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Collective motion of Josephson vortex lattice in long stacked junction fabricated from Bi-2212 whisker

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Abstract

We study the I–V characteristics of long Bi-2212 stacked junctions in the Josephson flux-flow regime in parallel magnetic field ($B\|b$). We measure both voltage position of the flux-flow step, V_{ff}, corresponding to the maximum velocity of Josephson vortex lattice, and the flux-flow resistivity, ρ_{ff}, as a function of magnetic field $B = 0.1$–4 T. We found plateau-like features of constant V_{ff} on dependence $V_{\mathrm{ff}}(B)$ corresponding to washboard frequencies 600 GHz and 3 THz. We discuss these features as mode locking of washboard frequency with active intrinsic modes of the stack. We found also that field dependence of flux-flow resistivity can be well described by a recent model [A. Koshelev, Phys. Rev. B 62 (2000) R3616] which takes into account both out-of-plane and in-plane dissipation. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Recently a great deal of interest aroused to the studies of Josephson flux flow in layered high-T_c materials [1–7]. As it was pointed out in Ref. [1], the sliding of the Josephson vortex lattice can generate high-frequency electromagnetic oscillations in THz region. The oscillation frequency in that case can be tuned by magnetic field or by driving current. In Ref. [2] it was proposed that the Josephson flux flow can excite transverse Josephson plasma oscillations in layered superconductors. Besides, flux-flow resistivity can serve as important instrument for studies of out of plane and in-plane quasiparticle conductivity in superconducting state of high-temperature superconductors [3]. Experimentally the Josephson flux flow in high-T_c materials has not been studied yet so much [4–7]. There were only few papers on that matter at low-magnetic fields [4–6] and even less for the case of high fields [7]. Furthermore Josephson flux-flow resistivity at high fields has not yet been experimentally studied at all.

The present studies have been addressed to the studies of Josephson flux-flow behavior in high-quality Bi-2212 layered structures emphasizing on

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detailed studies of the field dependencies of flux-flow resonance step and flux-flow resistivity at low temperatures. A wide range of magnetic fields has been covered starting from 0.1 T and up to fields 4 T above which the flux-flow features become indistinguishable on the current voltage (*I–V*) characteristics.

2. Experimental

The stacked structures have been fabricated by double-sided processing of high-quality Bi-2212 whiskers by focused ion beam (FIB). The stages of fabrications were similar to ones described in Ref. [8]. Fig. 1a shows schematically the geometry and orientation of the structure with respect to the crystallographic axes. The typical structure sizes L were $L_a = 10$–30 μm, $L_b = 1$–2 μm, $L_c = 0.03$–0.05 μm. The measurements have been carried out in commercial cryostat of Quantum Design PPMS facility. The magnetic field has been oriented parallel to the *b*-axis within accuracy 0.2°. Field has been changed in steps of 0.1 T. In each fixed value of the field the back and forth *I–V* characteristics have been measured using fast oscilloscope.

3. Results and discussion

3.1. Flux-flow spectroscopy

Fig. 1b–c shows a set of the *I–V* characteristics illustrating a development of the flux-flow step with increase of magnetic field. In zero magnetic field the *I–V* characteristics are typical for mesa-type junctions. They exhibit hysteresis and multi-branched structure, corresponding to successive transition of the elementary junctions into a resistive state. The value of J_c was within 100–400 A/cm^2. Magnetic field oriented parallel to the *b*-axis (see Fig. 1a) suppresses critical current and at the same time leads to the appearance of resistive non-hysteretic branch, the so-called flux-flow step (Fig. 1b). The step appears as a strong enhancement of current at fixed voltage, V_{ff}. We define V_{ff} as a maximum voltage of non-hysteretic branch. This step is associated with a resonance when Josephson vortex lattice achieves Swihart velocity c_0,

