Dilute vortices on the surface of superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$

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Properties of dilute pancake vortices on the surface of $Bi_2Sr_2CaCu_2O_{8+\delta}$ superconductors are investigated by measuring the field, temperature, and time dependencies of the critical current of the surface intrinsic Josephson junctions. It is found that the pinning of the surface vortices has two crossovers over the entire temperature range in the superconducting state. For temperatures below and above ~20 K, strong collective pinning and weaker point defect pinning are observed, respectively. Further increasing the temperature leads to the depinning of the surface vortices. We find that the depinning of the surface vortices can occur at a much lower temperature than that for the bulk vortices, depending on the surface-layer crystalline perfectness or the density of point defects that have been intentionally introduced experimentally.

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I. INTRODUCTION

Cuprate superconductors have layered structures, which lead to the anisotropic physical properties of the materials. In the case of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) superconductors with a large anisotropic factor, experiments have confirmed the existence of intrinsic Josephson coupling between the neighboring superconducting planes (CuO_2 double layers).[1] When a magnetic field is applied parallel to the c axis of the superconductor, pancake vortices are formed in each plane, with magnetic interaction within the planes and both magnetic interaction and Josephson coupling out of the planes.[2] These interactions, together with the pinning force lead to a variety of interesting phenomena of the vortex dynamics. Large efforts are taken to understand the complex vortex phase diagram of the layered superconductors with applied fields ranging from a few G to tens of T.[3,4]

Intrinsic Josephson junctions (IJJs) based on intrinsic Josephson coupling can be made out of Bi-2212 crystals, which provide a unique way for the studies of the properties such as c-axis transport and quasiparticle tunneling spectra. Measuring the magnetic-field dependence of the Josephson critical current I_c can also provide information on the vortex phase diagram and pancake correlations among the neighboring planes.[5–10] In the high-field regime, it is found that below about 20 K, I_c increases with increasing temperature, which is explained as an improving alignment of vortex pancakes along the c axis. At higher temperatures, a rapid decrease of I_c is observed, which results from a solid-liquid phase transition. The melting line has been discussed in these experiments in both the high-field[6] and low-field[8] regimes.

For the dilute vortices in the low field, many experiments using techniques other than IJJs have shown that around 20 K, there may exist a change of dominating pinning mechanism in the Bi-2212 system, which can dramatically influence its properties such as magnetization relaxation behavior,[11,12] superconducting phase coherence in the c direction,[13,14] and Campbell penetration depth.[15] Tonomura *et al.*[16] observed the real-time movement of vortices on the sample surface using field-emission electron microscope, and found that the way they move strongly depends on the sample temperature. Below 25 K vortices move slowly and smoothly. This is attributed to the collective pinning by many tiny centers like oxygen defects, while above 25 K vortices move plastically due to the replacement of collective pinning by individual pinning from larger centers.[16]

Among the numerous studies on pancake vortices, the properties near the sample surface have been of a special interest. Recently, Grigorenko *et al.*[17] considered the tilt of pancake vortex stacks and pointed out that the vortex line tension near the sample surface will become smaller (compared to the bulk value) due to the absence of the vortices above the sample. Mints, Kogan, and Clem investigated possible termination of pancake vortices near the surface in samples of finite size.[18] Furthermore, in a number of experiments such as those using the decoration technique or various kinds of microscopes, vortices are often detected on the cleaved surface of the Bi-2212 crystals. In these cases, vortices in the topmost superconducting plane that exposes to various environments are expected to behave differently compared to those in the bulk since the plane may have a certain deteriorated superconducting property and there are no vortices above it.

In this paper, we investigate the properties of dilute vortices in the surface plane of Bi-2212 crystals by measuring the Josephson critical current I_c' of the surface IJJs,[19] which are formed between the two outmost superconducting planes.[20–22] The study is based upon the fact that pancake vortices in the two planes can be easily displaced by an exerting force from the magnetic-field change so that Josephson vortices appear between them. This results in a substantial decrease of I_c'. Useful informations on the surface vortex structure and pinning, which are otherwise difficult to be distinguished from the bulk ones, have been obtained from the field, temperature, and history dependencies of I_c'.

Samples with intentionally changed, controllable T_c' and I_c' are fabricated[19] to model the deteriorating situation of the surface plane by adjusting its doping level.[21,22] From our experiments, we find that surface vortices behave similarly as the bulk ones at low temperatures, but differently at higher temperatures. Qualitatively, distinctive behaviors for the surface vortices are detected in three temperature ranges, which point to different pinning mechanisms in action. Below 20 K, strong collective pinning is observed. In the intermediate temperatures, pinning is dominated by fewer but larger defects. At higher temperatures, the pinning force becomes

TABLE I. Basic sample parameters.

	T_c(K)	T'_c(K)	$I'_c(0)(\mu\text{A})$	S (μm^2)
A	88	66	140	10×10
B	88	66	120	$\pi\times 5^2$
C	88	77	180	10×10
D	88	77	310	12×12

weak and surface vortices start to depin from defects by thermal fluctuations. An important observation of the present work is that depinning for the surface vortices can occur at a much lower temperature than that for the bulk ones, and it depends on the deteriorating situation of the surface plane.

In the following section, we shall describe our sample fabrication and measurement techniques. Results and discussion are presented in Sec. III. Section IV is a conclusion.

