Current-driven vortex state in $Bi_2Sr_2CaCu_2O_{8+\delta}$ with columnar defects

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The effects of applied current on the vortex-lines dynamics in heavy-ion-irradiated $Bi_2Sr_2CaCu_2O_{8+\delta}$ are studied through Monte Carlo simulation. From the analysis of current-voltage characteristics, we find a clear peak effect in the critical current density, prominent near the melting transition of the vortex solid, when the magnetic field is increased toward the matching field. The peak field corresponds to a fractional ($\approx 1/3$) filling factor of the vortices to columnar defects. This enhanced vortex pinning occurs simultaneously with a rapid change in the interlayer-coupling nature of the current-driven vortex state. In addition, numerical results on current-driven moving vortex lines could also explain other anomalies obtained from the recent Josephson plasma measurements. [S0163-1829(99)03637-6]

The nature of disordered vortex matter and vortex pinning is a vital topic in studies of high-T_c superconductors.[1] Among other things, topologically line defects such as columnar defects (CDs) produced by heavy-ion irradiation are known to yield a low-temperature glassy phase of vortices, called Bose glass (BG), resulting in a large critical current J_c under magnetic field B. The existence of BG phase has been confirmed by theoretical[2] and experimental[3–5] analyses based on the temperature-driven continuous melting transition into vortex liquid (VL). Nevertheless, many unusual behaviors related to the c-axis vortex correlation have recently been reported and are being actively debated, in the vicinity of the melting or freezing transition of BG.

Josephson plasma resonance (JPR) measurements on irradiated $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) (Refs. 6,7) first suggested that two kinds of VL with different c-axis correlations may exist, based on the observation of double JPR peaks. The paper argued that the pancake vortex gas decomposed at low field may exhibit a dramatic phase change into partially linelike liquid, as the field increases towards the matching field B_Φ, just above the irreversibility line (IL). The numerical simulation[8] supports this scenario to demonstrate that a field-driven type of interlayer coupling transition occurs in the VL phase at a specific coupling field $B_{cp} \approx B_\Phi/3$. Also, the c-axis electric resistivity[9] and reversible magnetization[10] show dip anomalies around the coupling field, that may be partially interpreted as entropy reduction due to partial alignment of vortices along CDs.

Furthermore, in the low-temperature BG phase, quite recent irreversible magnetization measurements[10–12] revealed that an anomalous magnetization peak manifests itself in a high-temperature range just below IL, implying a novel peak effect in $J_c(B)$ as a function of B. Such nonmonotonic behavior of J_c cannot be explained from the collective pinning theory[1,2] which usually predicts monotonic magnetic field dependence of $J_c(B) \propto 1/B$ for $B < B_\Phi$. Experimentally, the peak field B_{pk} scales with B_Φ, and B_{pk} almost coincides with the above B_{cp} in the VL phase. Thus, the interlayer coherence of the vortex state can give crucial clues to explain the peak effect of J_c in the nonequilibrium glassy phase (*irreversible* regime), but the direct relationship remains unclear for the solid phase, in comparison with the well-developed JPR theory[13] for the high-temperature VL phase.

In this work, we simulated the current-voltage (I-V) characteristics of a BSCCO model with *randomly distributed* CDs ($\parallel c$ axis), by using Monte Carlo (MC) dynamics at finite temperatures. Focusing on the field dependence of I-V curves that obey the BG scaling law, we obtained direct numerical evidence for a sharp peak effect in $J_c^{ab}(B)$ at $B_{pk}/B_\Phi \approx 1/3$, in excellent agreement with the magnetization study. For the VL phase, a remarkable dip appears in the in-plane Ohmic resistivity $R^{ab}(B)$ at the same $B = B_{pk}$. We found that such definite signs of a reduction in the vortex mobility occur simultaneously with a rapid change in the interlayer-coupling nature of the current-driven vortex state. Such a change could also explain unusual experimental data of JPR (Refs. 14,15) for the low-temperature BG vortex state.

