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Staircase-type magnetic-field dependence of the activation energy of Josephson interlayer vortices in $Bi_2Sr_2CaCu_2O_8$

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The anomalous depinning of Josephson interlayer vortices in $Bi_2Sr_2CaCu_2O_8$ high-T_c superconductor occurring at nearly field-independent temperature $T_x = 20-40$ K has been studied by means of ac susceptibility measurements with magnetic field applied parallel to CuO_2 planes. From the frequency dependence $T_x(v_m)$ we define the flux-creep activation energy for Josephson vortices $U_{JV}(H)$ which increases with field and shows well-defined plateaus. In contrast, the activation energy of in-plane pancake vortices $U_{PV}(H)$ decreases with field, i.e., demonstrates a qualitatively different behavior.

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The characteristic feature of most high-T_c superconducting (HTS) cuprates is the Josephson coupling between superconducting CuO_2 layers (ab planes). A penetration of applied magnetic field ($H \| ab$) between weakly coupled CuO_2 planes in the form of Josephson vortices (JV) has unambiguously been demonstrated in superconducting quantum interference device (SQUID) imaging experiments.[1,2] The investigation of JV phases and transitions between them is one of the central aspects in the mixed state theory of layered superconductors. Thus, it has been predicted that an interplay between vortex lattice-layered atomic structure commensurability, vortex-vortex interaction, and thermal fluctuations results in various vortex states varying the anisotropy, applied magnetic field, and temperature.[3–11] In particular, the occurrence of JV lattices (both pinned and floating), glasses, waving and smectic solids, and liquids is expected. From the experimental point of view, however, little is known regarding JV states as well as transitions separating these states. For instance, the JV depinning transition which takes place at nearly field-independent temperature $T_x \ll T_c$ in strongly anisotropic HTS such as $Bi_2Sr_2CaCu_2O_8$(Bi2212)[12–16] remains still unexplained.

Motivated by these studies, in the present work we have investigated dynamics of JV in Bi2212, associated with the ''anomalous'' (not yet understood) depinning transition, by means of ac susceptibility measurements. The obtained results revealed an unprecedented steplike increase of the flux-creep activation energy (U_{JV}) with magnetic field applied parallel to superconducting CuO_2 planes. The results provide evidence that the U_{JV} vs. H behavior is an intrinsic property of JV, only weakly interacting with the in-plane Abrikosov pancake vortices (PV).

Two Bi2212 single crystals grown using the self-flux method and annealed in air at 400 °C for ten hours have been studied. The crystals demonstrate a zero-field superconducting transition temperature $T_c = 83.5$ K and $T_c = 82.9$ K at midpoint and transition width $\Delta T_c(10\text{-}90\%) = 1.6$ K. Similar $U_{JV}(H)$ dependencies were measured for both crystals. Here we present the data obtained on the crystal with $T_c = 83.5$ K of size $a \times b \times c = 1.7 \times 0.64 \times 0.02\ \mathrm{mm}^3$. The crystal characterization details as well as dc magnetization measurements have been presented elsewhere.[17] Ac susceptibility measurements were performed using PPMS Quantum Design commercial equipment with both dc (H) and ac (h_{ac}) magnetic field applied either parallel to the crystal ab-planes ($H \| h_{ac} \|$ ab geometry) or parallel to the c-axis ($H \| h_{ac} \| c$ geometry). The misalignment angle between applied field and the main surface of the crystal (ab-planes) was about ~4°. The measured frequency range was typically $500\ \mathrm{Hz} \leq v_m \leq 10$ kHz. The amplitude of ac field was chosen to be $h_{ac} = 10$ Oe enabling a high signal/noise ratio. All measurements were made in a zero-field-cooled (ZFC) regime.

