Shapiro step response in the vortex state of $Bi_2Sr_2CaCu_2O_{8+\delta}$

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Abstract

We report the first observation of Shapiro step effect in the Josephson vortex state of $Bi_2Sr_2CaCu_2O_{8+\delta}$ in high magnetic field ($H \geq 1T$). We observed phase locking between external microwave radiation and Josephson oscillation in whole stack of N intrinsic Josephson junctions at fields tilted with respect to the c-axis. Steps were observed in Josephson flux-flow (JFF) on the $I - V$ characteristic at voltage $V_{st} = pNh\nu/2e$, with p integer, $\nu =$ 45-142 GHz. The amplitude of both Shapiro steps and Josephson critical current increase sharply with tilting angle and then decrease. We attribute this behavior to the interaction between Josephson and pancake vortices.

Key words: Josephson junctions; vortex state; phase-locking

The most anisotropic high-T_c superconductors such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ can be considered as a vertical c-axis stack of superconductor-insulator-superconductor Josephson junctions [1]. We study dynamics of Josephson vortex lattice (JVL) driven by steady current across the layers in tilted magnetic fields. We use method based on Shapiro step effect for studying phase-locking of Josephson junctions and JVL flux-flow. Stacked intrinsic long Josephson junctions were fabricated by double-sided processing of high quality $Bi_2Sr_2CaCu_2O_{8+\delta}$ (T_c=80 K) whiskers by using a focusing ion beam technique [2]. The oxygen doping level was $\delta \sim$0.25, indicating the slightly overdoped regime. The inset of Fig. 1 shows schematically the arrangement of the junctions. The length of the junction is L=30μm with a width of W=2.0μm. The critical current density j_c at 4.2 K in the absence of magnetic field was 1-2$\times 10^3$ A/cm^2. The magnetic field $H \geq 1T$ was rotated in plane perpendicular to the long dimension L by using split pair superconducting magnets with fine goniometer having angular resolution 0.01°. External microwaves at the frequencies ranging from 45 GHz to 142 GHz were applied from the backward-wave-oscillators. The microwave frequency was always higher than Josephson plasma frequency at chosen magnetic field and temperature in experiment [3]. The sample was mounted on the substrate which was placed at the center of the rectangular waveguide with the electric component of the microwaves oriented along the c-axis. The $I - V$ characteristics were measured at several tenths of Hz using a low noise oscilloscope.

Under various field angles to the b-axis, θ, we find collectively phase locked Shapiro steps shown in Figs. 1, 2. Steps occurred at the same voltages given by $V_{st} = pNh\nu/2e$, where N is the whole number of the junctions in the stack. Amplitude of Shapiro steps ΔI_n scales as $(H\sin\theta)^-1$ in the wide angle range $\theta >$15°. The step amplitude increases very rapidly at small angles and has a maximum at $\theta <$0.6°. Josephson critical current has the same angular dependence. We consider the sharp increase of both I_c and ΔI_n to be related with pinning of the Josephson vortices by pancake vortices, the latter being pinned by crystal much stronger because of normal vortex core. At the higher angles the reduction of I_c is caused by the Josephson strings that

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are created by the deviation from the straight alignment of the pancakes along the c-axis. The field affects only through the the cosine of the gauge-invariant phase difference between neighbor layers [3–5].

Fig. 1 shows the $I-V$ characteristics in the parallel field. In the absence of microwave irradiation (P_m=0), the critical current is strongly suppressed to ∼1/30 of j_c at H=0. The linear slope with slight upturn in the $I-V$ characteristics at finite voltage corresponds to the Josephson flux flow state. One can see multiple Josephson flux flow branches above 36 mV. Shapiro steps appeared on the first flux-flow branch when the junction is irradiated by microwaves [6]. In the present case Shapiro effect is markedly different from conventional one because dc voltage appears due to Josephson vortices flux-flow. Therefore the dc voltages of the Shapiro steps are closely related to Josephson vortex dynamics. If the Josephson vortices move at different speed in some layers that changes voltage position of step V_{st}. At the matter of fact that V_{st} remains constant it follows that the Josephson vortices move at the same speed over the whole stack of junctions. The observation of sharp enough Shapiro steps indicates that the Josephson vortices move keeping the high spatial regularity.