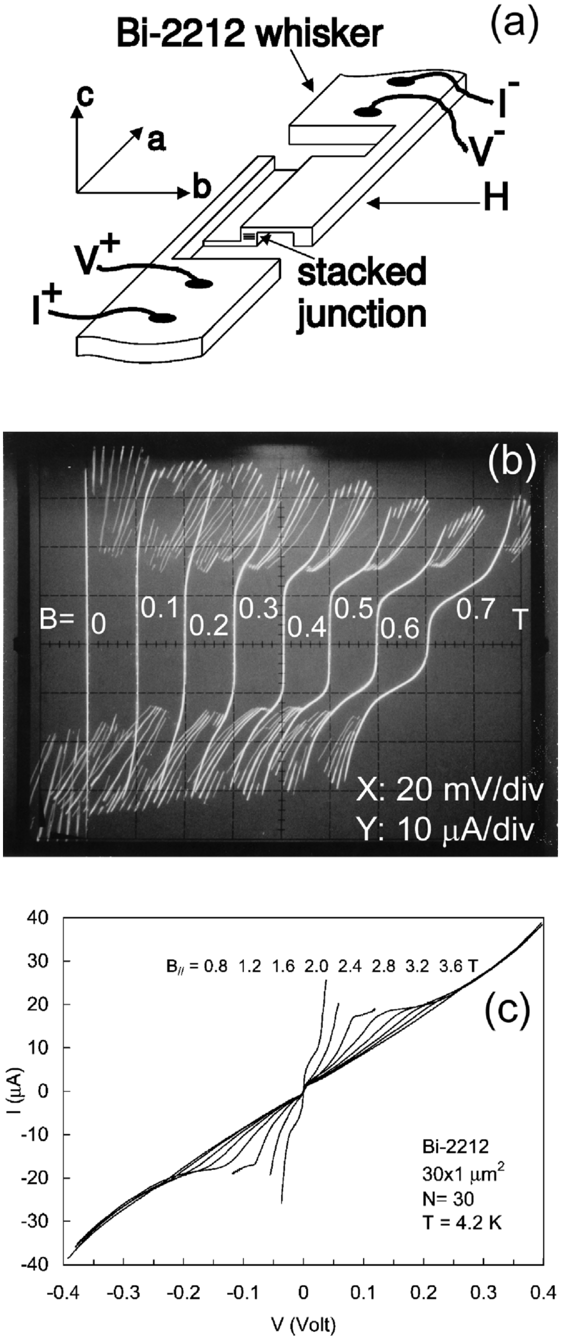

Fig. 1. Schematic view of the junction in experimental setup (a) and *I–V* characteristics of the long ($L_a = 30$ μm, $L_b = 1$ μm) Bi-2212 stacked junction in magnetic field parallel to *b*-axis, $B_{\parallel}$, for the 0–0.7 T (b) and 0.8–3.6 T (c) field ranges. The number of elementary layers $N = 30$, $T = 4.2$ K. Note: the multibranched structure is not shown in (c).

the velocity of electromagnetic field propagation in layered material. For one of the simplest mode of anti-phase-neighboring layers it can be expressed as follows [1]:

$$c_0 = cs/2(\lambda_{ab}\sqrt{\varepsilon_c}) \tag{1}$$

with c the light speed in vacuum, s the spacing between elementary superconducting layers, λ_{ab} the in-plane London penetration depth, ε_c the interlayer dielectric constant.

The frequency of electromagnetic radiation, ν, generated by sliding lattice at the resonance condition (washboard frequency) can then be expressed as:

$$\nu = \frac{c_0 sB}{2\Phi_0} \tag{2}$$

with Φ_0 the magnetic flux quantum.

By sweeping magnetic field one can tune a frequency of generated electromagnetic radiation. The generated frequency can be directly found by position of the flux-flow step via Josephson relation:

$$\nu = \frac{2eV_{\rm ff}}{hN} \tag{3}$$

with N, the number of elementary layers in the stack, h, Plank constant. If the radiation generated by Josephson flux-flow excites some active modes in the system with some particular frequency f_i (like plasma frequency [2] or optical phonon modes [9]) one can expect to observe resonance features on $V_{\rm ff}(B)$ dependence when $\nu = f_i$, or

$$V_{\rm ff} = \frac{hN}{2e} f_i. \tag{4}$$

The resonance is usually accompanied by mode locking regime. Therefore one could expect to observe some plateau like features on $V_{\rm ff}(B)$ dependence near $V_{\rm ff}$ values given by relation (4) (Fig. 2). We undertook experimental search for the resonance plateaus on $V_{\rm ff}(B)$ dependence.

