Interaction between flux-flow and phonon resonances in small Bi-2212 mesa structures

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Abstract. Resonant phenomena are important for the use of intrinsic Josephson junctions as THz-oscillators, due to the decreased linewidth of emitted radiation when biasing the junctions near a resonance. We perform a detailed study of flux-flow characteristics and phonon resonances in small Bi(Pb)$_2$Sr$_2$CaCu$_2$O$_{8+x}$ mesa structures. Magnetic field dependence of flux-flow characteristics up to 17 T and temperature and magnetic field dependence of phonon resonances at temperatures from 2 K to 80 K and in fields up to 15 T are analyzed. A shift of the phonon resonances in the presence of external magnetic fields and an interaction between flux-flow and phonon resonances are observed.

1. Introduction
Intrinsic Josephson junctions (IJJs) in high temperature superconductors are widely studied as potential high-power coherent THz-oscillators [1, 2]. One method for generating THz-radiation is the so called flux-flow oscillator: in external magnetic fields $H$ applied parallel to the $ab$-plane (along the CuO$_2$ layers), Josephson vortices penetrate the Josephson junctions and an applied bias current along the $c$-axis (perpendicular to the CuO$_2$ layers) accelerates the vortex lattice. The moving vortex lattice emits electromagnetic radiation. The emission-power can be increased when many junctions in the stack radiate in-phase, i.e. when vortices are arranged in a rectangular lattice. In the static case, the rectangular lattice is promoted by geometrical confinement if the junction length perpendicular to the magnetic field is reduced to $L \approx 4\lambda_J \approx 3 \mu$m [3], where $\lambda_J$ is the Josephson penetration depth.

The linewidth of emitted electromagnetic radiation can be decreased when the junctions are biased on resonances in the current voltage ($I$-$V$) characteristic. In the vicinity of resonances, the value of the differential resistance is small, which results in a decreased linewidth of the emitted THz signal [4]. Various resonances are known to exist in $I$-$V$ characteristics of IJJ: cavity resonances (Fiske steps) [5], resonances to external electromagnetic radiation (Shapiro steps) [6], a flux-flow step [7], and phonon resonances [8–11].

Here, we perform a detailed study of flux-flow characteristics and phonon resonances in small Bi(Pb)$_2$Sr$_2$CaCu$_2$O$_{8+x}$ (Bi(Pb)-2212) mesa structures. Magnetic field dependence of flux-flow characteristics up to 17 T and temperature and magnetic field dependence of phonon resonances at temperatures from 2 K to 80 K and in fields up to 15 T are analyzed. A shift of the phonon resonances in the presence of external magnetic fields is observed and the interaction between flux-flow and phonon-resonances is analyzed.
Figure 1. (a) $I$-$V$ characteristic at $T = 1.6$ K and $H = 0$, the branches are not traced out completely in this plot. (b) $I$-$V$ characteristics at $T = 1.6$ K in different parallel magnetic fields ($H = 4, 7, 10$ and $17$ T). The first four quasiparticle branches at $H = 0$ are shown for comparison. The inset shows the magnetic field dependence of the maximum flux-flow voltage per IJJ, calculated from the quasiparticle branch separation.

2. Experimental

Lead doped Bi(Pb)-2212 single crystals with $T_c = 91$ K were used in this study. Mesa structures were fabricated on top of single crystals by photolithography and argon-ion etching. The mesas were shaped by focused ion beam to reduce their area. Details of sample fabrication can be found in [12]. Measurements were performed at temperatures from 1.6 K to 79.2 K and in magnetic fields up to 17 T. The sample was placed on a rotatable sample-holder where the angle between the magnetic field and the sample could be varied in steps of 0.02°. In addition to $I$-$V$ characteristics, intensity (probability) plots were measured by sweeping the bias current and recording voltage vs. bias current over several thousands sweeps. The intensity is presented as a grayscale plot in the $I$-$V$ plane with a typical resolution of $2000 \times 2000$ pixel. Figure 1(a) shows the $I$-$V$ characteristic at $T = 1.6$ K of a mesa with size $1.9 \times 1.4$ µm², $I_c = 200$ µA and $N = 25$ intrinsic junctions in the stack (obtained from the number of branches in the $I$-$V$ characteristic). A contact resistance was subtracted from this and all other $I$-$V$ characteristics [3], except in Fig. 3(d).

3. Results and discussion

In magnetic fields parallel to the $ab$-plane, Josephson vortices penetrate the barriers and form a vortex lattice inside the stack of IJJ. The applied bias current exerts a Lorentz force on the Josephson vortex lattice which is pinned only at the edges of the junction. At the critical current, the vortices start to move due to the Lorentz force being greater than the pinning force. A flux-flow voltage is established across the stack which gives rise to a flux-flow branch in the $I$-$V$ characteristic. The Josephson vortices are accelerated to a maximum velocity equal to the velocity of electromagnetic waves $c_n$ inside the junction and a flux-flow (velocity matching) step appears at $V_{FFS} = H N_F s c_n$ [5], where $N_F$ is the number of junctions which are in the flux-flow state and $s$ the interlayer spacing in Bi-2212 ($s = 15$ Å). It should be noted that not all $N$ IJJ are necessarily in the flux-flow state ($N_F \leq N$), which creates uncertainty in the determination of $c_n$ from $V_{FFS}$.

