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Probing the mechanism of interaction of Josephson vortices and pancake vortex lines in $Bi_2Sr_2CaCu_2O_{8+x}$ with columnar defects

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Attractive interaction between pancake-vortex lines (PVLs) and Josephson vortices (JVs) in layered high-temperature superconductors is attributed to the local polarization of PVL at a crossing point by the currents circulating around the JV. To verify this mechanism we measured the Josephson flux-flow resistance in Bi-2212 stacked structures in a presence of PVLs for two cases, when PVLs are free and when they are trapped by columnar defects that highly suppress their local polarization. We found that the trapping PVLs by columnar defects (CDs) significantly eliminates interaction between PVLs and JVs. That observation strongly supports the local PVL polarization as a mechanism for their attractive interaction with JVs.

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The layered structure of high temperature superconductors provides possibility for existence of specific vortex excitations in those materials: pancake vortex lines (PVLs) and Josephson vortices (JVs). PVL is excited by magnetic field component perpendicular to the layers and consists of 2D Abrikosov vortices or pancake vortices located in the elementary superconducting layer coupled along the flux line by magnetic and Josephson interaction [1]. JVs are excited by parallel magnetic field component, they are centered in the elementary insulating layers separating elementary superconducting layers [2]. Vortices of the same type experience repulsive interaction with each other. To the contrast, PVLs and JVs attract each other tending to be crossed [3]. That property has been used to visualize JVs by PVLs [4]. This attractive interaction results also in a variety of exotic combined vortex phases like mixed chain-lattice state [5] and pancake chain states [4] which appear in tilted magnetic fields containing both parallel and perpendicular components. In dynamic regime referred to as Josephson flux-flow (JFF) this interaction leads to the negative JFF resistance at small perpendicular magnetic fields [6, 7] and to the appearance of excess current on the I-V characteristics [7, 8].

Theoretically it was shown that in the crossing state PVL is locally polarized by the superconducting currents circulating around JV [see e.g. 9]. This polarization can be regarded as a measure of the interaction. The in-plane length scale of local polarization is considered to be about λ_{ab} [3, 9]. One can then expect that the interaction can be essentially suppressed with a reduction of the polarizability of PVL.

That mechanism can be verified experimentally by the presence in the system of columnar defects which diameter D is known to be much less than characteristic polarization length $\lambda_{ab}/D \approx 30$ in Bi-2212. On the other hand, D is 2–3 times bigger than $\xi(0)$, providing conditions for strong pinning of PVL by CD. Therefore, the trapping of PVL by CD should significantly suppress its interaction with JVs (Fig.1). To verify this

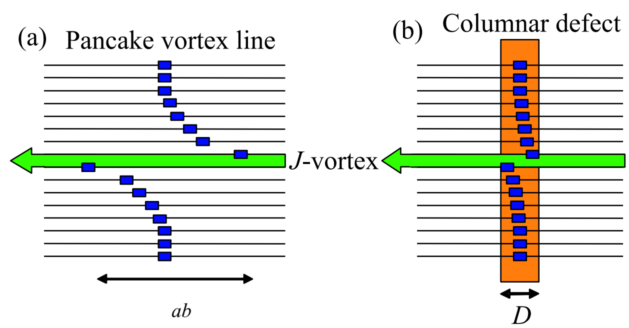

Fig.1. Schematic view of local polarization of pancake vortex line by currents circulating around Josephson vortex (shown as an arrow) for two cases: (a) free PVL, (b) PVL trapped by columnar defect (shown as a rectangular)

idea we carried out comparative experiments on JFF on pristine and irradiated by heavy ions Bi-2212 mesas at small perpendicular magnetic fields when all the PVLs in the irradiated sample were trapped by CDs.

