opens at the melting transition, resulting in the sharp peak in the third harmonic of the AC magnetic response.

In figure 3 we plot the vortex phase diagram in BSCCO as determined by the nonlinear magnetic response measured at 37 Hz. The squares indicate the solid-solid transition line as determined by the sharp drop of $|V_3(H)|$ and the diamonds indicate the melting transition as determined by the narrow peak in $|V_3(H)|$. The AC measured order-disorder transition line closely resembles the DC measured line [22]. We note, however, that in the AC measurements the signature of the transition varies with the frequency. For example, at 60 K at low frequencies of 3.7 and 37 Hz the signature of the transition is a peak in $|V_3(H)|$ implying a melting transition. At the same temperature but at higher frequency of 970 Hz the signature changes to a sharp drop in $|V_3(H)|$, which implies a solid-solid transition. Analogous change in the signature of the order-disorder transition with the frequency of AC field was recently reported in linear response measurements [2]. The change in the transition signature is explained by enhancement of the irreversibility of the vortex system at shorter measurement times (higher frequencies), and supports the idea that the solid-solid and the melting lines are two segments of the same order-disorder line [2, 8].

Figure 3. *B-T* Phase diagram of the order-disorder transition line. The squares indicate the solid-solid transition line as determined by the sharp drop of $|V_3(H)|$ and the diamonds indicate the melting transition as determined by the narrow peak in $|V_3(H)|$.



In conclusion, the solid-solid and melting vortex transitions in $Bi_2Sr_2CaCu_2O_{8+x}$ are manifested by a sharp drop and a sharp peak in the AC nonlinear magnetic response, respectively. The sharp drop suggests the existence of an intermediate soft lattice vortex state in-between the ordered and disordered vortex phases. The sharp peak at the solid-liquid transition manifests the hysteretic nature of the first order melting transition.

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