The BSCCO superconductor under the $B \parallel c$ axis is described by the vortex-variable representation[8,16] of the Lawrence-Doniach model.[17] We treat a Josephson-coupled stack of two-dimensional N_z superconducting layers including N_v pancake vortices on each layer, where pancake vortex coordinates $\{r_i(z)\}$ form the ith vortex-line ($i = 1,2,\ldots,N_v$) penetrating through all the layers. The in-plane inter-vortex repulsive interaction is given by a modified Bessel function $\epsilon_0 d K_0(|r_{ij}|/\lambda_{ab})$ with the magnetic penetration depth λ. We typically choose $\lambda_{ab} = 2000$ Å, the coherence length $\xi_{ab} = 10$ Å, layer thickness $d = 10$ Å, and the effective mass anisotropy $\gamma = \sqrt{M_c/M_{ab}} = 100$, where in-plane energy scale $\epsilon_0 d/k_B = 1000$ K. We also set $N_v = 16$ and $N_z = 40$, where periodic unit cells with image potentials are used on each layer. The CD ($\parallel c$ axis) is modeled[2] by the cylindrical potential well with a radius $c_0 = \xi_{ab}$ and depth $U_0 = (\epsilon_0 d/2)\ln[1 + (c_0/\sqrt{2}\xi_{ab})^2] = 343$ K [$\times k_B$], and we totally used ten random sets of CD configurations for the sample average. The density of CDs was fixed to be B_Φ

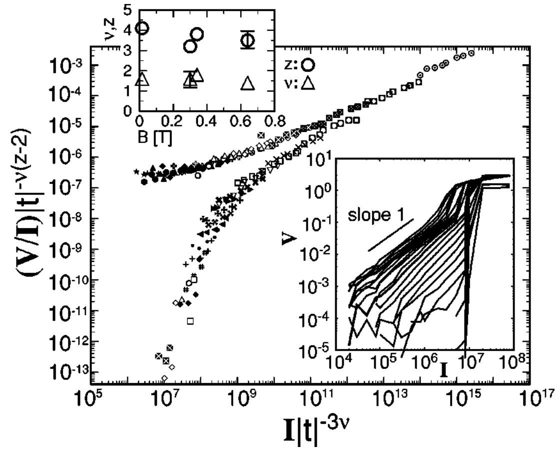

FIG. 1. Scaling plot of the I-V characteristics at the magnetic field $B=0.3$ T. The inset shows raw data at various temperatures ranging from 4.5 to 81 K: 4.5, 9, 13.5, and 18 to 81 K in 3K steps. They can be collapsed to two scaling curves with $T_{\rm BG}=52$ K, $\nu=1.6$, and $z=3.2$.

$=1$ T. I-V characteristics are calculated by newly adding a uniformly tilted potential $-(\Phi_0/c)z\times I\Sigma_i\Sigma_z r_i(z)$ with the Lorentz force of the applied current I driving vortices. The induced voltage V is obtained from the average vortex drift velocity v in the MC time scale,[18] through the Josephson relation $V=B\times v/c$, by following the earlier reports.[19,20]

A current-free $(I=0)$ MC study[8] showed that the BG melts into VL such that the Lindemann melting criterion holds, and the obtained melting line $T_{\rm BG}(B)$ is similar to the experimentally observed IL. Starting from this equilibrium vortex state, newly calculated I-V curves show the transition from Ohmic to non-Ohmic behavior around $T=T_{\rm BG}$, with decreasing T. The second-order phase transition theory of BG-VL melting[2] predicts that isothermal I-V curves should obey the scaling law of the resistivity $V/I=|t|^{\nu(z-2)}F_{\pm}(I|t|^{-3\nu})$, where ν and z stand for spatial and dynamical critical exponents, respectively, with reduced temperature $t=T/T_{\rm BG}-1$. Both $F_+(x)$ and $F_-(x)$ are universal functions with dimensionless x for $t>0$ and $t<0$, respectively. Indeed, the numerical I-V data at a fixed magnetic field nicely collapse into the upper (Ohmic) and lower (non-Ohmic) scaling branches, as typically shown in Fig. 1. We numerically obtained the critical exponents of $\nu=1.2$–1.8 and $z=3.2$–4.0 (see the upper inset), which seem insensitive to B in the field range of 0.015 T$\leqslant B \leqslant$0.64 T.[21] These values reflect the collective property of BG, in comparison with $\nu=1.1\pm0.2$ and $z=1.7\pm0.2$ from the MC simulation of the single vortex line,[19] and $z=6\pm0.5$ from that of the dirty boson model.[22] Our results also agree with the experimental results on Josephson-coupled layered superconductors with large anisotropy: $\nu=1.8\pm0.2$ (1.1 ±0.2) and $z=4.4\pm0.3$ (4.9 ± 0.2) from electric transport measurements for $Tl_2Ba_2CaCu_2O_8$ thin films with $B_\Phi=3.1$ T (0.2 T).[3,5]