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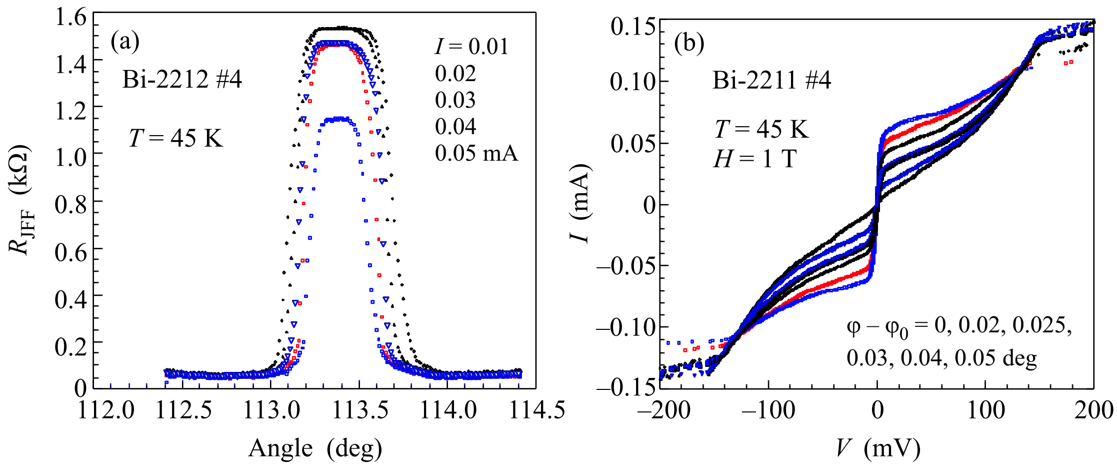

Fig.2. Angular dependence of Josephson flux-flow resistance of Bi-2212 mesa #4 at various currents from 0.01 to 0.05 mA, $H = 1\,\mathrm{T}$, $H \parallel b$-axis (a), the I-V characteristics of the same mesa with small deviations from parallel orientation of the field (b). $T = 45\,\mathrm{K}$

Experiment has been done on mesa type structures fabricated by focused ion beam (FIB) technique from $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212) single crystal whiskers [10]. The in-line type structures have typical sizes $L_a x L_b x L_c = 20\mu\mathrm{m} \times 5\mu\mathrm{m} \times 0.2\mu\mathrm{m}$. We used double sized FIB processing technique [11] for structure fabrication. Experimentally we studied Josephson flux-flow transport on those stacked structures in magnetic fields oriented either strictly parallel to the layers, $H \parallel b$, [12] or with a presence of small c-axis component creating PV lines [7]. The experiment has been done first on pristine sample and then has been repeated on the same sample at exactly the same conditions (sample position, temperature, field orientation etc.) in a few days after irradiation. The irradiation was made by Pb-ions with energy of 1 GeV at GANIL accelerator (Caen, France). The defects were introduced along the c-axis with a concentration $c = 3 \cdot 10^8\,\mathrm{cm}^{-2}$ corresponding to the matching field ($H_{\mathrm{match}} = c\Phi_0$) of about 60 Oe. At so small concentration the average distance between CDs is about 80 times bigger than the diameter of CD. That provides good conditions to avoid their coalescence and also to avoid an interaction between the trapped PVs. The magnetic field has been provided by electromagnet that can be rotated in a programmable way by the step motor within accuracy of 0.01 degrees.

The effect of PVls on JFF is demonstrated on Fig.2. Fig.2a shows Josephson flux-flow resistance $R_{\mathrm{JFF}}(\varphi)$ of mesa #4 as a function of tilting angle of magnetic field $H = 1\,\mathrm{T}$ around the b-axis. The strictly parallel orientation, $H \parallel a$, corresponds to the maximum $R_{\mathrm{JFF}}(\varphi)$. At Fig.2a that corresponds to some angle $\varphi_0 = 113.41°$. A deviation from φ_0 induces the c-axis field component $H_c = H \sin(\varphi - \varphi_0)$. That in turn creates PV lines. Interaction of JFF with PVL slows down JFF and that results in a sharp decrease of JFF voltage or JFF resistance measured at the fixed current across the layers [6]. The peak is very sharp with a half width ranging from 0.15° to 0.3° with current variation from 0.01 to 0.05 mA. The top flat part of the peak corresponds to the absence of PVLs when the c-axis field component is less than $H_{c1} \approx 10\,\mathrm{Oe}$, while the low resistive flat part corresponds to the nearly pinned JFF state. The peak wings move outwards with current. It means that for higher current, i.e. higher driving force, the higher perpendicular component needs to stop Josephson flux-flow.

