Investigation of the vortex order-disorder phase transition line in $Bi_2Sr_2CaCu_2O_{8+x}$ using ac techniques

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(Presented on 8 November 2007; received 5 September 2007; accepted 26 October 2007; published online 24 January 2008)

ac magnetic measurements were employed in the study of the vortex phase diagram in $Bi_2Sr_2CaCu_2O_{8+x}$. The Bragg-glass to vortex-glass (solid-solid) and the Bragg-glass to liquid (melting) transitions are manifested in these measurements by an increase or a decrease in the screening signal, respectively. The ac measured solid-solid transition line extends to high temperatures where a melting transition is observed in dc measurements. Increasing the frequency of the ac field can further enlarge this region of the solid-solid transition. These results confirm that the solid-solid and the solid-liquid transition lines are two segments of the same order-disorder phase transition line. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2833818]

INTRODUCTION

Previous studies of the vortex phase diagram in $Bi_2Sr_2CaCu_2O_{8+x}$ showed the existence of at least three vortex phases: quasiordered solid (Bragg glass), disordered solid (vortex glass), and liquid phases.[1–6] The Bragg glass collapses into a disordered phase through either a thermal—or a disorder-driven first order transition. This order-disorder vortex phase transition is manifested in dc magnetic measurements by a step in the magnetization above the irreversibility line, or by a second magnetization peak (SMP) below it. Thus, the order-disorder vortex phase transition line is composed of two segments: a solid-solid transition line up to approximately 40 K and a solid-liquid (melting) line at higher temperatures. However, the continuity of these two transition lines was questioned because of a wide temperature range below the irreversibility line where the SMP is not always observed, resulting in an apparent temperature gap between the two lines.[7–10] In later studies of this gap,[11] it was shown that the SMP could not be observed because of fast relaxation of the bulk currents. It is thus expected that the magnetic signature of the solid-solid vortex transition should persist for shorter experimental time windows. For this reason, ac measurements rather than the relatively slow dc measurements offer the possibility for recovering the magnetic signature of the solid-solid transition.

In a recent work, Avraham *et al.*[5] demonstrated that by reducing the irreversibly of the superconductor, exploiting a vortex "shaking" technique, the magnetic signature of the melting transition—a sharp step in the dc magnetization signal—is found at temperatures much lower than 40 K at inductions where conventional dc magnetization loops exhibit a SMP. In this work, we demonstrate the continuity of the transition line by taking the opposite approach, namely, increasing the irreversibility of the vortex system. This is achieved by reducing the time window of the measurements exploiting ac techniques. We show that this enhanced irreversibility allows us not only to close the experimental gap between the solid-solid and solid-liquid lines but also to "drag" the SMP to temperatures well above 40 K where a signature of a melting is observed in the slower dc measurements. The present ac results complement the dc measurements of Avraham *et al.*[5] in confirming previous claims[4–6] that the solid-solid line and the solid-liquid line are two segments of the same order-disorder phase transition line.

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EXPERIMENTAL

Measurements were performed on a $1.5\times1.5\times0.05\ \mathrm{mm}^3$ optimally doped $Bi_2Sr_2CaCu_2O_{8+x}$ crystal with $T_c\approx92$ K, exploiting GaAs ion implanted single Hall probe with active area of $0.3\times0.3\ \mathrm{mm}^2$ located at the central part of the crystals. The ac response was measured between 20 and 92 K with dc fields up to 5 T and ac fields with amplitude between 0.2 and 2 G and frequencies between 1 and 970 Hz. The noise level of the probe was $1.4\times10^{-3}\ \mathrm{G}/\sqrt{\mathrm{Hz}}$ at 1 Hz and $9\times10^{-6}\ \mathrm{G}/\sqrt{\mathrm{Hz}}$ at 970 Hz.

