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Dual flux-to-voltage response of YBa$_2$Cu$_3$O$_{7-\delta}$

asymmetric parallel arrays of Josephson junctions

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Abstract

We fabricated a parallel array of 440 YBa$_2$Cu$_3$O$_{7-\delta}$ bicrystal grain boundary Josephson junctions having an inductive asymmetric loop configuration within the array. Families of current-voltage characteristics ($IVCs$) have been measured in the temperature range (4.7-92) K for various values of a magnetic flux applied via a control current $I_{ctrl}$. For both positive and negative current biases, $I$, current-driven chains of magnetic vortices are propagating along the array producing flux-flow current resonances on the $IVCs$. However, at 77 K and above, due to the system’s inductive asymmetry the flux-flow is suppressed (enhanced) for negative (positive) $I$. Consequently, the system shows a dual flux-to-voltage response. For negative $I$ it operates like a flux-interferometer having a rather sinusoidal $V(I_{ctrl})$ response. In contrast, for positive $I$ the device’s response $V(I_{ctrl})$ remains periodic but highly non-sinusoidal due to the interplay between multiple flux-flow modes. Below 60K such a dual behaviour is far less pronounced as a result of flux-flow modes being suppressed due to a decrease of the dissipation coefficient with temperature.
A parallel array of Josephson junctions (PAJJs) in an applied magnetic flux $\Phi$ can either exhibit flux-flow [1-5] or behave like a sensitive flux-to-voltage interferometer (magnetometer) [6]. When damping is low flux flow dominates PAJJ’s dynamics and they can be used as microwave generators [7-8] or superconducting transistors [9-10]. In both these cases the experimental signature of flux-flow is a series $m$ of current resonances on the current-voltage characteristics (IVCs) whose voltage positions change periodically with the flux $\Phi$. The flux periodicity is different for each current resonance $m$, and is given by a simple relation: $\Phi_0/m$ [3] (here $\Phi_0$ is the flux quantum). Consequently PAJJ’s voltage response $V(\Phi)$ although periodic in $\Phi_0$ is highly non-sinusoidal due to the interplay between multiple flux-flow current resonances, all having different flux periodicities. In contrast, when damping is high, flux-flow is weak and the current resonances have a reduced impact on the IVCs. As a result the PAJJ behaves like a flux-interferometer having a rather sinusoidal $V(\Phi)$ response [6]. All PAJJs investigated so far have been operated in either a flux-flow dominated regime or behaved as flux-interferometers. Here we report on a PAJJ device that simultaneously shows a flux-flow dominated highly non-sinusoidal $V(\Phi)$ response (for positive $I$) and a sinusoidal flux-interferometer-like $V(\Phi)$ response (for negative $I$). We induced such a dual behaviour by implementing an inductive asymmetric loop configuration within the array characterized by an enhanced flux-flow for positive $I$ and a suppressed flux-flow for negative $I$. This dual flux-to-voltage behaviour is evident for temperatures in the range (77-89) K, while below 60K is far less pronounced due to a decrease in the dissipation coefficient with temperature resulting in the flux-flow modes being suppressed. Primarily we fabricated such asymmetric APJJs in order to enhance both the current amplification in superconducting transistors [11] and the power of microwave generation at 77K and above [12]. Indeed, the inductance asymmetry ensures the bias current produces a net inhomogeneous magnetic field along the array through self-field effects that lacks inversion
symmetry and results in a highly asymmetric $I_c(I_{ctrl})$ curve with high current gains [11]. On the other hand, the asymmetry, ensures that the reflected vortices at the edges of the PAJJ do not propagate backwards deep into the array to destructively interfere with the incoming train of vortices. This protects the flow of vortices in one direction (to the left in Fig.1) and the associated electromagnetic radiation amplification [12]. Here we complete these reported investigations by showing the voltage response of such APJJs.

Since the flux-flow current resonances are the main feature in the IVCs we measured a brief summary of the physics behind it will be given next. When a magnetic field, $B$, is applied perpendicular to a $dc$ current-biased planar one-dimensional PAJJ, magnetic flux vortices will enter the array in the form of Josephson vortices. The bias current, $I$, flowing across the array produces a Lorentz force, $F_L$, which drives the Josephson vortices unidirectionally, forming a lattice of vortices moving with a speed, $v$. Theory shows that this is accompanied by an emission of small amplitude electromagnetic waves that propagate along the array [1]. When the vortex spacing is commensurate with the wavelength of emitted waves, resonant modes occur. This can be viewed as the phase-locking condition of the vortex velocity and the phase velocity of one of the self-induced modes. The experimental signature of such phase locking between a train of propagating vortices and their induced electromagnetic waves radiation in a PAJJ is a series of flux-flow current resonances on the IVCs [1, 2].