Fig. 3a shows experimental dependence of $V_{\rm ff}(B)$ measured at $T = 4.2$ K for Bi-2212 stack $30 \times 1\ \mu\text{m}^2$ and containing 30 elementary junctions. Generally $V_{\rm ff}(B)$ dependence has a quasi-linear form. The plateau features, however, are clearly seen at $V_{\rm ff}$ equal to 35 and 180 mV. More distinctly

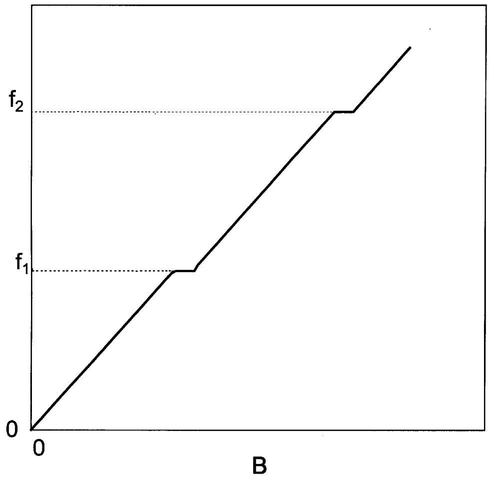

Fig. 2. Schematically shown $V_{\rm ff}(B)$ dependence expected for the system with the two resonance frequences f_1 and f_2 (see text).

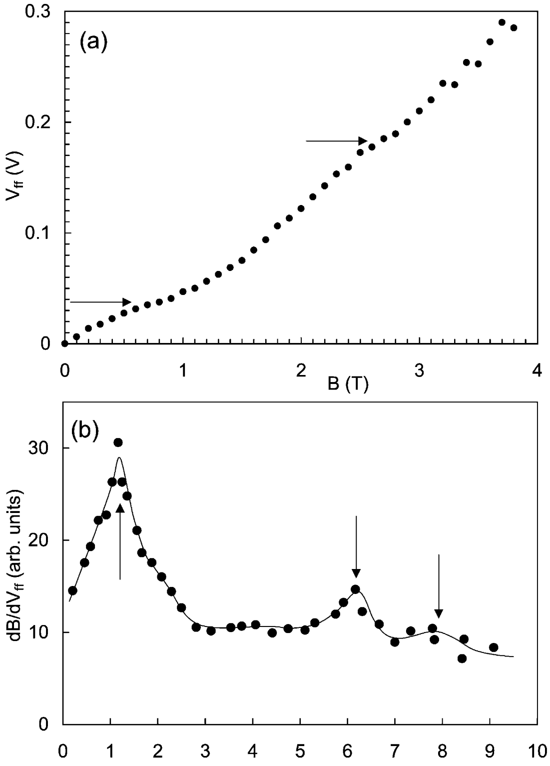

Fig. 3. Flux-flow voltage $V_{\rm ff}$ dependence on the magnetic field $B \| b$ (a); corresponding $dB/dV_{\rm ff}(V_{\rm ff}/N)$ dependence (b). The resonance plateau features are marked by arrows. Solid line in (b) is guide to eye.

that is seen in the derivative picture $\mathrm{d}B/\mathrm{d}V_{\mathrm{ff}}(V_{\mathrm{ff}})$ where the peaks corresponding to the plateau features appear. At voltage scale reduced per one junction, V_{ff}/N, one can see a big peak at 1.2 mV and two smaller peaks at 6 and 8 mV (Fig. 3b). From Eq. (3) that corresponds to 600 GHz, 3 and 4 THz.

Recently resonance peaks at 6 and 8 mV have been observed as the subgap structure on the *I–V* characteristics of Bi-2212 mesas [10,11] at zero magnetic field. Later they have been interpreted as the resonance of the Josephson oscillations with *c*-axis optical phonon modes [9]. The subgap structure at 6 and 8 mV has been reproduced then in many experiments on Bi-2212 [10–12] and Bi(Pb)-2212 [13] mesa structures. We can conclude that peak structure at 6 and 8mV is well reproduced in our experiment, but as resonance of flux-flow washboard frequency with the *c*-axis optical phonons.

A big peak at 1.2 mV in our data has not been observed in subgap structure in previous tunneling experiments on mesas at zero magnetic field. It can be therefore reasonable to consider it as a result of some excitations induced specifically by flux-flow motion. One mechanism most likely related to our case have been proposed by Koyama and Tachiki [2]. They consider possibility of excitation of transverse Josephson plasma by Josephson flux flow. The estimate of plasma frequency from that model is in reasonable agreement with experimental value 600 GHz. Alternatively this peak might be attributed to the flux-flow resonance on acoustic phonons [9,14] which probably has not been resolved in tunneling experiments. Further experiments on the temperature dependence of this peak and on its dependence on stack material need to be done to distinguish those alternatives.