RESULTS AND DISCUSSION

Figures 1(a)–1(c) show the in-phase ac signal for the indicated frequencies measured in an ac field of 0.7 G as a function of the external field H at 32, 44, and 80 K, respectively. As expected, at all temperatures the in-phase signal shows relatively high screening at low fields.[12–14]

A significant feature in Fig. 1(a) is the diamagnetic anomaly observed around 420 G. The location of this anomaly is independent of the frequency and amplitude of the ac field. We use the word "diamagnetic" to indicate that the screening of the superconductor increases (the signal becomes more negative) with the increase in the applied field H. We argue that the diamagnetic anomaly signifies a Bragg glass to vortex glass phase transition. The bulk persistent current j increases at the transition, as manifested by the SMP in dc magnetization measurements.[1,15,16] The screening signal is expected to increase with the critical current j_c,[17] and thus the transition from ordered to disordered solid, as-

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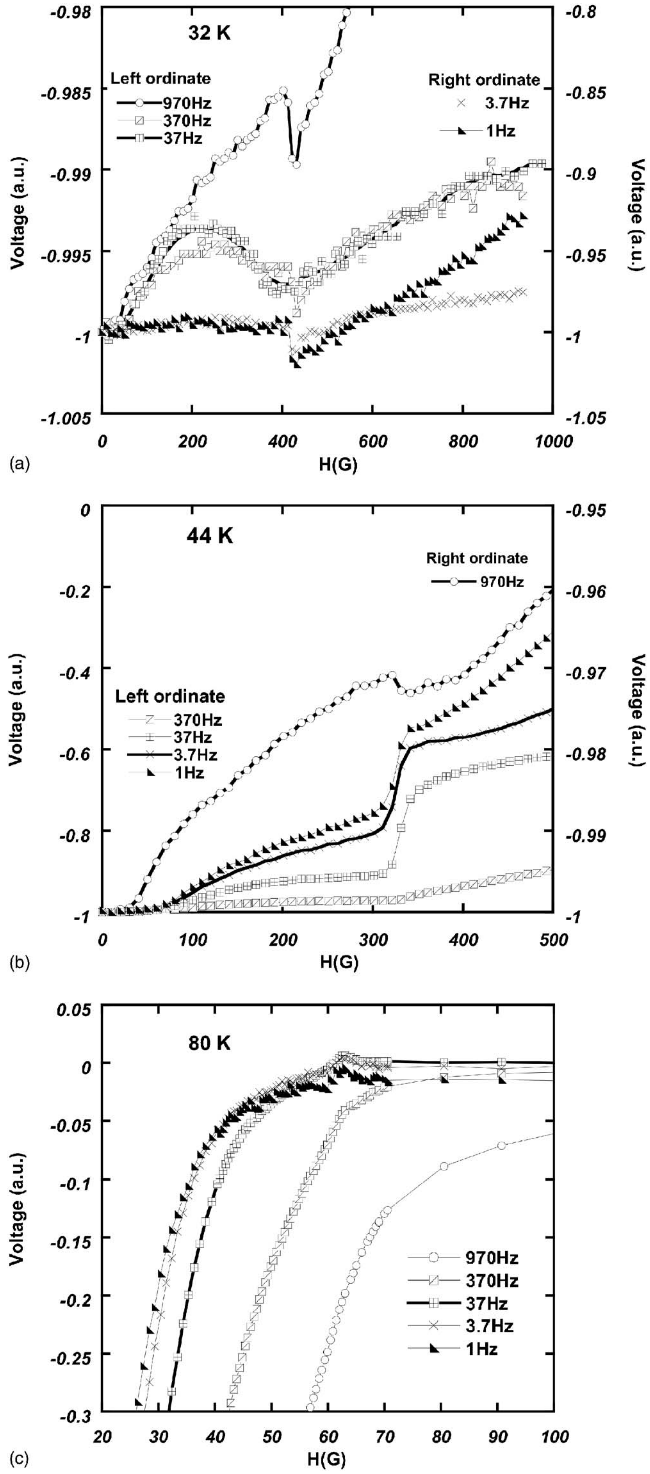

FIG. 1. In-phase ac signal measured in 1 G ac field as a function of external dc field at (a) 32 K, (b) 44 K, and (c) 80 K for the indicated ac frequencies. The gray strip in each panel marks the field range in which the anomalies are observed. The right ordinates in (a) refers to data for 1 and 3.7 Hz and in (b) for 970 Hz.

sociated with a jump in the critical current, causes an increase of the screening, as observed experimentally.