II. EXPERIMENT

Our study was carried out on mesa-structured IJJs fabricated on Bi-2212 crystals grown by the floating-zone method. Small crystals, roughly $0.6\times 0.6\times 0.05$ mm^3 in size, were glued onto the Si substrates. Au films of about 50 nm in thickness were evaporated onto the fresh surface immediately after the cleavage of the crystals at liquid-nitrogen temperature in vacuum, which resulted in the ideal Au/Bi-2212 interface and therefore ideal surface IJJs. The definition of the mesa area was performed via conventional photolithographic patterning and Ar ion-beam etching, as described in detail elsewhere.[21,22]

The basic parameters of the four mesas on separate crystals used in the present experiment are listed in Table I. Sample A had an area S of 10×10 μm^2 (square-shaped). The superconducting transition temperature T_c of the crystal was 88 K. By using a lower evaporation rate of the Au films, we obtained a transition temperature T'_c of 66 K for the surface superconducting plane.[21,22] Hence, the surface IJJ of the sample had two electrodes of different transition temperatures and a reduced value of $I'_c\sim 140$ μA measured at 4.2 K. Sample B was the same as A except for its circular shape. The bulk crystal property of samples C and D was the same as those of samples A and B, but the evaporation rate of the Au film was adjusted higher to yield higher T'_c and I'_c/S values.

I-V curves were measured and recorded by an oscilloscope in three-terminal configuration. A special circuit was designed for the compensation of the lead resistance as well as possible Au/Bi-2212 interface resistance to give the vertical zero-voltage I'_c. Most measurements were performed with the applied field below 200 G, which was supplied by a 100-turn coil, 12 mm in diameter, wound up using 0.13-mm-thick Cu wire. The coil and sample substrates were fixed on the same surface of the Cu block in sample chamber, with the mesa placed near the center of the coil. This arrangement assured a good alignment of the field in the direction perpendicular to the junction plane. Since the ratio of the coil diameter to the junction size was over 1000, the field could be considered as homogeneous in the junction area. For the field above 200 G, a larger coil placed outside the sample chamber with its direction carefully adjusted was used. Misalignment between the field and c-axis was found to be negligible in both cases. This was confirmed from the measurements on I'_c during cooling with and without a fixed applied field. Both measurements showed nearly the same I'_c at low temperatures, indicating that there were no Josephson vortices appearing as a result of the field misalignment.

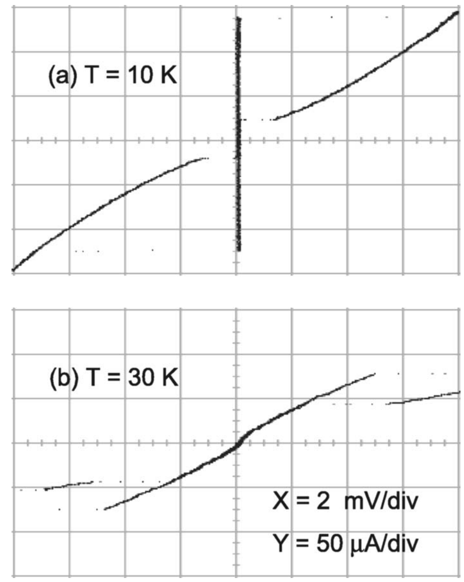

FIG. 1. (a) *I-V* curve of the surface IJJ of sample A measured at 10 K during cooling down from room temperature with a 100-G field applied perpendicular to the junction plane. At 4.2 K, the field is removed. As the temperature increases from 4.2 K up to about 20 K, the *I-V* curve does not show much change. Above 20 K, it changes suddenly and dramatically, with the critical current reduced almost to zero. (b) The result recorded at 30 K.

III. RESULTS AND DISCUSSION

In Fig. 1, we show a typical result obtained from sample A. An out-of-plane magnetic field $B=100$ G is first applied at room temperature, and the sample is cooled down to 4.2 K slowly. Figure 1(a) shows the *I-V* curve at 10 K recorded during cooling. At 4.2 K, the field is turned off, upon which the *I-V* curve does not show a noticeable change, and it changes only slightly as the temperature increases up to $\sim$20 K. Above the temperature, however, the *I-V* curve shows a sudden and dramatic change. A result measured at 30 K during warming is shown in Fig. 1(b) from which we can see that I'_c is suppressed almost to zero. When the temperature further increases, I'_c will start rising again near 45 K and above 57 K, it decreases steadily to zero where the temperature reaches T'_c.

In Fig. 2(a), the overall temperature dependence of I'_c up to T'_c recorded during warming the sample is shown as a line with solid squares. The usual temperature dependence of I'_c in the absence of the field is also shown for comparison (line with open squares). From the figure, we can see that for

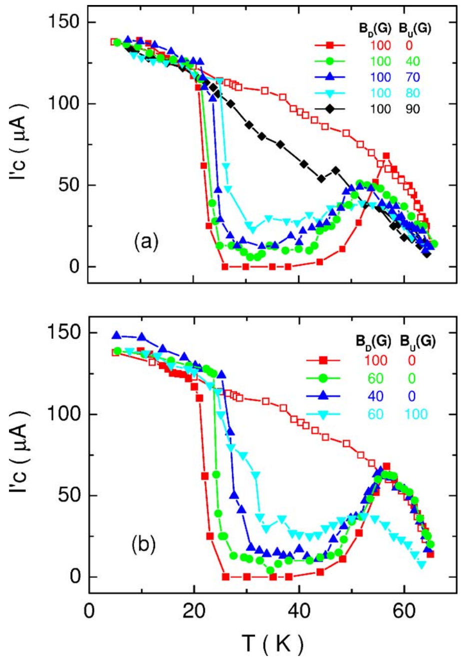

FIG. 2. (Color online) Temperature dependence of the critical current of the surface IJJ of sample A measured during warming under applied field B_U. The sample is first cooled down in the field B_D. (a) With the same $B_D = 100$ G. (b) With different B_D values. Lines with open squares are the results obtained in the absence of the field.

temperatures below 20 K or above 57 K, the two curves almost merge together. However, in the temperature range of $20 \sim 57$ K, I_c' can have a considerable decrease. These results, obtained from an interplay with magnetic field and temperature, indicate two clear transitions near 20 and 50 K among different vortex structures.

