Vortex lattice melting induced by force-free current in $Bi_2Sr_2CaCu_2O_{8+y}$

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(Received 6 September 2007; published 27 December 2007)

To investigate the melting transition of the vortex lattice under a force-free current parallel to the c axis, we have measured the field dependence of c-axis resistance, critical current, and I-V characteristics in vortex states of $Bi_2Sr_2CaCu_2O_{8+y}$ single crystals. The melting transition field H_m observed in the critical current measurements was almost 20% smaller than H_m determined by the resistance measurements. Furthermore, it was found that H_m is reduced as the parallel current increases by measurements of the differential resistance with various bias currents. We have first demonstrated to induce the vortex-lattice melting transition by the force-free current. Although monotonical decrease of H_m with increasing current is consistent with the theoretical expectations, the whole behavior of the current dependence of H_m does not obey them.

DOI: 10.1103/PhysRevB.76.224527 PACS number(s): 74.25.Qt, 74.72.Hs, 74.25.Bt, 74.25.Fy

High-T_c superconductors have presented a special research field for understanding the nature of a vortex system with large thermal fluctuation and anisotropy. Especially in $Bi_2Sr_2CaCu_2O_{8+y}$ (Bi2212), since the coupling between CuO_2 superconducting layers is quite weak which causes the large anisotropy, the stacking layers work as superconductor-insulator-superconductor (SIS) Josephson junctions, so-called intrinsic Josephson junctions (IJJ's).[1] Vortices in the magnetic field parallel to the c axis are constructed by pancake vortices in these layered materials.[2] The pancake-vortex phase diagram has been extensively studied in past decades.[3] The existence of the first order melting transition from a solid to a liquid phase has been confirmed.[4] At present, the solid phase is interpreted as Bragg glass phase because the long-range translational order of Abrikosov lattice is destroyed by disorders like oxygen vacancies in real materials.[5]

The problem of how these equilibrium vortex phases are modified under the current flow has attracted much attention. In conditions that the field is perpendicular to the current, the Lorentz force acts on vortices to make the vortex flow. Theoretically, Koshelev and Vinokur predicted that a disordered vortex system crystallizes with high currents.[6] Direct observation by the neutron diffraction in 2H-$NbSe_2$ indicated that moving vortices recover a lattice order in high currents,[7] because the effect of pinning relatively becomes weak by the driving force. After the discovery of the melting transition in high-T_c superconductors, influence of the current on the melting transition has been studied.[8–10] In the case of Bi2212, the field of the melting transition measured using a micro-Hall sensor was almost independent of the in-plane current density up to 250 A/cm^2.[9] Contrary, resistance measurements using eight-terminal geometry showed that the melting transition temperature was reduced depending on currents.[10]

On the other hand, when the current is applied parallel to the field direction (force-free or parallel current configuration), it is suggested that the thermal fluctuation is enhanced in the Bragg glass phase, and the melting transition tends to occur at lower fields or temperatures.[11] Alternative theoretical construction of vortex phase diagram with the force-free current has been done by Savel'ev *et al.* for the case of Bi2212.[12] A suppression of the melting fields in large force-free currents has been also reproduced. Furthermore, they found a reentrant behavior of the transition in lower fields.

Although there are extensive studies on the dynamical melting transition in a current perpendicular to the field, it is rare, especially in high-T_c superconductors, in the case of the force-free configuration.[13] To observe behavior of the melting transition with the force-free current, we have measured field dependence of the c-axis resistance, differential resistance with bias dc current, and the c-axis critical current. In this paper, we report that the melting transition of Bragg glass depends on the current and can be induced by external c-axis current.

Single crystals of Bi2212 were grown by traveling-solvent floating-zone technique.[14] A platelet of single crystals was cut into narrow strips using a dicing machine. The width of the strips is 50–60 μm. After four gold contacts were formed on the surface, the center of strips of the single crystals was three-dimensionally milled using a focused ion beam (JFIB-2100, Micrion) for the measurements of the c-axis electric transport properties. The same fabrication processes have been used in the case of Bi2212 whiskers[15] and single crystal.[16] The shape of the sample is schematically shown in the upper inset of Fig. 1. The center part consists of a stack of IJJ's. The sample dimensions w, l, and t, whose

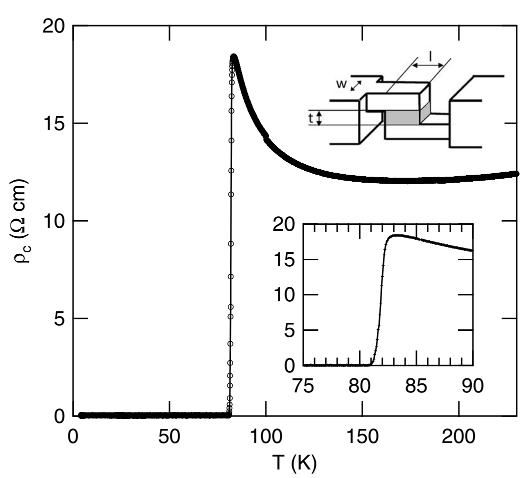

FIG. 1. Temperature dependence of the c-axis resistivity. A part near the superconducting transition is magnified in the lower inset. The upper inset shows a schematic draw of the sample shape.