Figure 1(c) shows the in-phase ac signal measured at 80 K for the same frequencies as in the Fig. 1(a). A "paramagnetic" anomaly, i.e., less screening, is clearly observed at fields around 65 G. Similar to the observation at 32 K [Fig. 1(a)], the anomaly induction at 80 K is independent of frequency and amplitude of the ac field. This anomaly induction coincides with the melting transition observed in similar samples in dc experiments.[18] The transition from an ordered vortex solid to a vortex liquid results in reduced screening and hence a paramagnetic anomaly. We note that such anomaly was previously reported and interpreted as signifying a melting transition.[19–21]

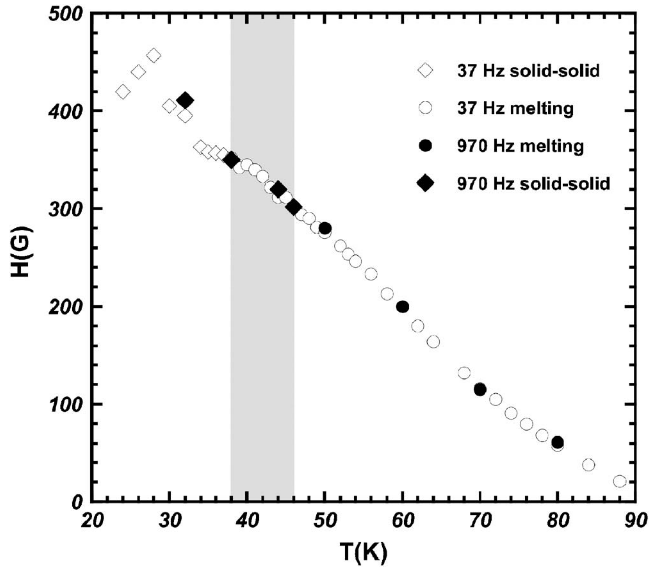

FIG. 2. *H-T* vortex phase diagram deduced from the onset of the diamagnetic and paramagnetic anomalies in the ac response. Vortex phase transitions from ordered to disordered solid are presented by open and solid diamonds (37 and 970 Hz, respectively). Melting transitions are presented by open and solid circles (37 and 970 Hz, respectively). The grey strip marks to the temperature range where the frequency determines the signature of the transition.

Figure 1(b) shows the behavior of the in-phase ac signal at an intermediate temperature of 44 K. In this figure, a clear anomaly is observed around 320 G. However, while a diamagnetic anomaly (enhanced screening) is observed at high frequency (see the 970 Hz data), a paramagnetic anomaly (reduced screening) is observed at lower frequencies. A similar crossover in the nature of the anomaly was observed at all temperatures between ~38 and ~46 K. Thus, at this temperature range, the frequency of the ac field determines the signature of the vortex transition: A diamagnetic anomaly at high frequencies implies a vortex solid-solid transition, whereas paramagnetic anomaly at low frequencies implies a melting transition.

The results of our ac measurements are summarized in the *H-T* phase diagram presented in Fig. 2. The positions of the anomalies that represent vortex phase transition from ordered solid to disordered solid are presented by diamond. Open and solid diamonds mark the solid-solid transition line for 37 and 970 Hz, respectively. Open and solid circles correspond to the melting transition measured at 37 and 970 Hz, respectively. Evidently, at high frequency (970 Hz), the solid-solid transition line extends to significantly higher temperatures (above ~46 K) as compared to the lower frequency (37 Hz) for which the solid-solid transition line terminates at ~38 K. These results can be understood by noting that the frequency in the ac measurements defines the mea-

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surement time window. For shorter measurement time (i.e., higher frequencies), the bulk persistent current j is still high enough to produce the signature of a vortex solid-solid transition. In the temperature range of 38–46 K, the time window defined by low frequencies, e.g., 37 Hz, is long enough to allow for a decay in j to such a level that the magnetization is reversible and a signature of a melting transition can be detected.

SUMMARY

By tuning the reversible/irreversible behavior of the sample, one can change the magnetic signature of the vortex phase transition. Thus, by reducing the irreversibility, exploiting vortex shaking techniques, Avraham *et al.*[5] were able to extend the melting line to below 40 K, i.e., to temperatures where the solid-solid transition line was originally observed. In the present work, we enhance the irreversible characteristics by reducing the time window of the experiment and find that the solid-solid transition line is extended to above 40 K (up to $\sim$46 K for 937 Hz), into the range where the melting transition line was originally observed in dc measurements. These complementary experiments reconfirm that the solid-solid line and the solid-liquid line are two segments of the same order-disorder phase transition line.

ACKNOWLEDGMENTS

This research is supported in part by the Israel Science Foundation (ISF) and by the Heinrich Hertz Minerva Center for High-Temperature Superconductivity.

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