A. Transition around 20 K

Many authors have considered the effects of trapped (Abrikosov) vortices on the critical current of a Josephson junction both theoretically and experimentally.[23–25] There can be three types of vortices trapped in Josephson junctions: straight vortex lines, kinked or bent vortex lines, and vortices captured only in one electrode. The straight vortex lines influence the critical current via "core mechanism." Namely, the decrease of the critical current is proportional to the core area of vortices, which can be negligible when the vortex density is small.

Our results for temperatures below 20 K, as discussed above should belong to this case. After field cooled to 4.2 K where thermal fluctuation plays a trivial role, vortex lines exist in a near straight-line state with magnetic interaction and Josephson coupling to keep the pancake vortices in different planes aligned, as is schematically shown in Fig. 3(a). In the case of the Bi-2212 material, the in-plane coherence length ξ_{ab} is on the order of 3 nm so that the total core area of the pancake vortices under a 100-G magnetic field is around 1.4×10^{-2} μm^2 for the present junction area of 100 μm^2. This leads to an area ratio of 1.4×10^{-4} between

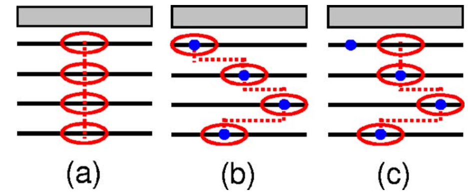

FIG. 3. (Color online) Three possible vortex states near the sample surface. Grayish rectangles and solid lines are the Au films and CuO_2 double layers respectively. Ellipses are vortex pancakes and dots are defect pinning centers. (a) Straight vortex line pinned collectively at low temperatures. (b) Vortex line bent under magnetic pressure and pinned by point defects at intermediate temperatures. (c) At higher temperatures, depinning occurs first at the surface plane, leading to the realignment of the pancakes in the top two planes.

the vortex cores and the junction. Hence, I_c' does not have a noticeable change in the cases with and without vortices. When the field is removed at 4.2 K, vortices are pinned strongly to overcome the repulsive force between them and I_c' remains the same. Tiny oxygen defects are believed to be the dominating pinning centers in this case,[16] and because of their high density many oxygen defects act collectively on individual vortex lines, which provide a strong pinning strength.

When the temperature exceeds 20 K, I_c' decreases rapidly, which we believe should result from the bending of vortex lines in the second-or third-type configuration discussed above. In the simplest situation of one bent flux line [see Fig. 3(b)], there are two vortex pancakes existing in the top two superconducting planes, misaligned and connected by a Josephson string. The critical current change $\Delta I_c'$ in this case is given by $\Delta I_c'/I_c' \propto (a/W)^2$, where a is the horizontal distance between the two misaligned pancake vortices and W is the junction width.[23,24] Thus, when a is of the order of W, I_c' can be reduced almost to zero, as in the present case shown in Fig. 2(a).

The bent or kinked vortices above 20 K appear as a result of the weakening of the pinning force, which causes the vortices to move in different directions under an exerting force from the magnetic-field change. Some vortex lines can move out of the junction and others may still stay pinned at random locations, forming the bent or kinked structure. Tonomura *et al.*[16] suggest some larger and sparser defects to be the pinning centers in this temperature range because the vortices move plastically contrary to the manner at lower temperatures where vortices move slowly and smoothly.

It is interesting to note that a similar crossover of the pinning mechanisms have also been observed in the magnetization,[11,12] ac transverse permeability,[13,14] and Campbell penetration depth measurements.[15] In these experiments, the applied field was higher and was not removed, and the crossover reflects the influence of thermal fluctuation and pinning center on vortex lattice. In view of Larkin's collective pinning theory,[4] the pinning correlation length L_c is shorter than the plane spacing d at low temperatures and the lattice is in the strong pinning regime. As the temperature rises so that L_c increases and becomes larger than d, the lattice switches into the weak pinning regime.[26]

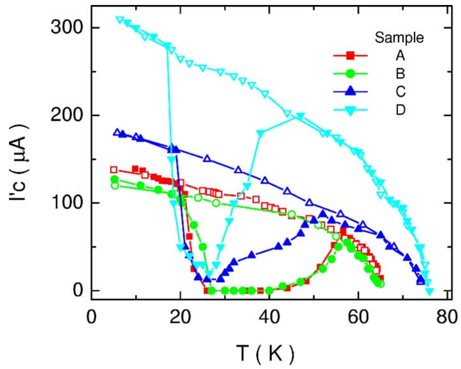

FIG. 4. (Color online) Critical current versus temperature for four samples A, B, C, and D measured during warming with $B_U=0$. Samples are first cooled down in the field $B_D=100$ G. Lines with open symbols are the zero-field results.