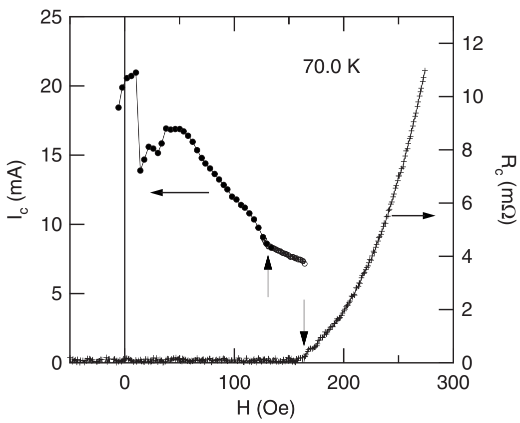

FIG. 2. Magnetic field dependence of the c-axis critical current and the c-axis resistance at 70 K are plotted in the left and right axes, respectively. Anomalies corresponding to the melting transition of vortex lattice are observed by both measurements in different fields: 131 Oe for I_c and 163 Oe for R_c.

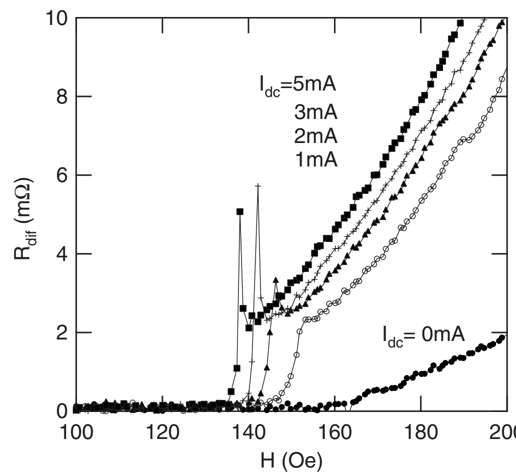

FIG. 3. Differential resistance as a function of field with various bias dc currents at 70.0 K. Amplitude of the applied ac current is 1 mA. With increasing bias current, the fields of the steps or the peaks, which are signs of the vortex-lattice melting transition, are suppressed.

definitions are shown in the inset, are 47, 79, and 1.1 μm, respectively.

Both electric resistance and I-V measurements by current-driven mode have been performed with the same four-probe configuration, using ac resistance bridge (LR-700, Linear Research), and a set of current source (Keithley2400) and nanovoltmeter (Keithley2182), respectively. In the measurements, magnetic field is applied along the c axis. Figure 1 shows temperature dependence of the resistance after the fabrication of sample for the c-axis electric transport measurements. This shows the typical behavior of the c-axis resistivity in Bi2212. Although the in-plane resistance of the bridge parts connected to IJJ's is included in the measured resistance in this sample shape, the contribution is negligible because the in-plane resistivity is about 10^{-4} times smaller than the c-axis resistivity in Bi2212. The superconducting transition temperature which is determined by zero resistance was 81 K.

The melting transition can be detected as a sharp increase of resistance during the field sweep.[8,9] The same feature was also observed in the c-axis resistance R_c of our sample as shown in Fig. 2. At 70 K, the field H_m, where the melting transition occurs, was 163 Oe. Meanwhile, the melting transition is detectable in the field dependence of the critical current I_c.[13] I_c is determined from maximum current in the first branch, where the voltage is nearly zero. The field dependence of I_c at 70 K is plotted in Fig. 2. At zero field, I_c reaches 21 mA, which corresponds to 570 A/cm^2. A steplike structure is observed at 131 Oe in I_c-H curve. This anomalous step corresponding to the melting transition has been observed in our previous study.[13] Since I_c reflects the strength of interlayer coupling, measurements of I_c might be a probe to investigate the interlayer correlation of pancake vortices. In the measurement of Josephson plasma resonance (JPR),[17,18] indeed, I_c clearly shows a jump at the melting transition. Although such a phenomenon has not been known in the previous studies of I-V measurements,[19–21] we have succeeded to detect a step which is accompanied by the melting transition.[13] Interestingly, the field of the I_c step is significantly smaller than H_m in $R_c(H)$ as seen in Fig. 2. It seems that the melting transition occurs in lower fields due to the influence of the c-axis current.