Shown in Figs. 1(a) and 1(b) is the out-of-phase compo-

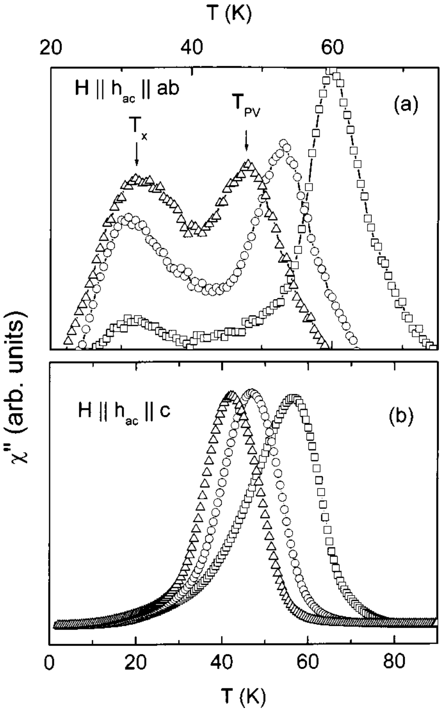

FIG. 1. Out-of-phase component of ac susceptibility $\chi''(T)$ measured for $H = 300$ Oe (□), $H = 1$ kOe (○), and $H = 2$ kOe (△) with a frequency $v_m = 2$ kHz in $H \| h_{ac} \| ab$ (a) and $H \| h_{ac} \| c$ (b) geometry. (a) Two dissipation peaks occurring at T_x and T_{PV} (a) are related to ''depinning'' of Josephson interlayer and Abrikosov in-plane pancake vortices (PV). (b) The peaks in $\chi''(T)$ correspond to ''depinning'' of PV.

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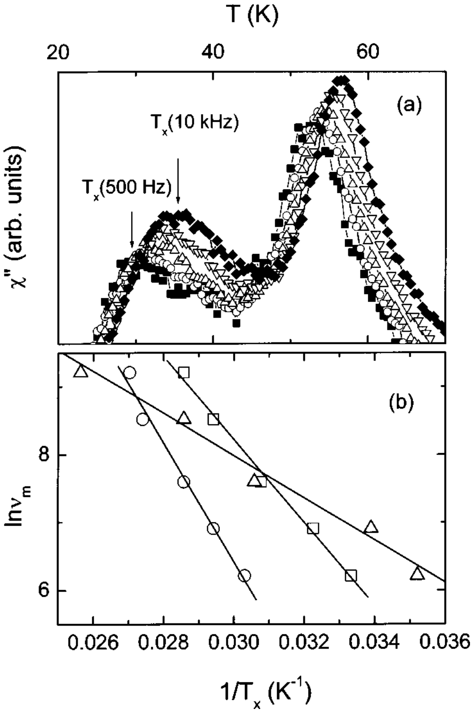

FIG. 2. (a) Out-of-phase component of ac susceptibility $\chi''(T)$ obtained in $H\|h_{ac}\|ab$ geometry with $H=750$ Oe, and frequencies $v_m=500$ Hz (■), $v_m=1$ kHz (○), $v_m=2$ kHz (△), $v_m=5$ kHz (∇), $v_m=10$ kHz (♦). The frequency-dependent depinning temperature $T_x(v_m)$ of Josephson interlayer vortices measured with $v_m=500$ Hz and $v_m=10$ kHz is shown by arrows. (b) Arrhenius plot, $\ln v_m$ vs. $1/T_x$, for $H=400$ Oe (△), $H=750$ Oe (□), and $H=3$ kOe (○); solid lines are obtained from Eq. (1) with $v_0=3.3\cdot 10^7$ Hz, $U_{\mathrm{JV}}=312$ K for $H=400$ Oe, $v_0=3\cdot 10^{11}$ Hz, $U_{\mathrm{JV}}=611$ K for $H=750$ Oe, and $v_0=1.5\cdot 10^{14}$ Hz, $U_{\mathrm{JV}}=875$ K for $H=3$ kOe.

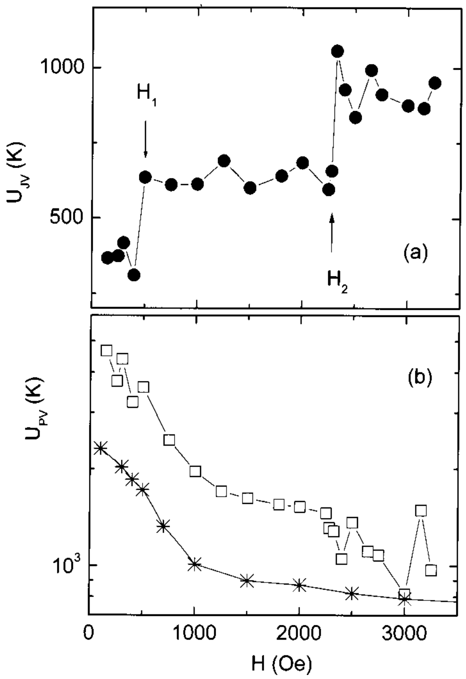

FIG. 3. Magnetic field dependence of vortex creep activation energy for Josephson interlayer vortices $U_{\mathrm{JV}}(H)$ (a), and Abrikosov pancake vortices $U_{\mathrm{PV}}(H)$ (b); $U_{\mathrm{PV}}(H)$ was obtained in both $H\|h_{ac}\|ab$ (□) and $H\|h_{ac}\|c$ (*) configurations.