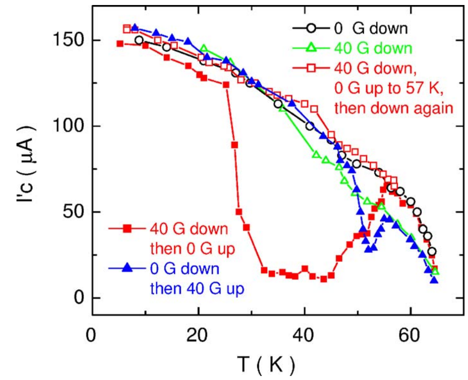

FIG. 5. (Color online) Critical current of the surface IJJ versus temperature for sample A, obtained in several different measurements as indicated in the figure.

In our experiment, the transition between the different vortex structures near 20 K is found to be well defined. In the measurement described above, if we do not remove the field at 4.2 K but at 23 K, we can observe a quick change of the *I-V* curves [from Fig. 1(a) and 1(b) similarly] and a reduction of critical current to the same level as shown in Fig. 2(a) at the corresponding temperature. However, if we remove the field at 18 K, the *I-V* curve will not show any change.

Experimentally, it does not need the complete removing of the field for the observation of the transition near 20 K since the straight vortex lines will move and bend if the exerting force on the vortices after the magnetic-field change is larger than the pinning force. In Fig. 2(a) we plot the corresponding temperature dependence of I_c' when the field is reduced to several different values, from which we can see that the transition shifts towards higher temperatures for smaller field reduction, and a field reduction of 20 G (line with down-triangles) seems enough for the clear bending of the vortex lines. In Fig. 2(b), we show the temperature dependence of I_c' measured during warming after the sample is first cooled in the fields of 100, 60, and 40 G, respectively. The line with down triangles shows the I_c'-T dependence on warming where the applied field is 60 G during cooling and increases up to 100 G at 4.2 K. In this case, the bent vortices are formed under a compulsive force instead of the previous repulsive one.

The transition near 20 K has been observed also for the other samples listed in Table I, which we show in Fig. 4. These results demonstrate that the transition is rather general, almost independent of the sample parameters. Since it has been observed in the other measurements on bulk vortices,[11–15] the results indicate that surface vortices have similar behaviors as the bulk ones in this temperature range, as is shown in Figs. 3(a) and 3(b).

B. The second transition

The results in Fig. 2 also show a second transition between different vortex structures near 50 K. For the result shown as a line with solid squares, for instance, following a sharp drop at about 20 K the critical current I_c' will keep its suppressed value until 45 K. After that it begins to rise until 57 K where it reaches the value obtained in the absence of the magnetic field (line with open squares). In Fig. 4, similar behaviors can be seen also for the other samples. But unlike the first transition near 20 K, the second transition apparently occurs at different temperatures for samples with different surface-layer parameters.

To understand further the behavior near and above the transition, we show in Fig. 5 some additional measurements on sample A. The line with solid squares is the I_c' result measured on warming up to 64.5 K (1.5 K below T_c') after the sample is cooled under a field of 40 G which is later removed at 4.2 K. During warming, if we stop at above 57 K and start cooling the sample again, the measured I_c' will be represented by the line with open squares, which basically follows the result without the field (line with open circles). In contrast, if we stop and start cooling the sample at a lower temperature, say 45 K, I_c' will keep its suppressed value at that temperature and remain unchanged down to 4.2 K. (The results are not shown in the figure for clarity.) In this case, the kinked structure of the vortices is believed to be sustained during the cooling process.

Also shown in Fig. 5 is the I_c'-T dependence measured during field-cooling under 40 G (line with open triangles). In the low temperature range the data almost equal the zero-field values (line with open circles). At higher temperatures, however, they become smaller, which is believed to result from the vortex misalignment induced by thermal fluctuations. In the intermediate temperatures, both thermal fluctuations and random pinning centers can cause misalignment of the vortex lines and reduce the phase coherence along the c axis, as discussed by Daemen *et al.*[27,28] based upon an extension of the work of Miller *et al.*[23]

The line with solid triangles in Fig. 5 is the result measured during warming after first cooled down in zero filed and a 40-G field is applied later at 4.2 K. We see that at about 48 K the field can penetrate the sample (see Sec. III E), forming vortices with kinked structure. I_c' becomes smaller than the zero-field values and even crosses the line with open triangles. Above 57 K, the two lines with solid and open triangles merge together, as is case for the lines with solid and open squares near 57 K. The merging of the

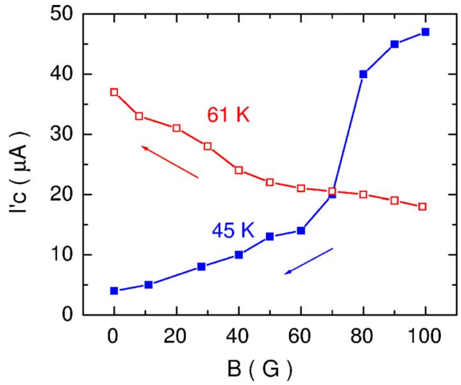

FIG. 6. (Color online) Critical current of sample B recorded during decreasing the field after first cooled from above T_c to the indicated temperatures in $B_D=100$ G.

lines indicates that above 57 K, I_c' is basically a function of the applied field only and does not depend on the history.