To check the suppression of H_m under the external c-axis current, we have measured a differential resistance with various dc bias currents. In the measurements, ac current (I_{ac}=1 mA) is superimposed on the dc bias current (I_{dc}). The differential resistance (R_{dif}) obtained from voltage response for I_{ac} is plotted in Fig. 3 as a function of magnetic field at various I_{dc}. The data without the bias current are the same as R_c in Fig. 2, where a small step at the vortex lattice melting is observed at ~163 Oe at 70 K. With increasing I_{dc}, the step develops to a clear jump and its field is reduced monotonically. This is consistent with the results of $R_c(H)$ and $I_c(H)$. These facts support that H_m is suppressed in the presence of the c-axis force-free current.

As H_m depends on the c-axis current, we can demonstrate to induce the melting transition only by increasing the current at a fixed temperature and field. In an intermediate field between 131 and 163 Oe at 70 K, for example, sharp jumps of the voltage were observed in I-V characteristics as shown in Fig. 4. The current I_m, where the voltage jump occurs, monotonically increases with decreasing magnetic fields. When I_m goes over to the critical current of the first branch, the jump disappears from the first branch. This jump is not related to the multiple branches in I-V of IJJ's, because the jumps appear in quite narrow range of fields and the voltage of jumps is smaller than that of typical voltage interval of the multibranch in I-V (~10 mV).[1] To our knowledge, this is the first experimental demonstration inducing the melting transition of vortex lattice using a parallel current instead of changing environmental parameters like temperature or magnetic field.

Current density dependence of H_m is summarized in Fig. 5 with the field dependence of I_m. The c-axis current penetrates into the sample from the edges as far as a range of the c-axis penetration depth λ_c. Since λ_c of Bi2212 has been

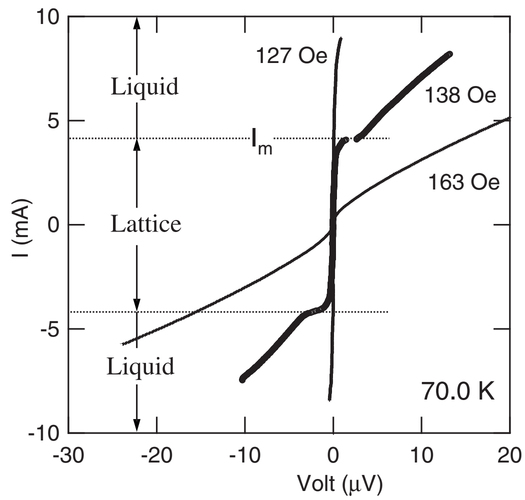

FIG. 4. *I-V* characteristic in 138 Oe which shows a melting transition induced by the *c*-axis current (a bold line). Sharp jumps in the voltage are observed at I_m. I_m increases with decreasing magnetic fields. As comparisons, *I-V* curves in higher and lower fields are plotted by thinner lines.

reported 50–150 μm depending on the doping level,[22] we assumed that the applied current uniformly penetrates the whole sample, and simply divided the current by the area of the *ab* plane to calculate the current density *j*. Both results of H_m and I_m coincide well in the *H-j* diagram suggesting that the observed phenomena in two experiments were the same. The field of the step observed in the critical current measurements is on the extrapolated line of the bias-current dependence of H_m as indicated by a solid square in Fig. 5. The reduction of H_m is almost 20% at the maximum current. Interestingly, H_m is rapidly suppressed in low-current regime.

As an extrinsic origin of the decrease of H_m, joule heating in the junction has to be checked, because H_m would de-

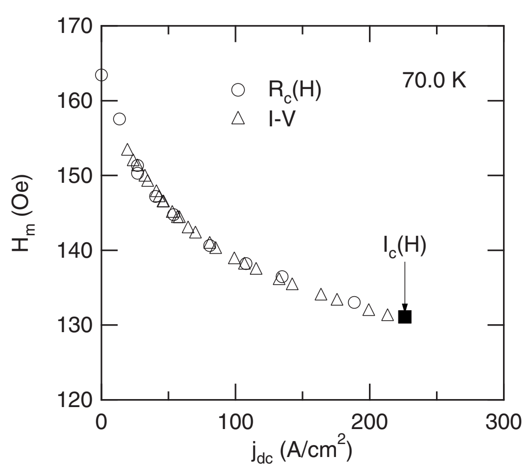

FIG. 5. Bias current dependence of the fields of the melting transition at 70 K. Circles and triangles are data from $R(H)$ and *I-V* measurements, respectively. A point obtained from $I_c(H)$ as the melting transition is added by a solid square. H_m decreases monotonically, as the bias current increases.

crease if its temperature increases. According to the other experiments on the heating of IJJ's, the overheating of mesa-type IJJ's was ~40 K by 1 mW thermal dissipation.[23] The heating power in our case is about 10 nW at I_m estimated from *I-V* curves. This corresponds to a 0.4 mK increase as a rough estimation, which is negligible.