The anomalous behaviors in question can be seen in the magnetic field dependence of the above vortex transport properties. First, the in-plane induced-voltage $V(B)$ derived from the Ohmic branch is shown in Fig. 2. A large dip structure appears near $B\approx B_\Phi/3$, implying a rapid decrease in the vortex mobility in the flux-flow state of the VL phase. The

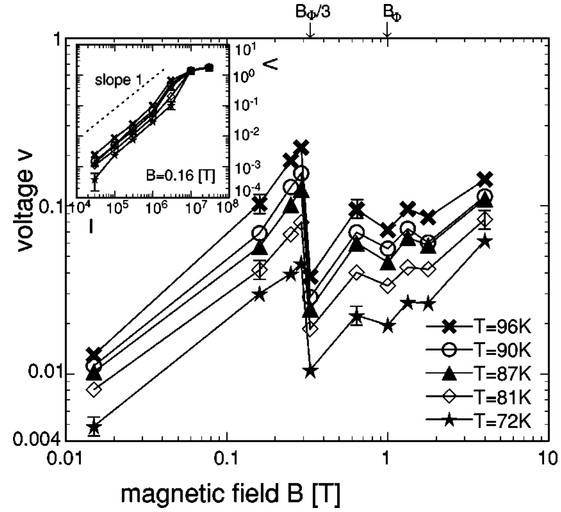

FIG. 2. In-plane induced-voltage for the vortex liquid phase at various temperatures: fixed current 1×10^6 [A/cm^2]. The inset shows the Ohmic characteristics.

reduced vortex mobility in the *ab* plane may suppress the phase slip between adjacent superconducting layers, through the weak but non-negligible interlayer Josephson coupling. As a result, a reduction of c-axis resistivity could also occur, as was experimentally observed above IL.[9]

Typical examples of the non-Ohmic branch of I-V curves at various magnetic fields are shown in the inset of Fig. 3. Non-monotonic behavior of J_c can be expected since the curves in a family cross each other. We set a threshold voltage (with criterion $V_c=10^{-2}$) to estimate the effective critical current density J_c from the calculated I-V curves. As is seen from Fig. 3, the obtained $J_c(B)$ at various temperatures exhibits a clear peak effect around $B\approx B_\Phi/3$. We find an additional bump in the vicinity of the integer filling $B/B_\Phi=1$, which may be thought of as remnant of the Mott insulator predicted at low temperature. Notably, the peak field $B_{\rm pk}\approx B_\Phi/3$ seems to be almost independent of temperature,

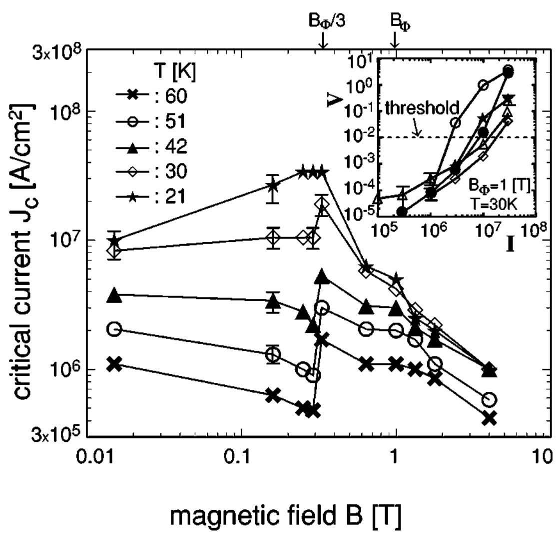

FIG. 3. Magnetic field dependence of the critical current density J_c at various temperatures. Inset: Nonlinear I-V characteristics below the melting temperature.