C. Depinning of the surface-layer vortices

A history-independent behavior would imply a negligible pinning in both or either of the top two superconducting planes forming the surface IJJ so that vortices are always aligned there. Further measurements on additional *I-V* branches from the inner IJJs show that, while I_c' fully recovers to its zero-field values at the end of the second transition (see, e.g. Fig. 4), I_c remains suppressed roughly at a third of the zero-field values at the corresponding temperatures and a full recovering can only be seen very near $T_c=88$ K. Therefore defect pinning is still effective in the inner planes in this temperature range but should be negligible in the surface plane. A picturized view near the second transition is shown in Figs. 3(b) and 3(c).

To get a more detailed view on the depinning process of the surface-layer vortices, we show in Fig. 6 the results on I_c' with decreasing field obtained from sample B, which illustrate a clear difference for temperatures below and above the second transition (samples B and A have almost the same properties except their geometric shape, see Table I and Fig. 4). The sample is first cooled in a 100-G field to 45 and 61 K, respectively. From the figure, we can see that at 45 K, I_c' decreases with decreasing field. The curve in the figure is obtained with the field decreasing step by step at the values indicated by the solid squares. It is history dependent and would pass a different route if the steps are different. At this temperature, bent vortex lines are created by the changing field and pinned by the defects, as is depicted in Fig. 3(b). The situation at 61 K, on the other hand, is completely different: I_c' increases continuously with decreasing field and would also follow the curve when the field increases and then decreases again. This is so at least for the field above 40 G (at lower fields, I_c' has a swift decrease/increase within 1 s). In this case, vortices in the surface plane are not pinned by defects. They will move freely and align themselves with those in the plane below, as is shown in Fig. 3(c).

How the qualitatively different results at 45 and 61 K evolve between each other, namely, in the temperature range

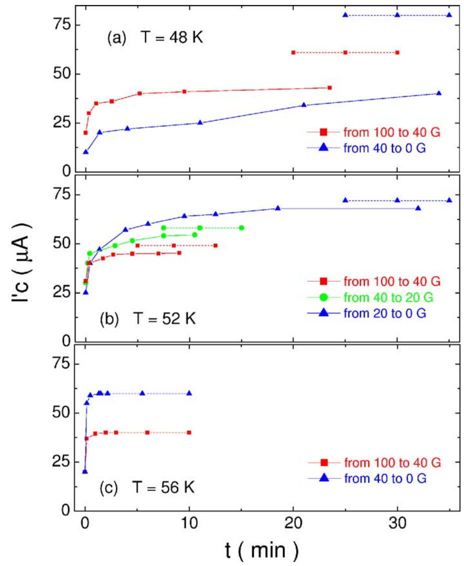

FIG. 7. (Color online) I_c' versus time for sample B after cooled to three different temperatures of (a) 48 K, (b) 52 K, and (c) 56 K in a 100-G field, and then decreasing the field to different values as indicated in the figure (solid lines). Dashed lines represent the "equilibrium" I_c' values with bending-free vortices.

where the second transition occurs? We find that they have a continuous change in the time domain. If we perform a measurement similar to the ones in Fig. 6 but at a temperature, say, 52 K, I_c' will decrease first when the field reduces to a certain value. Then it will increase with time and approach the value in the fixed field without vortex bending, namely, the I_c' value obtained from field cooling above T_c to 52 K. Detailed time dependence of I_c' at three temperatures are plotted in Fig. 7 for several field reductions. In the figure, the dashed lines are the results with bending-free vortices in the corresponding field. It is clear that I_c' changes with time faster at higher temperatures [from (a) to (c) in Fig. 7] and also for field reductions in the higher field ranges [see Fig. 7(b)]. In the case of Fig. 7(c) at 56 K, we also measured the time dependence of I_c' for the field reductions from 150 to 100 G and from 200 to 150 G. It is found that I_c' soon changes very fast and follows the field change instantly. It turns out to increase with decreasing field, just as the results measured for temperatures above the second transition do. These results indicate that there is also a field boundary (between 100 and 150 G at 56 K), in addition to the temperature boundary, above which vortex pinning by defects in the surface plane becomes negligible. Both boundaries may be seen approximately as the field and temperature values below (above) which a decrease of I_c' when partly reducing the field can(not) be observed.

D. Sample dependence and discussion

As can be seen in Fig. 4, the second transition for samples C and D occurs at temperatures considerably lower than those for samples A and B. From Table I, we can see that the bulk superconducting property for all the samples is the same. The difference for samples C and D is that the Au film is evaporated at a higher speed onto the cleaved sample surface, resulting in less residual-gas molecules involved at Au/Bi-2212 interface[21,22] and therefore in higher T_c' and I_c'. These have two consequences. Firstly, the surface planes should have less defects and be more ideal from the crystal structure point of view. Therefore, defect pinning becomes weaker. Secondly, Josephson coupling in the surface IJJs becomes stronger. Both of them tend to make it easier for the surface vortices to align themselves with the underlying ones [namely, from Fig. 3(b) to 3(c)].

Experimentally, unlike the results of samples A and B, the vortex states for samples C and D in the temperature range between the first and second transitions appear quite unstable on the oscilloscope screen, with I_c' occasionally jumping to a higher value and then back again. Also, in Fig. 4, I_c' for samples C and D shows the recovering from its suppressed values soon after the first transition near 20 K, whereas samples A and B keep their suppressed values to higher temperatures.