Note that the change of the slope of $V_{\mathrm{ff}}(B)$ near $B = 1.5$ T has been observed earlier [7], but has been interpreted as a crossover from a dilute to the dense vortex lattice.

3.2. Flux-flow resistivity

The motion of the Josephson vortex lattice induces a dissipation in the layered structure mainly due to the quasiparticle current across the layers [15]. However, as it was shown recently by Koshelev [3] for strong enough fields $B > B_{\mathrm{cr}}$ ($B_{\mathrm{cr}} = \Phi_0/\pi\gamma s^2$ with γ the anisotropy of London penetration depth) the contribution of in-plane dissipation becomes dominant. Even for low fields the in-plane dissipation was shown to contribute to the Josephson flux-flow resistivity when $\sigma_{ab}/\sigma_c \gg \gamma^2$.

The expression for flux-flow resistivity ρ_{ff} has been obtained for both limits of low and high fields [3]:

$$\rho_{\mathrm{ff}} \approx \frac{4.4\gamma s^2 B}{\Phi_0(\sigma_c + 0.27\sigma_{ab}/\gamma^2)} \quad \text{at } B < B_{\mathrm{cr}}; \tag{5}$$

$$\rho_{\mathrm{ff}} = \frac{B^2}{B^2 + B_\sigma^2}\rho_c, \qquad B_\sigma = \sqrt{\frac{\sigma_{ab}}{\sigma_c}}\frac{\Phi_0}{\sqrt{2}}\frac{1}{\pi\gamma^2 s^2}, \quad \text{at } B > B_{\mathrm{cr}}. \tag{6}$$

As it can be seen from Eqs. (5) and (6) the $\rho_{\mathrm{ff}}(B)$ is linear at low fields, then becomes quadratic and finally saturates to the value ρ_c at fields higher than B_σ. Eqs. (5) and (6) provide the possibility to extract σ_{ab}/σ_c and γ from the measurements of flux-flow resistance.

Experimentally flux-flow resistance has been measured only at low fields [4]. To verify the theoretical predictions [3] we have carried out measurements of the flux-flow resistivity in Bi-2212 long stacked junctions in both limits of low and high fields. The flux-flow resistance has been extracted from the experimental *I–V* characteristics by the extrapolation of linear part of the flux-flow step to the zero voltage bias. The most part of experiments has been carried out at liquid helium temperature.

The results of our measurements are shown in Fig. 4. The data are fitted well to Eq. (6) (solid line) with $B_\sigma = 1.85$ T, $\sigma_c = 1.3 \times 10^{-3}\ \Omega^{-1}\,\mathrm{cm}^{-1}$. At low fields $\rho_{\mathrm{ff}}(B)$ dependence is linear in accordance with Eq. (5). Using the found value for B_σ we get from Eq. (5) $(\sigma_{ab}/\sigma_c)^{1/2}/\gamma^2 = 10^{-2}$. Then from the fit of linear dependence of $\rho_{\mathrm{ff}}(B)$ to Eq. (6) we get $\gamma = 1300$, $\sigma_{ab}/\sigma_c = 3 \times 10^8$. Finally we get for σ_{ab} the value $4 \times 10^5\ \Omega^{-1}\,\mathrm{cm}^{-1}$. That is nearly expected values. For γ we found earlier the similar value from the fit to field dependence of critical current across the layers [16]. The found value for σ_c is near the value $\sigma_c = 2 \times 10^{-3}$

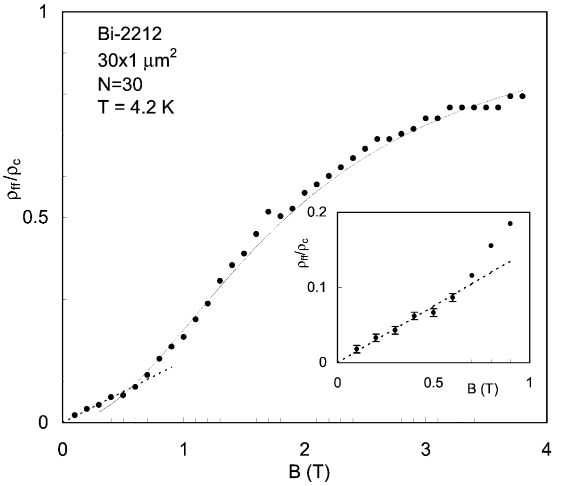

Fig. 4. Normalized flux-flow resistivity ρ_{ff}/ρ_c vs applied magnetic field $B \| b$. Lines are fit of Eqs. (5) and (6) to the experimental data with parameters: $B_\sigma = 1.85$ T, $\rho_c = 770\ \Omega$ cm, $\gamma = 1300$, $\sigma_{ab}/\sigma_c = 3 \times 10^8$. Inset shows the close-up of the linear region at low fields.