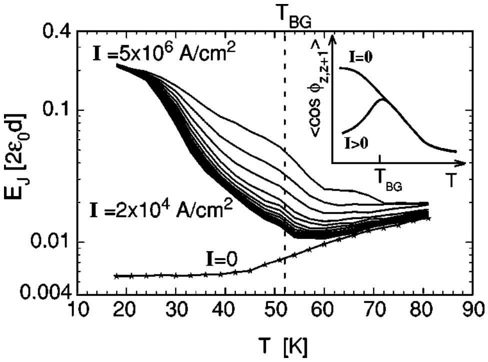

FIG. 4. Temperature dependence of the interlayer Josephson fluctuation energy at 0.3 T and various applied currents: $I=0$, 2, 3, 5, 8, 10, 20, 30, 50, 80, 100, 200, 300, 500×10^4 [A/cm^2]. Inset: schematic drawing of the interlayer phase coherence as a function of temperature.

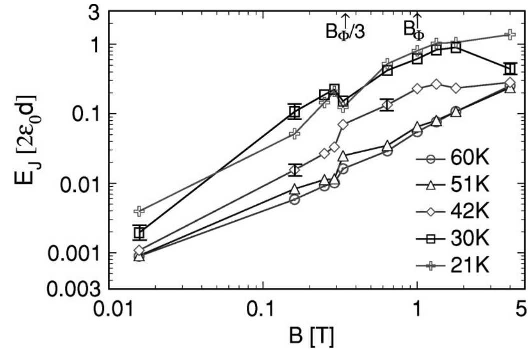

FIG. 5. Magnetic field dependence of interlayer Josephson fluctuation energy in the Bose glass phase: fixed current $I=3\times10^5$ [A/cm^2].

and these peaks become prominent at rather higher temperature close to the melting temperature $T_{\rm BG}(B)$. These numerical features are in striking agreement with the irreversible magnetization data.[10,11] Just at $B=B_{\rm pk}$, we also found a sudden increase in the average trapping rate of current-driven vortices to CDs, leading to an enhanced pinning force. While it looks similar to a sort of matching effect of 1/3 filling, there is a distinct feature that the defects are not regularly but randomly distributed, and conversely thermal fluctuations are important for the pinning force.

In order to directly examine the *c*-axis vortex correlation in the presence of driving current, we approximately calculated the interlayer Josephson fluctuation energy $\langle E_J\rangle \simeq(\epsilon_0/\pi d\gamma^2)(1-\langle\cos\phi_{z,z+1}\rangle)$, where $\phi_{z,z+1}$ represents the gauge-invariant phase difference between two adjacent superconducting layers, based on the average quasi-elastic energy part of vortex lines[16] $E_J=\Sigma_z(2s/\epsilon_0/\pi)[1+\ln(\lambda_{ab}/s)]\times(|r_{i,z+1}-r_{i,z}|^2/4r_g^2-1)$ for $|r_{i,z+1}-r_{i,z}|<2r_g$, and $E_J=\Sigma_z(2s/\epsilon_0/\pi)[1+\ln(\lambda_{ab}/s)]\times(|r_{i,z+1}-r_{i,z}|/r_g-2)$ otherwise, with Josephson string $r_g=\gamma\xi_{ab}$ and interlayer spacing s (we set $s=d$). As one result, we found a current-induced decoupling of the BG phase below the melting line. Figure 4 shows the temperature dependence of $E_J(T)$ ($B=0.3$ T) at various currents. In the absence of the applied current, $E_J(T)$ monotonically increases with increasing temperature. On the other hand, in the presence of the applied current, E_J in the Bose glass phase is very sensitive to the applied current, in contrast to the liquid phase, as is schematically drawn in the inset of Fig. 4. $E_J(T)$ (or $\langle\cos\phi_{z,z+1}\rangle$) shows nonmonotonic temperature dependence accompanied by a reentrant (or cusplike) behavior at $T=T_{\rm BG}$. In particular, as the temperature decreases below $T_{\rm BG}$, the interlayer fluctuations continue to grow rapidly, implying rapid loss of the interlayer coherence.