In a stack of $N$ coupled Josephson junctions, $N$ different velocities of propagation of electromagnetic waves exist [13, 14]. Each velocity, corresponds to a different flux-flow mode. The mode with $n = N$ with the lowest velocity of electromagnetic waves corresponds to a
Flux-flow branch in parallel fields from 1 to 17 T at $T = 1.6$ K, inset shows magnetic field dependence of the maximum flux-flow voltage, determined from $I$-$V$ characteristics. The dashed horizontal line indicates the voltage position of the phonon at $N_{FF}V_2(H = 10$ T) = 139.4 mV, with $N_{FF} = 17$. (b) Flux-flow branch with normalized voltage and current shifted by a value corresponding to the position where $V/H = 1$ mV/T.

Figure 1(b) shows $I$-$V$ characteristics in parallel magnetic fields ($H = 4, 7, 10$ and 17 T) at $T = 1.6$ K. The first four quasiparticle (QP) branches at $H = 0$ are shown also. The effect of the magnetic field on the $I$-$V$ characteristic is an increase of the voltage where the IJJ switch to the QP-state due to the appearance of the flux-flow branch and a decrease of the separation of the QP-branches $\Delta V_{QP}$. At the maximum flux-flow voltage $V = V_{FFS}(H)$, $N_{FF}$ IJJ are in the flux-flow state, i.e. $V_{FFS}(H) = N_{FF}v_{FFS}(H)$, where $v_{FFS}(H)$ is the maximum flux-flow voltage per junction. On the first QP-branch, one junction has switched to the QP state, while the remaining $N_{FF} - 1$ junctions still are in the flux-flow state. The voltage on the first branch is $V = (N_{FF} - 1)v_{FFS}(H) + v_{QP}$, where $v_{QP}$ is the voltage per IJJ in the QP-state. On the second QP-branch, two junctions have switched to the QP-state and $N_{FF} - 2$ junctions are in the flux-flow state giving a voltage of $V = (N_{FF} - 2)v_{FFS}(H) + 2v_{QP}$ and so on for higher branches. The separation between the QP-branches is therefore reduced in the flux-flow state and is given by

$$\Delta V_{QP}(H, I) = v_{QP}(I) - v_{FFS}(H),$$

where it is indicated that $\Delta V_{QP}$ and $v_{QP}$ also depend on the bias current $I$, as seen in Fig. 1(b). The flux-flow voltage per IJJ can thus be calculated from measurements of $\Delta V_{QP}$. The result is shown in the inset of Fig. 1(b). Such a determination is unambiguous because it does not suffer from the uncertainty in $N_{FF}$. On the other hand, the maximum flux-flow voltage $V_{FFS}(H)$ over the stack of all IJJ can be obtained directly from the position of the flux-flow step. Figure 2(a) shows the flux-flow branch in fields from 1 to 17 T and $V_{FFS}(H)$ is shown in the inset. $V_{FFS}(H)$ is almost linear up to $\approx 10$ T and levels out at higher fields. The slope of $V_{FFS}$ vs. $H$ from 0 to 10 T is $V_{FFS}(H)/H = 11.0$ mV/T, whereas the data in the inset of Fig. 1(b) gives a slope of $v_{FFS}(H)/H = 0.65$ mV/T. From these two values the number of junctions in the flux-flow state is estimated to $N_{FF} = 17$. From $N_{FF}$ and $V_{FFS}(H)/H$, the mode velocity is calculated to $4.3 \times 10^5$ m/s. This value is higher than the velocity of the lowest mode $c_N \approx 2.5 - 2.7 \times 10^5$ m/s reported in Refs. [5, 7].

The flux-flow branch is linear for small voltages, see Fig. 2(a), but the slope $(dI/dV)$ increases rapidly at the flux-flow step. Figure 2(b) shows the flux-flow branch in normalized units:
Figure 3. (a) The first QP branch at temperatures from 5.1 K up to 79.2 K. The voltage positions of the resonances are indicated by dashed vertical lines. (b)-(c) I-V characteristics measured at $H = 5$ T and $T = 1.6$ K at two different angles $\theta$ between $ab$-plane and $H$. (b): $\theta = 0^\circ$, (c): $\theta = 2^\circ$. (d) Intensity plot at $H = 15$ T, $T = 1.6$ K and $\theta = 5^\circ$. Light/dark gray corresponds to high/low intensity, respectively. The phonon at $V_1$ is hysteretic. A contact resistance is not subtracted.

$I - I(V/H = 1$ mV/T) vs. $V/H$. By scaling this way, the curves almost coincide for fields above 8 T.