Fig.2b shows the I-V characteristics of JFF state in strictly parallel field, $\varphi - \varphi_0 = 0$, and in the presence of the c-axis field component that induces PVLs. The concentration of PVLs is proportional to the value of the c-axis component or to $\varphi - \varphi_0$ at small angle deviation. Since the c-axis component is oriented parallel to the transport current there is no Lorentz force acting on PVLs. Therefore, due to there attractive interaction with JVs they play a role of pining centers to the JFF [8]. Dynamically, this interaction induces an excess damping of the driven Josephson vortex lattice (JVL). The mechanism of dynamical interaction of JVL with PV lines has been recently discussed in Ref. [7]. One can see that an excess damping appears as an excess current on the IV characteristics at the fixed voltage or at the constant JVL velocity.

The main result of the paper is shown in Fig.3 which shows a dependence of Josephson flux-flow resistance on the field tilting angle (i. e. on perpendicular component

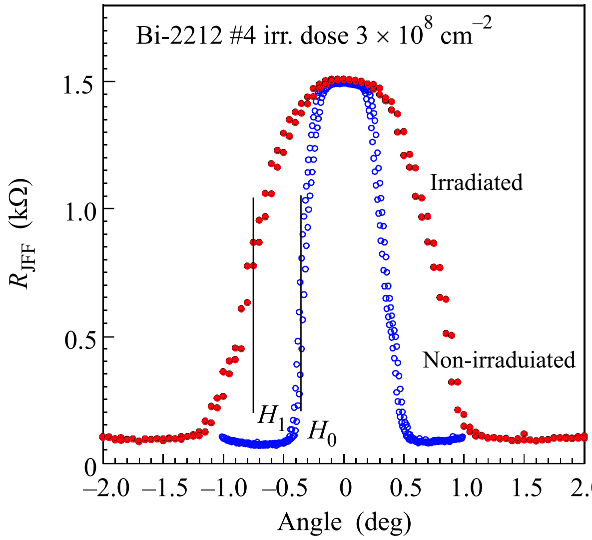

Fig.3. Josephson flux-flow resistance R_{JFF} of Bi-2212 mesa #4 as a function of field tilting angle φ in the bc-plane for both, pristine (open symbols) and irradiated (full symbols) sample. $\varphi = 0$ corresponds to the orientation $H \parallel b$-axis, $H = 1\,\mathrm{T}$. The characteristic perpendicular fields H_0 and H_1 corresponds to the most sharp drop $R_{\mathrm{JFF}}(\varphi)$ for pristine and irradiated sample. Measuring current is 0.06 mA, $T = 45\,\mathrm{K}$. Concentration of columnar defects $c = 3 \cdot 10^8\,\mathrm{cm}^{-2}$

of the field, $H_\perp$) for both pristine and irradiated samples. In both cases the rotation scans have been done up and down and results are well reproduced, as shown in Fig.3. The first prominent feature is that at zero $H_\perp$ JFF resistance does not depend on the presence of CDs. That means that CDs of small concentration negligibly affect Josephson flux-flow. There are also no considerable changes at nearly pinned state. The most considerable effect of CDs is the shift of both positive and negative wings of the peak with some their broadening. The shift measured at the half of the peak height is 0.38° for both polarities. That gives a field value $H_\perp$ of 66 Oe which is with experimental accuracy very close to the matching field $H_{\mathrm{match}} = 62\,\mathrm{Oe}$.

Let us denote the field of the sharpest drop of $R_{\mathrm{JFF}}(H)$ for pristine and irradiated samples as H_0 and H_1. That corresponds to the concentration of the PVs the most effectively stops JFF. For irradiated sample this characteristic field H_1 is higher. The simple explanation of that is the following. With field increase the PVs first sit inside the CDs and do not interact effectively with JVs. At $H > H_{\mathrm{match}}$ all CDs are occupied and the PVs appear in some space between CDs and begin effectively interact with JVs. In this simple model the characteristic field H_1 to stop JFF in irradiated sample should be equal to $H_1 = H_0 + H_{\mathrm{match}}$. That is exactly what is observed in the experiment.

The smearing of $R_{\mathrm{JFF}}(H_\perp)$ curve for irradiated sample is apparently related with depinning of PVLs by thermal fluctuations. As it was shown in Ref. [7], that probability in Bi-2212 highly increases with temperature approaching to 60 K.

In a summary, we found that the trapping of pancake vortex lines by columnar defects significantly suppresses their interaction with Josephson vortices. We consider that as a result of a loss of the local polarizability of the trapped pancake vortex lines.

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