On the other hand, the I_c' recovering of sample D is seen to continue all the way up until the end of the second transition, while for sample C there is a slowdown. From these results, sample D seems to have a more ideal surface-layer structure compared to sample C, although both are fabricated with the same experimental parameters. We have observed the similar results of sample C in several other samples, and it is possible that there are few accidental defects on the surface plane in these cases, originally existing or produced during sample fabrication. The functioning of these defects is still observable after the second transition, seen as a small difference between the two lines with solid and open up triangles in the temperature range of 52 to 60 K in Fig. 4.

Measurements on the I_c' change for sample C with partial field reduction in the field and temperature ranges of interest reveal a very different behavior compared to those of sample B. We can only observe a swift I_c' decrease for the field lower than 15 G at 48, 52, 56, and 60 K, and for temperatures above 60 K, I_c' always increases instantly with decreasing field. Similar to the previous discussion, depinning of the surface vortices from defects for sample C should occur above ~48 K for nearly all nonzero field.

In Fig. 8, we show the field dependence of I_c' (above the penetration field, see Sec. III E) for samples B and C after zero-field cooled to several temperatures. During the measurements, the data were taken at about 3 min after each field increase, which therefore represent the results with the surface vortices having basically depinned from the defects. It can be seen that the dependence is basically linear for both samples on the logarithmic plotting. If we use a power-law dependence of $I_c' \sim 1/B^{\alpha}$, α is found to be 0.3 for sample B and is in a range of $0.7 \sim 1.0$ for sample C.

There are many theoretical and experimental discussions on the influences of the vortex state on α. For a poor pancake alignment along the c axis, theoretical analysis indicates that α can be on the order of unity[29,30] or 0.5.[31] For better alignment, α is found to decrease.[29] Experimental results in a higher field have confirmed the power-law dependence with α in a range of 0.8–1, which is understood as resulting from the pancake liquid state.[6,9,32] In the lower-field regime, a reduced α is observed, which is attributed to a vortex lattice

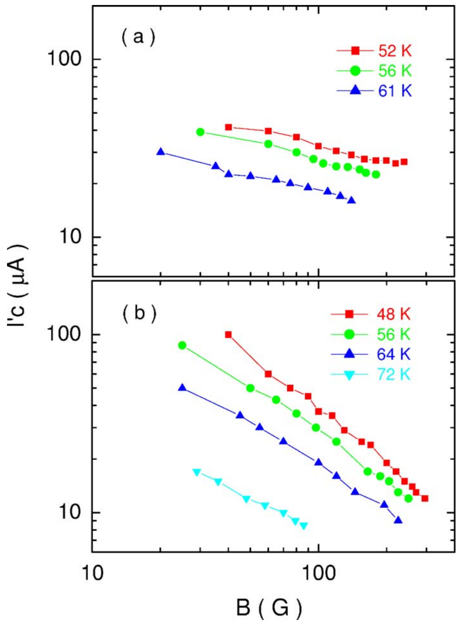

FIG. 8. (Color online) I_c' with increasing field on logarithmic scales for (a) sample B and (b) sample C after zero-field cooled to the indicated temperatures. Considering a power-law dependence of $I_c' \sim 1/B^{\alpha}$ leads to $\alpha = 0.3$ for the data in (a) and $\alpha = 0.7 \sim 1.0$ for the data in (b).

formation[8] or a weakly pinned vortex state.[9] Viewing from these results, the data in Fig. 8(b) may suggest that the surface vortices in sample C are in a "liquid" state relative to the underlying ones after their depinning from defects. This means that a surface vortex, though sitting averagely on an underlying one, is subject to thermal fluctuations with in-plane displacements exceeding, say, the pancake size. On the other hand, similar pancake displacements in sample B are much smaller, which is caused by some unknown and further weaker pinning source in replace of the defects. This may seem puzzling considering that the Josephson coupling for sample C is larger than that for sample B, which should reduce α and enhance a vortex solid-line formation. However, if the above speculation is true, then pinning is playing a more important role than Josephson coupling in the present case.

From the above discussions, we conclude that the introduction of impurity molecules will substantially influence the behaviors of the surface vortices by changing the (defect) pinning strength and layer couplings. In the case of an ideal surface, depinning can happen quickly, leaving a wide temperature range up to T_c' where the surface vortices can move easily (possibly in a melting state[33]) and align themselves on top of the underlying ones.

E. Penetration field

In the previous subsections, we have mentioned that for zero-field cooled samples, there exists a threshold field value B_p, below which I_c' does not change with field (see Fig. 5). Above B_p, I_c' first has a sudden drop and then decreases steadily with increasing field. In Fig. 9, the results of sample

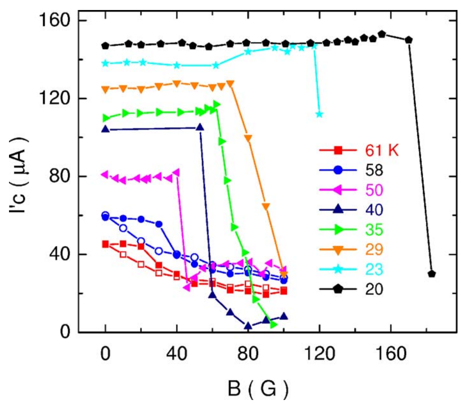

FIG. 9. (Color online) Magnetic-field dependence of I_c' of sample A after zero-field cooled to the indicated temperatures (lines with solid symbols). The two lines with open symbols are measured with decreasing field from 100 to 0 G after the sample is cooled to 58 and 61 K in a 100-G field (for comparison).

A measured in a wide temperature range is shown.