There are several possible origins for the observed suppression of the melting transition field by the force-free current. First, H_m can be decreased when the effective Josephson coupling between the superconducting layers is suppressed by the *c*-axis current. The current density *j* flowing through an IJJ is given by $j_c \sin(\phi_0+\Delta\phi)$, where ϕ_0 is the phase difference due to applied external current $j_{\rm ex}$, and $\Delta\phi$ originates from the phase perturbation for pancake vortices configuration. If $\Delta\phi$ is small enough, $j \approx j_{\rm ex}+j_c\sqrt{1-(j_{\rm ex}/j_c)^2}\sin\Delta\phi$. Hence the effective critical current for $\Delta\phi$ will be reduced as $j_c\sqrt{1-(j_{\rm ex}/j_c)^2}$ by the external current. The reduction of the critical current leads to increase of anisotropy $\gamma(\equiv\lambda_c/\lambda_{ab}) \propto j_c^{-1/2}$.[24] Since the melting transition field has been theoretically calculated to be proportional to γ^{-2},[25] we expect that H_m becomes small like $\sqrt{1-(j_{\rm ex}/j_c)^2}$ with increasing $j_{\rm ex}$. While this can explain the monotonical decrease of H_m, the concave curvature of H_m as seen in Fig. 5 is inconsistent with the convex one expected from this model. The saturation of H_m in large currents is also unexplained. Even when the external current density reaches j_c, namely the effective Josephson coupling is zero, H_m does not become zero in the experiments. In regard to the melting transition in highly anisotropic materials, the electromagnetic coupling between pancake vortices might have an important role as well as the Josephson coupling.[26] Even without the Josephson coupling, pancake vortices can align along the *c* axis by the electromagnetic interaction, which sustain the vortex lattice or Bragg glass phase. The reason why H_m does not become zero in j_c may be related with the remanent electromagnetic coupling in Bi2212.

Besides the reduction of interlayer coupling of pancake vortices, instability of Bragg glass phase in the presence of the force-free current causes the melting transition as was considered by Kohandel *et al.*[11] In their calculation, the mean-squared fluctuation of a vortex is enhanced with increasing current. Using the Lindemann criterion, they deduced the current dependence of the melting transition field, which is proportional to $1-(j_{\rm ex}/j_c)^2$.[11] This curvature is different from the data in Fig. 5. Another theoretical calculation on this issue has been done by Savelev *et al.*, in which the fluctuation of vortex lattice is investigated using the parameters of Bi2212 in a wide range of magnetic field.[12] While they found the appearance of a reentrance of melting transition in low fields, the current dependence of the melting transition field in high fields tends to decrease convexly as shown in Fig. 2(a) of Ref. 12. Consequently, the decreasing behavior of the current dependence of H_m is consistent with both theories, however the significant suppression of H_m in low current densities is an open question.

In the case of Bi2212, the lattice structure of the pancake vortices is influenced by the Josephson vortices, i.e., vortex chains embedded in triangular vortex lattice,[27] which structure was explained by a model of crossing lattices.[28] The existence of the Josephson vortices anomalously reduces the melting transition field of pancake-vortex lattice.[28,29] In the present situation, the c-axis current can generate Josephson vortices. Dynamical motion of the Josephson vortices may modify the lattice structure of the pancake vortices and the melting transition field with the parallel current. To explain the experimental results, more theoretical considerations may be required, for instance, on the interplay of the pancake vortices and the Josephson vortices induced by the c-axis current.

In conclusion, we have measured the field dependence of the c-axis resistance, critical current, and I-V characteristics in Bi2212 single crystals to study the dynamical aspect of the melting transition of vortex lattice under the force-free current. We have observed a step in the field dependence of the critical current, which is identified to be the vortex lattice melting. The melting transition field from the critical current measurements is almost 20% smaller than H_m determined by resistance measurements. We showed that H_m is reduced as the parallel current increases by measurements of the differential resistance with various bias currents, and first demonstrated to induce the melting transition by the force-free current. In comparison with theoretical models, the behavior of the current dependence of H_m is different from the theoretical expectations except the monotonical suppression of H_m. Further theoretical consideration is needed to explain the experimental results totally.

This research is partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Young Scientists (B), 17760017, 2005.

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