In summary, we have observed Shapiro steps in the Josephson flux-flow regime of $Bi_2Sr_2CaCu_2O_{8+\delta}$ stacked junctions in the case of strong interaction of JVL with pancake vortices. Pancake vortices significantly affect the amplitude of Shapiro steps and keep phase-locking all Josephson junctions to an external frequency. The position and the magnitude of Shapiro steps in the Josephson flux flow state provide strong evidence of the coherent motion of the Josephson vortex lattice in the lowest mode of vortex propagation.

Acknowledgements

M.B.G. acknowledges support from JSPS,Y.I.L. acknowledges support from the CRDF grant No.RP-12397-MO-02 and grant of Russian Ministry of Science and Industry No.40.012.1.1.11.46

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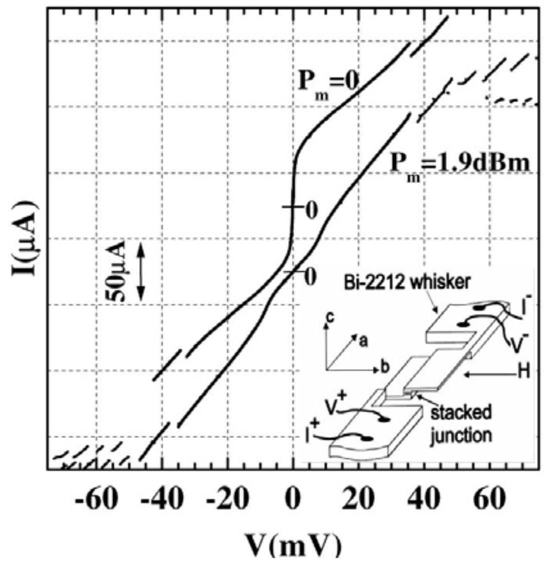

Fig. 1. $I-V$-characteristics of the stacked intrinsic Josephson junction with and without microwave irradiation in magnetic field of 2.25 T applied parallel to the layers at 6.3 K. The applied microwave frequency is 75.0 GHz. N, estimated from number of branches, is 60±3. For clarity, the zero levels of the two curves are vertically shifted. Inset: Schematic view of the stacked intrinsic Josephson junction.

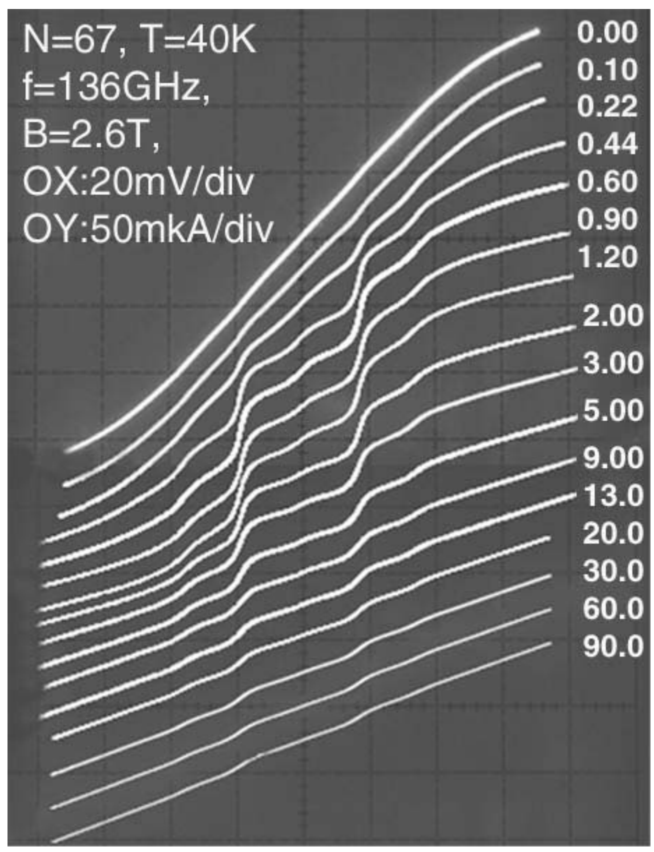

Fig. 2. The angular dependence of the Shapiro step response.