The PAJJs were fabricated by depositing high quality epitaxial, 100nm thick $c$-axis oriented YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) films on 10x10 mm$^2$, 24° symmetric [001] tilt, SrTiO$_3$ bicrystals by pulsed laser deposition [13]. A 200 nm thick Au layer was deposited in situ on top of the YBCO film to facilitate fabrication of high quality electrical contacts for electric transport measurements. The films with a critical temperature, $T_c$, of 92K were subsequently patterned by optical lithography and etched by an Ar ion beam to form a parallel array of 440
Josephson junctions (JJ). The array consists of 22 identical sets of 20 JJ each. All 440 JJ are 3 µm wide. The junctions are separated by superconducting loops of identical width (3 µm) but variable length. Thus, within each set of 20 JJ the length of the loops, and consequently, their inductance $L_i$, varies logarithmically from 13 µm to 8 µm. Consequently, the screening parameter $\beta_L = 2\pi L_i I_{cJ} / \Phi_0$ is also changing monotonically within each set of 19 superconducting loops. Here $I_{cJ}$ is the maximum Josephson critical current of each junction and $L_i$ is the inductance of the superconducting loop between JJ$_i$ and JJ$_{i+1}$, with $i=1, 2, ..., 19$.

An optical micrograph of a small part of such a PAJJ (containing 4 such sets of 20 JJ each) is shown in Fig. 1. We designed our PAJJ to have an average $\beta_L$ of about 1.5 at 77K. We also implemented an asymmetric inductive loop configuration within the array by varying the value of $\beta_L$ monotonically within each set of 20 JJs by about ±15% around its average. We chose a logarithmic dependence for $\beta_L$ because it introduces a smaller degree of asymmetry than a linear dependence. This asymmetry enhances (suppresses) the flux-flow for the case when the PAJJ is biased with a positive (negative) bias current. To understand this direction-dependent vortex-flow it is helpful to recall the mechanical analog of the system. The equations of motion of a PAJJ are identical of those of a chain of N identical pendulums, each of which is viscously damped and free to move transverse to the axis of the chain, driven by a constant torque, and coupled to its nearest neighbours by torsional springs $K_i$ [2]. Since $L_i$ varies monotonically along each set of 20 JJ so does the harmonic coupling $K_i$ along each set of 20 pendulums. A vortex corresponds to a kink (soliton) propagating along the chain. Since it is easier for a kink to propagate in the direction of decreasing $K_i$ than in the opposite direction it means the flux-flow is enhanced in the direction of decreasing inductance relative to the opposite direction. A similar asymmetric harmonic coupling $K_\tau$-induced ratchet potential that lacks inversion symmetry producing such a preferential directional motion for fluxons in JJ arrays has been previously investigated theoretically in.
The bias current, $I$, is applied symmetrically via the central top and bottom electrodes. A magnetic field, $B$, is applied perpendicular to the planar array’s structure via a control current $I_{ctrl}$. Consequently, an external magnetic flux $\Phi$ is coupled into the array. We have fabricated two such devices and both showed a similar behaviour.