$\Omega^{-1}\,\mathrm{cm}^{-1}$ obtained from interlayer tunneling experiments on small Bi-2212 stacks [17].

The found value for σ_{ab} is several times higher than value found from the microwave measurements [18,19]. The corresponding value for ρ_{ab} is $\approx 2.5 \times 10^{-6}\ \Omega$ cm. This is about five times less than expected value from linear extrapolation of $\rho_{ab}(T)$ of our whiskers to $T \rightarrow 0$ [20] and may be an indication of faster than linear drop of $\rho_{ab}(T)$ at low temperatures.

4. Conclusions

We studied Josephson flux-flow features on the I–V characteristics of long Bi-2212 stacks fabricated from single crystal whiskers by FIB technique. We found plateau like features on fdependence of maximum flux-flow voltage on magnetic fields, corresponding to washboard frequencies 600 GHz, 3 and 4 THz. We consider that as resonance features for excitation of transverse Josephson plasma and c-axis optical phonons by Josephson flux-flow oscillations. We found also that experimental data on flux-flow resistivity are well described by the recent theory [3] considering contribution of in-plane dissipation to the flux-flow resistivity.

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References

[1] L.N. Bulaevskii, et al., Phys. Rev. B 53 (1996) 14601.
[2] T. Koyama, M. Tachiki, Solid State Commun. 96 (1995) 367.
[3] A.E. Koshelev, Phys. Rev. B 62 (2000) R3616.
[4] J.U. Lee, J.E. Norman, G. Hohenwarter, Appl. Phys. Lett. 67 (1995) 1471.
[5] Yu.I. Latyshev, P. Monceau, V.N. Pavlenko, Physica C 293 (1997) 174.
[6] G. Hechtfischer, R. Kleiner, K. Schlenga, W. Walkenhorst, P. Müller, H.L. Johnson, Phys. Rev. B 55 (1997) 14638.
[7] G. Hechtfischer, R. Kleiner, A.V. Ustinov, P. Müller, Phys. Rev. Lett. 79 (1997) 1365.
[8] Yu.I. Latyshev, S.J. Kim, T. Yamashita, IEEE Trans. Appl. Supercond. 9 (1999) 4312.
[9] Ch. Helm, Ch. Preis, F. Forsthofer, J. Keller, K. Schlenga, R. Kleiner, P. Müller, Phys. Rev. Lett. 79 (1997) 737.
[10] A. Yurgens, D. Winkler, N. Zavaritsky, T. Claeson, Proceedings of the Conference on Oxide Superconductor Physics and Nano-Engineering II, SPIE Proceedings, vol. 2697, SPIE, Bellingham, WA, 1996.
[11] K. Schlenga, G. Hechtfischer, R. Kleiner, W. Walkenhorst, P. Müller, H.L. Johnson, M. Veith, W. Brodkorb, E. Steinbeiss, Phys. Rev. Lett. 76 (1996) 4943.
[12] Ya.G. Ponomarev, et al., Solid State Commun. 111 (1999) 513.
[13] G. Oya, A. Irie, Physica C 362 (2001) 138.
[14] C. Preis, C. Helm, K. Schmalzl, J. Keller, R. Kleiner, P. Müller, Physica C 362 (2001) 51.
[15] J.R. Clem, M.W. Coffey, Phys. Rev. B 42 (1990) 6209.
[16] Yu.I. Latyshev, J.E. Nevelskaya, P. Monceau, Phys. Rev. Lett. 77 (1996) 932.
[17] Yu.I. Latyshev, T. Yamashita, L.N. Bulaevskii, M.J. Graf, A.V. Balatsky, M.P. Maley, Phys. Rev. Lett. 82 (1999) 5345.
[18] S.-F. Lee, et al., Phys. Rev. Lett. 77 (1996) 735.
[19] H. Kitano, et al., J. Low Temp. Phys. 117 (1999) 1241.
[20] Yu.I. Latyshev, I.G. Gorlova, A.V. Nikitina, V.U. Antokhina, S.G. Zybtsev, N.P. Kukhta, V.N. Timofeev, Physica C 216 (1993) 471.