B_p, or $H_p = B_p/\mu_0$, has been discussed in much detail by several authors and is explained as the value for the magnetic field penetration into the sample.[34,35] It is experimentally found that H_p can depend on the speed of increasing the applied field. When the speed is low, the field penetration can happen via flux creep process, which causes H_p to decrease. For a vanishing speed, H_p will approach the values of the lower critical field H_{c1} of the sample. For the actual non-zero speed, many factors which can prevent the penetration of vortex lines into the sample, including Bean-Livingston surface barriers,[36] bulk pinning,[37] and geometrical barriers[38] have been considered.

In Fig. 10, we plot the temperature dependence of B_p in the range of 20 to 72 K for samples A, B, and C. All curves show an upturn feature with decreasing temperature, which agrees with many published results.[34,35] The upturn of B_p is believed to result from the bulk pinning crossover. The stronger the pinning, the more difficult it will be for the vortex penetration. Comparing these results, we find that the upturn of sample B, which is circular in shape, is stronger than the square-shaped samples A and C at temperatures below 25 K.

Wang *et al.*[35] have found that for the Bi-2212 materials, B_p depends on the sample size and geometry at all temperatures below T_c. In particular, the circular samples have a larger B_p than the square ones if their sizes are the same. In our experiment, the mesa sizes are nearly the same for samples A, B, and C (see Table I and Ref. 19). It can be seen from Fig. 10 that the results for the two square samples A and C do not show much difference in the entire temperature range. The circular sample B has a larger B_p at low temperature, consistent with the observations of Wang *et al.*,[35] but its result merges into those of samples A and C above 25 K. The reason for this is presently not clear.

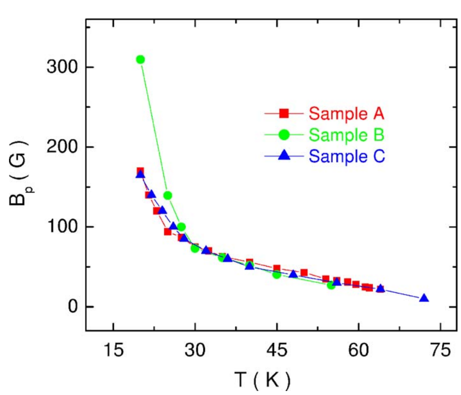

FIG. 10. (Color online) Penetration field B_p as a function of temperature for samples A, B, and C.

IV. CONCLUSION

The surface IJJs on the Bi-2212 crystals have been used to detect the properties of pancake vortices on the sample surface by measuring the changes of I_c' resulting from the displacements of vortices in the two superconducting planes. Two clear transitions demonstrating pinning crossovers with increasing temperature have been observed for the surface vortices. Trapped dilute vortex lines, prepared by field cooling to temperatures below ~20 K, are pinned collectively and can exist stably under a magnetic pressure. Above ~20 K, they become unstable and easily switch to a kinked structure as a result of the weakening of pinning. Further increasing the temperature leads to the depinning of the surface vortices. It is found that the depinning for the surface vortices can occur at a much lower temperature than that for the bulk ones, depending on the surface-layer crystalline perfectness or the density of point defects that have been intentionally introduced experimentally. These results can be useful for a number of surface-sensitive experiments designed to detect the vortex properties in the Bi-2212 materials.

Mints, Kogan, and Clem[18] found that pancake vortex stacks existing in the bulk may terminate near the surface in samples of finite size. Such a termination is energetically favorable and can occur for samples smaller than a characteristic length R_c. In their work, R_c for the Bi-2212 materials is estimated to be 30 μm in the limit of zero Josephson coupling and will reduce to microns when Josephson coupling is taken into account. From this consideration, the termination will most probably happen in the surface layer of the mesa structure where the coupling is the weakest, and it should lead to a much reduced I_c' in a way less sensitive to the temperature. In the present work, we have not found the termination phenomenon in the four samples, which all have the size of ~10 μm. It will be interesting to carry on further investigation on the issue in micron- or sub-micron-sized samples which have become available recently.[39]

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[1] R. Kleiner, F. Steinmeyer, G. Kunkel, and P. Müller, Phys. Rev. Lett. **68**, 2394 (1992); R. Kleiner and P. Müller, Phys. Rev. B **49**, 1327 (1994).

[2] J. R. Clem, J. Supercond. **17**, 613 (2004).

[3] G. Blatter, M. V. Feigelman, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, Rev. Mod. Phys. **66**, 1125 (1994).

[4] M. Tinkham, *Introduction to Superconductivity* (McGraw-Hill, New York, 1996).

[5] S. Luo, G. Yang, and C. E. Gough, Phys. Rev. B **51**, 6655 (1995).

[6] A. Yurgens, D. Winkler, T. Claeson, G. Yang, I. F. G. Parker, and C. E. Gough, Phys. Rev. B **59**, 7196 (1999).

[7] A. Yurgens, M. Konczykowski, N. Mros, D. Winkler, and T. Claeson, Phys. Rev. B **60**, 12480 (1999).

[8] S. Ooi, T. Mochiku, and K. Hirata, Physica C **378-381**, 523 (2002); **362**, 269 (2001); K. Hirata, S. Ooi, and T. Mochiku, *ibid.* **335**, 139 (2000).

[9] M. Suzuki, T. Watanabe, and A. Matsuda, Phys. Rev. Lett. **81**, 4248 (1998).