Experimentally, the JPR measurements exhibit a rapid decrease in the resonance field B_r when temperature T decreases below the IL, accompanied by a cusp on the IL [at $T=T_{\rm BG}(B)$].[14,15] Here, the resonance field B_r satisfies $\omega_p^2(B_r,T)=\omega_p^2(0,T)\langle\cos\phi_{z,z+1}\rangle$. This suggests a rapid decrease in the interlayer coherence with decreasing T, showing decoupling of layers in the glassy phase. So far, several mechanisms such as thermal depinning[23] and glasslike low-energy excitation modes[24] have been proposed, but they still remain controversial. Recently, Matsuda *et al.*[25] argued that the anomaly may be attributed to the nonequilibrium critical state in an irreversible regime, by noting that the critical currents in the Bean critical-state model (due to inhomogeneous field distribution) probably promote strong decoupling of vortex lines. The above numerical result provides direct evidence for the occurrence of stronger current-driven decoupling at lower temperature below the melting line. As temperature is increased, thermally depinned pancake vortices (zigzag structure) tend to form straight vortex-lines under the driving Lorenz force, thereby leading to a restoration of the interlayer coherence with increasing temperature. Therefore, the driving current plays a new and crucial role in determining the *c*-axis correlation especially for the irreversible regime of the BG vortex phase.

In Fig. 5, we also plot the field dependence of $E_J(B)$ for such a BG phase, with a fixed current $I=3\times10^5$ A/cm^2. Around the peak field $B_{pk}\approx B_\Phi/3$, we can see an upward (or downward) jump indicating a decoupling (or recoupling) transition along the *c* axis for $T\gtrsim30$ K (or $T\lesssim30$ K), thus implying a direct correlation between the *c* axis anomaly and the peak effect. Note that the current-free system shows only the decoupling transition at the BG phase.[8] From the JPR measurement on irradiated BSCCO, Hanaguri *et al.*[14] observed double JPR peaks only for $T\lesssim30$ K, in the BG phase. The origin of the unusual peak may be ascribed to the reentrant B dependence of E_J caused by the above recoupling transition; as the magnetic field is increased with a microwave frequency fixed at ω_f, the resonance may occur twice at two different fields, satisfying $\omega_p(B_{r1})=\omega_p(B_{r2})=\omega_f$, merely in the reentrant case. In addition, as should be expected in the case of a decoupling transition, there seems no double-peak anomaly for 30 $\text{K}\lesssim T\lesssim T_{\rm BG}$.

It is also interesting to note that the difference between the decoupling and recoupling transitions also appears in the field-dependent behavior of J_c (Fig. 3) in the lower field regime of $B<B_\Phi/3$. There the gradual increase in $J_c(B)$ occurs in the low-temperature range (below 30 K) of the recoupling transition, whereas the decrease in J_c occurs in the high-temperature range (above 30 K) of the decoupling transition. At sufficiently low field, since the intervortex interaction is negligible, J_c is determined by the depinning current of individually pinned vortices at CDs. At very low temperature, when the field increases, the untrapped vortices tend to be effectively pinned due to a cage effect[26] from intervortex

repulsive interactions, and as a result J_c may be an increasing function of B, with enhanced interlayer coupling of vortex lines. In contrast, for the high-temperature regime near the melting, thermal fluctuations may activate decoupled movement of untrapped pancake vortices in the presence of the driving current. Then $J_c(B)$ decreases with B for $B < B_\Phi/3$, which is then followed by the large trapping or pinning rate via the interlayer decoupling at $B \approx B_\Phi/3$. Thus, strong collaboration between thermal fluctuation and intervortex interaction is important for the peak effect and the c-axis vortex correlation as well, unlike other mechanisms including the dimensional crossover[27] in a pristine sample, and the matching effect[28] on regular defect arrays.

In summary, we carried out a dynamical Monte Carlo simulation of current-driven flux-lines in irradiated BSCCO and found a direct relationship between the CD-induced peak effect and c-axis interlayer coherence of the vortex state. The numerical results could illustrate the unusual critical state observed in the irreversible magnetization and JPR measurements, on which the driving current sheds new light.

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