nent of ac susceptibility $\chi''(T)$ obtained in $H\|h_{\mathrm{ac}}\|ab$ and $H\|h_{\mathrm{ac}}\|c$ geometry, respectively, for various measuring H and frequency $v_m=2$ kHz. One can clearly see in Fig. 1(a) the occurrence of two dissipation peaks: one peak takes place at nearly field-independent temperature T_x, and another at the temperature $T_{\mathrm{PV}}(H)>T_x$ which shifts toward low temperature with the field increasing. It has unambiguously been demonstrated in Refs. 12–16 that the dissipation peaks at T_x and $T_{\mathrm{PV}}(H)$ are related to dynamics of Josephson interplane and pancake in-plane vortices, respectively. In particular, it has been found that the peak at T_x does not occur when ac current, induced by h_{ac} flows within the ab planes.[13] This can also be seen in Fig. 1(b), where the $\chi''(T)$ data obtained in the $H\|h_{\mathrm{ac}}\|c$ geometry, i.e., with ac current driving mainly PV, are given. In Fig. 2(a) we show $\chi''(T)$ obtained in $H\|h_{\mathrm{ac}}\|ab$ geometry at $H=750$ Oe for several measuring frequencies between $v_m=500$ Hz and $v_m=10$ kHz, which demonstrate the frequency dependence of both $T_x(v_m)$ and $T_{\mathrm{PV}}(v_m)$. We stress that the results presented in Figs. 1(a) and 1(b) and Fig. 2(a) are similar to those reported for several Bi2212 crystals with different T_c.[12–16] This suggests that the dynamics of JV is primarily determined by the crystal layered structure, and not by the doping level. While the frequency dependence of the dissipation peak associated with PV has thoroughly been investigated in the past,[18] here we focus our attention on the frequency-dependent dynamics of JV, i.e., the $T_x(\nu_m)$ which has not been studied before. As can be seen from Fig. 2(b), the data obtained for various ν_m can be well described by the equation (solid lines)

$$\nu_m=\nu_0\exp(-U_{\mathrm{JV}}/k_BT_x), \tag{1}$$

where $U_{\mathrm{JV}}(H)$ is the effective activation energy for motion of JV. The results presented in Fig. 2(b) for three measuring fields demonstrate also that U_{JV} increases with H. The $U_{\mathrm{JV}}(H)$ data obtained for more than 20 values of H in the field interval $150\,\mathrm{Oe}\leqslant H\leqslant 3250\,\mathrm{Oe}$ are summarized in Fig. 3(a). The restricted explored field range is due to (1) the emergence of the ''anomalous'' dissipation peak only above the field $H_{\mathrm{on}}=150$ Oe, and (2) the approximation of the two peaks with increasing field, see Fig. 1(a), such that the separation of $T_x(H)$ and $T_{\mathrm{PV}}(H)$ becomes difficult for $H>3250$ Oe. One can also observe in Fig. 3(a) the occurrence of two pronounced steps in $U_{\mathrm{JV}}(H)$, at $H_1\approx 500$ Oe and $H_2\approx 2300$ Oe.

It is instructive to compare the obtained $U_{\mathrm{JV}}(H)$ to the creep activation energy $U_{\mathrm{PV}}(H)$ of PV presented in Fig. 3(b). The $U_{\mathrm{PV}}(H)$ was extracted from the Arrhenius plot of the $T_{\mathrm{PV}}(v_m)$ data (not presented here), similar as shown in Fig. 2(b) for JV. As can be seen from Fig. 3(b), $U_{\mathrm{PV}}(H)$ decreases with field in both $H\|h_{\mathrm{ac}}\|ab$ and $H\|h_{\mathrm{ac}}\|c$ configurations, i.e., demonstrates a qualitatively difference from JV behavior.

We proceed with a discussion of $U_{\mathrm{JV}}(H)$ noting that several theoretical models which predict rearrangements and phase transitions in a parallel vortex system may be suitable for the discussion of discontinuities and plateaus in $U_{\mathrm{JV}}(H)$ shown in Fig. 3(a). The models can be separated into two groups: (1) the ones which consider parallel equilibrium vortex configurations and rearrangement between them neglecting the layered structure (see, e.g., Refs. 19 and 20 and references therein), and (2) the models which are essentially based on the layering.[3–11]