[10] N. Morozov, L. N. Bulaevskii, M. P. Maley, Y. I. Latyshev, and T. Yamashita, Phys. Rev. B **62**, R14681 (2000).

[11] M. Nideröst, A. Suter, P. Visani, A. C. Mota, and G. Blatter, Phys. Rev. B **53**, 9286 (1996).

[12] C. D. Dewhurst and R. A. Doyle, Phys. Rev. B **56**, 10832 (1997).

[13] M. F. Goffman, J. A. Herbsommer, F. de la Cruz, T. W. Li, and P. H. Kes, Phys. Rev. B **57**, 3663 (1998).

[14] V. F. Correa, J. A. Herbsommer, E. E. Kaul, F. de la Cruz, and G. Nieva, Phys. Rev. B **63**, 092502 (2001).

[15] R. Prozorov, R. W. Giannetta, N. Kameda, T. Tamegai, J. A. Schlueter, and P. Fournier, Phys. Rev. B **67**, 184501 (2003).

[16] A. Tonomura, H. Kasai, O. Kamimura, T. Matsuda, K. Harada, J. Shimoyama, K. Kishio, and K. Kitazawa, Nature (London) **397**, 308 (1999).

[17] A. N. Grigorenko, S. J. Bending, I. V. Grigorieva, A. E. Koshelev, T. Tamegai, and S. Ooi, Phys. Rev. Lett. **94**, 067001 (2005).

[18] R. G. Mints, V. G. Kogan, and J. R. Clem, Phys. Rev. B **61**, 1623 (2000).

[19] In our experiment, there are usually 10 IJJs in a mesa-structured junction stack. In the stack, all the inner superconducting planes have the bulk T_c values. However, the topmost plane has a reduced value $T_c' < T_c$ due to its contact with the Au wiring and to its intentionally reduced doping level. In this work, "the surface plane (or layer)" will be referred to as this plane and "the surface vortex" as that in this plane. We also use I_c' to denote the Josephson critical current of the surface IJJ having two different superconducting electrodes with T_c' and T_c. Clearly I_c' is smaller than I_c for the inner IJJs which all have identical electrodes with the same T_c. See Refs. 21 and 22.

[20] N. Kim, Y. J. Doh, H. S. Chang, and H. J. Lee, Phys. Rev. B **59**, 14639 (1999).

[21] X. B. Zhu, S. P. Zhao, G. H. Chen, H. J. Tao, C. T. Lin, S. S. Xie, and Q. S. Yang, Physica C **403**, 52 (2004).

[22] S. P. Zhao, X. B. Zhu, Y. F. Wei, G. H. Chen, Q. S. Yang, and C. T. Lin, Phys. Rev. B **72**, 184511 (2005).

[23] S. L. Miller, K. R. Biagi, J. R. Clem, and D. K. Finnemore, Phys. Rev. B **31**, 2684 (1985).

[24] A. A. Golubov and M. Y. Kupriyanov, Sov. Phys. JETP **65**, 849 (1987).

[25] V. N. Gubankov, M. P. Lisitskii, I. L. Serpuchenko, F. N. Sklokin, and M. V. Fistul, Supercond. Sci. Technol. **5**, 168 (1992).

[26] J. Kierfeld, Phys. Rev. B **69**, 144513 (2004).

[27] L. L. Daemen, L. N. Bulaevskii, M. P. Maley, and J. Y. Coulter, Phys. Rev. Lett. **70**, 1167 (1993).

[28] L. L. Daemen, L. N. Bulaevskii, M. P. Maley, and J. Y. Coulter, Phys. Rev. B **47**, 11291 (1993).

[29] L. N. Bulaevskii, V. L. Pokrovsky, and M. P. Maley, Phys. Rev. Lett. **76**, 1719 (1996).

[30] A. E. Koshelev, Phys. Rev. Lett. **77**, 3901 (1996).

[31] E. H. Brandt and E. B. Sonin, Phys. Rev. B **66**, 064505 (2002).

[32] T. Shibauchi, T. Nakano, M. Sato, T. Kisu, N. Kameda, N. Okuda, S. Ooi, and T. Tamegai, Phys. Rev. Lett. **83**, 1010 (1999).

[33] Ooi *et al.* find that the melting field will become lower when the measurement current (or I_c) is higher (Ref. 8). In the present experiment, we have confirmed that I_c', which is much smaller than I_c, does not affect the detected vortex properties. This can be done by comparing the results with zero or none-zero sweeping current before a vortex state is prepared.

[34] M. Nideröst, R. Frassanito, M. Saalfrank, A. C. Mota, G. Blatter, V. N. Zavaritsky, T. W. Li, and P. H. Kes, Phys. Rev. Lett. **81**, 3231 (1998).

[35] Y. M. Wang, A. Zettl, S. Ooi, and T. Tamegai, Phys. Rev. B **65**, 184506 (2002).

[36] C. P. Bean and J. D. Livingston, Phys. Rev. Lett. **12**, 14 (1964).

[37] C. P. Bean, Phys. Rev. Lett. **8**, 250 (1962).

[38] E. Zeldov, A. I. Larkin, V. B. Geshkenbein, M. Konczykowski, D. Majer, B. Khaykovich, V. M. Vinokur, and H. Shtrikman, Phys. Rev. Lett. **73**, 1428 (1994).

[39] X. B. Zhu, Y. F. Wei, S. P. Zhao, G. H. Chen, H. F. Yang, A. Z. Jin, and C. Z. Gu, Phys. Rev. B **73**, 224501 (2006).