Figure 3(a) shows the first QP branch at temperatures from 5.1 K to 79.2 K. Phonon-resonances are clearly seen. The voltage positions of the phonon resonances are temperature independent as indicated by the vertical dashed lines. In total, six different resonances are observed at voltages $V_{(1-6)} = 6.1, 7.9, 11.2, 14.5, 20.5$ resp. 25.6 mV. The resonances are observed on all QP-branches and show hysteretic steps due to the one by one switching of the junctions from the resonant state to the unperturbed QP branch, see Fig. 3(b-d). Similar subgap structures where observed in cuprates Bi-2212 and Tl-2223 in Refs. [8–11, 15] and could be explained by the coupling of the Josephson oscillations to longitudinal phonons [10, 16] or by inelastic tunneling [17]. By applying a $c$-axis DC bias current to the stack of junctions, the voltage across the junction barriers is oscillating with a frequency given by the AC Josephson relation $f = V/\phi_0$. The time-dependent electric fields across the junctions can excite lattice vibrations along the $c$-axis. In zero magnetic field, the current and the electric field are distributed uniformly along the $ab$-plane, i.e. the excited lattice vibrations have no dispersion in this direction ($k_a = k_b = 0$), which implies that phonons are longitudinally polarized.

In Fig. 3(b-c), I-V characteristics at $H = 5$ T and $T = 1.6$ K are shown for two different orientations of the sample relative to the magnetic field. As the field is strictly parallel to the $ab$-plane [Fig. 3(b)], a flux-flow voltage appears and as discussed above, the QP-branch separation decreases, which affects the voltage positions of the phonon resonances. This means, for obtaining the true phonon voltages, one has to ensure that no junction is in the flux-flow state. This can be achieved by measuring at a small angle away from parallel orientation, allowing Abrikosov vortices to enter the junctions. Abrikosov vortices pin the Josephson vortex lattice and no flux-flow voltage is established [Fig. 3(c)]. In this work, phonon voltages were obtained from I-V characteristics or intensity plots measured at an angle $\theta = 2^\circ - 5^\circ$ away from parallel position. The phonon voltages were obtained by measuring the voltage position of the resonance on several QP branches and by linear regression calculating the ratio $V_i(j)/j = V_i$, where $V_i(j)$ is the voltage position of the resonance on the $j$th quasiparticle branch, see Fig. 3(b). A shift in the voltage position is observed: $V_1(H = 15$ T) - $V_1(H = 0$ T) = 0.6 mV and
\( V_2 (H = 10 \text{T}) - V_2 (H = 0 \text{T}) = 0.3 \text{mV} \). Even at 15 T, phonon resonances are clearly seen and are hysteretic, see Fig. 3(d).

Two mechanisms for the shift of the phonon resonances are possible. The first is a splitting of the quasiparticle density of states due to the Zeeman-effect [18]. In this case, the excitation is of electronic nature. The Zeeman energy is \( E_{\text{Zeeman}} = \mu_B H \) and is equal to 0.058 mV/T. The second mechanism is induced by the non-uniformity of the \( c \)-axis current density along the \( ab \)-plane in parallel magnetic fields. Due to the non-uniformity of the current density, the phonons have a dispersion \( k_{ab} \) along the \( ab \)-plane [19], which results in a change of the phonon frequency. Inspection of the inset of Fig. 2(a) reveals a kink at \( V_{FFS} = 72.8 \text{mV} \) or \( v_{FFS} = 72.8 \text{mV}/17 = 4.3 \text{mV} \). In Ref. [10] two phonon resonances were reported between 3.9 and 4.6 mV. The kink in the magnetic field dependence of \( V_{FFS} \) can be explained by the interaction between flux-flow and phonons [19, 20]; in the vicinity of a phonon resonance, the dielectric function \( \varepsilon \) diverges, i.e. the phase velocity of electromagnetic waves inside the junction changes. This means, the flux-flow voltage is no longer proportional to the magnetic field. In the same way, the fact that \( V_{FFS} (H) \) levels out at high fields, see inset of Fig. 2(a), can be explained by the presence of the phonon resonance at voltage \( V_2 \). In the figure, this is demonstrated by the horizontal dashed line at voltage \( N_{FF} V_2 (H = 10 \text{T}) = 139.4 \text{mV} \), with \( N_{FF} = 17 \). On the other hand, we cannot completely exclude the parasitic influence of Abrikosov vortices at so high field.

In summary, we have studied flux-flow and resonant phenomena in small Bi(Pb)-2212 mesa structures. A shift of phonon frequencies in parallel magnetic fields was observed. Also, an interaction between flux-flow and phonon resonances is observed and is explained by the change of the velocity of electromagnetic waves near a resonance. Resonant phenomena may be important for the use of intrinsic Josephson junction as THz oscillators, because of the decreased linewidth of emitted radiation when biasing the junctions near a resonance.

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