When the Bean-Livingstone surface barrier (SB) for the vortex entrance is absent, the theory[19,20] predicts the occurrence of series of sharp maxima in the critical current for magnetic fields exceeding $H \sim 2H_{c1}$, where H_{c1} is the first critical penetration field applied parallel to the main surface of the sample. In layered superconductors, H_{c1} for penetration of JV between layers is given by the formula[21]

$$H_{c1} = \Phi_0/(4\pi\lambda_{ab}\lambda_c)[\ln(\lambda_{ab}/d) + 1.12], \qquad (2)$$

valid in a low temperature regime ($T \ll T_c$), where λ_{ab} and λ_c are in-plane and out-of-plane penetration depths, respectively, and $d \approx 15$ Å is the distance between weakly coupled CuO_2 superconducting planes in Bi2212. Taking the characteristic values of $\lambda_{ab} \approx 0.2\,\mu$m (Ref. 22) and $\lambda_c = \gamma\lambda_{ab} \approx 30\,\mu$m [the anisotropy parameter $\gamma = 150$ (Ref. 23)], one gets $H_{c1} \sim 2$ Oe.

However, as pointed out above, the ''anomalous'' peak at T_x emerges only for $H \geqslant 150\,\mathrm{Oe} \gg H_{c1}$. This may indicate the presence of the surface barrier preventing vortex penetration at $H = H_{c1}$. Within the framework of Lawrence-Doniach model and for $T \ll T_c$ the penetration field H_p for the bulk sample ($\lambda_{ab} \ll c$, c is the sample thickness) due to surface barrier can be estimated according to Ref. 24

$$H_p = \Phi_0/\pi\lambda_{ab}\gamma d. \qquad (3)$$

The estimation gives $H_p = 140$ Oe, which is surprisingly close to $H_{\mathrm{on}} \sim 150$ Oe. However, the expected characteristic field interval between two different nearest vortex configurations $\Delta H = 0.71 H_p$[25] ~100 Oe is an order of magnitude smaller than the experimentally observed field interval $\Delta H = H_2 - H_1 \sim 1.8 \cdot 10^3$ Oe between the two steps in $U_{\mathrm{JV}}(H)$, see Fig. 3(a).

Turning to the models which take into account layered structure, we can safely exclude from the analysis JV phase transformations expected to occur at high fields $H > H_0 \equiv \Phi_0/\gamma d^2 \sim 6$ T.[5]

On the other hand, we would like to emphasize the qualitatively different behavior of $U_{\mathrm{JV}}(H)$ and $U_{\mathrm{PV}}(H)$, illustrated by Figs. 3(a) and 3(b), which supports theoretical ideas of weakly interacting JV and PV lattices[26,27] in layered superconductors. It is also interesting to note the ''jumpy'' behavior of both $U_{\mathrm{JV}}(H)$ and $U_{\mathrm{PV}}(H)$ (in the $H \| h_{\mathrm{ac}} \| ab$ geometry) which takes place at $H < H_1$ and specially for $H > H_2$, see Figs. 3(a) and 3(b), as well as a smooth decrease of $U_{\mathrm{PV}}(H)$ with field between H_1 and H_2, where $U_{\mathrm{JV}}(H)$ is field independent. This observation suggests an intriguing possibility that a strength of mutual interaction between JV and PV is a nonmonotonous function of field and depends on a particular JV state.

Indeed, the staircase-like sequence of field-induced transitions obtained in Ref. 7 resembles very much the $U_{\mathrm{JV}}(H)$, see Fig. 3(a). According to Ref. 7, at $H/H_{c1} \sim 10^3$ the field range of stability of the next JV 1-phase (1 denotes the number of layers separating the JV in the c-axis direction) is about $\sim 10^3$ Oe, which coincides with the field range $\Delta H = H_2 - H_1 \approx 1800$ Oe, where the main plateau in the $U_{\mathrm{JV}}(H)$ is found.

At this stage it is difficult to speculate further on field-induced transformations in the Josephson vortex matter. It should be instructive to perform similar studies on less anisotropic superconductor, e.g., $YBa_2Cu_3O_{7-\delta}$, where the JV lattice-layered structure commensurability can be tuned by applied magnetic field.[8]

To summarize, we report here a steplike increase of the creep activation energy $U_{\mathrm{JV}}(H)$ for Josephson interlayer vortices in $Bi_2Sr_2CaCu_2O_8$ strongly anisotropic high-T_c superconductor. This observation suggests the occurrence of field-induced transformations in the JV matter associated with the JV depinning transition, which in its turn may shed light on the microscopic origin of the depinning transition itself. The here obtained results provide also an experimental evidence that the systems of Josephson interlayer and in-plane Abrikosov pancake vortices behave nearly independently in strongly anisotropic superconductors.

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