Families of $IVC$’s were measured by a 4 point-contact method at various temperatures between 4.7K and 92K and for different values of the control current $I_{ctrl}$. Because the system is discrete, we expect both its voltage and current responses to be periodic in the applied flux $\Phi$ (proportional to $I_{ctrl}$) with period $\Phi_0$. The flux periodicity corresponds to one additional flux quantum $\Phi_0$ in each loop. Since the loop area within each set of 20 $JJ$ varies slightly by $\pm 15\%$ around its average value the flux periodicity should be understood in terms of a virtual average $\Phi_0$ in each loop. The experimental observation of a flux periodicity in a system that lacks a precise geometrical periodicity but has a quasiperiodical structure emphasises the robustness of the interference effects. Such a robust flux periodicity has been previously observed in $PAJJs$ that were not designed on purpose to be aperiodical but were inherently slightly aperiodical due to the intrinsic variation of both junctions and loops parameters along the array. $I_{ctrl}$ was varied in the range (-8mA, 8mA) in small steps of 15µA. This allows a scan over $\Phi$ that spreads over more than 8 periods at a given temperature with about 130 $IVC$’s per period. As a result, at all temperatures investigated (77-92) K the flux-flow resonances observed were much more pronounced for positive bias currents (the direction of $I$ in Fig.1) than for negative ones. It was even possible for vortices to propagate in the low damping direction only. This is confirmed by the experiments at T=89K where flux-flow resonances are observed for positive bias currents only (see Fig. 2). For all temperatures measured the current step corresponding to the $m=1$ resonance had an amplitude about the same as the array’s maximum critical current $I_c$. A family of 30 consecutive $IVC$’s measured at 89K are plotted in Fig. 2. From such families of $IVC$’s scanned over $I_{ctrl}$ (or equivalently,
$\Phi$, $I_c(I_{ctrl})$ for both positive and negative currents could be constructed (see Fig. 3). At temperatures this close to $T_c$ the discreteness parameter $\beta_L$ is much smaller than 1. We performed numerical simulations based on a model developed earlier [6] in the limit of small $\beta_L$ and from the modulation of $I_c$ with $I_{ctrl}$ we estimate an average value for $\beta_L$ of 0.3 at 89K. Within this model, as for the case of two-junction interferometers, critical current modulation decreases monotonically with T while $\beta_L$ increases monotonically with T. In the limit of $\beta_L << 1$, $I_c$ versus $\Phi$ is expected to have a periodic pattern consisting of a series of maxima similar to a diffraction pattern of an optical multiple slit grating [6]. This behaviour is confirmed by the experiments at 89K: see the $I_c(I_{ctrl})$ dependence for negative bias currents and 3 different voltage criteria $V_{cr}$ in Fig. 3 showing a symmetric and periodic pattern with a periodicity of about 2 mA. A single large flux-flow resonance is clearly visible for positive bias currents only (see Fig. 2). Its presence strongly affects the $I_c(I_{ctrl})$ dependence for positive values which now consists of a periodic two peak structure instead. The family of 30 $IVCs$ shown on Fig. 2 corresponds to an $I_{ctrl}$ range covering precisely this periodic two peak structure. The current step resonance, corresponding to $m=1$, is tunable by varying $\Phi$ i.e., its voltage location strongly depends on $\Phi$ and, as expected, it has the same periodicity as $I_c(I_{ctrl})$. No such resonance is observed for negative bias currents (see the inset of Fig. 2) due to the inductance asymmetry along the array, as explained earlier. At lower temperatures (77-84)K $\beta_L$ increases due to an increase in $I_{cl}$ and, as expected, multiple flux-flow resonances are observed corresponding to $m=1, 2, 3$ and 4. Again, due to inductance asymmetry along the array, these resonances are much more pronounced for positive current biases. The impact of $PAJJ$’s asymmetry on the families of $IVC$’s at 81K and 77K, shown in Figs. 4 and 5, respectively, is evident. Firstly, the flux modulation of both current and voltage are significantly stronger for negative current biases (see Figs. 4a and 5a). Secondly, the voltage response $V(I_{ctrl})$ (see Figs. 4b and 5b) can be approximated, to a better degree than the case of
positive current bias, as sinusoidal for all negative current biases, while it is highly non-
sinusoidal for positive current biases. Then, for positive (negative) currents the extreme
values in $V(I_{ctrl})$ are reached for different (approximately the same) values of $I_{ctrl}$ as we
change the current criteria $I_c$ from 0.4 mA to 1 mA (-1 mA to -0.4 mA) in Fig. 4b and from
0.5 mA to 1mA (-1 mA to -0.5 mA) in Fig. 5a. Also, the amplitude of voltage modulation is
considerable larger for negative currents relative to the positive currents. It is important to
note that the families of $V(I_{ctrl})$ recorded for different current biases $I$ plotted in Figs. 3b, 4b
and 5b, they all lack inversion symmetry with respect to 0. This is because the PAJJ is not
magnetically screened and therefore the presence of the earth magnetic field breaks such
symmetry. Since the perpendicular component to the PAJJ planar structure of the earth
magnetic field $B_{normal}$ is about 25 $\mu$T it requires a significant shifting along the $I_{ctrl}$ current
axis in order to compensate for the earth magnetic field and therefore recover the inversion
symmetry. Indeed, the magnetic field corresponding to $I_{ctrl}=1.8$mA (the current period of
$V(I_{ctrl})$ curves) is about 2.4 $\mu$T which is much smaller than $B_{normal}$. The differences in the $IVCs$
and $V(I_{ctrl})$ between the positive and the negative current biases are far less pronounced at
temperatures below 60K. An example is shown in Fig. 6 for $T=57.5$ K. Similar characteristics
have been measured at several other temperatures below 60K, namely, at 4.7K, 10K, and 30K.
Indeed, the $IVCs$ have a good degree of symmetry at these temperatures (see Fig.6a). Also, in
this temperature range the $V(I_{ctrl})$ response becomes aperiodic (see Fig.6b) due to a significant
suppression of the flux-flow modes due to a decrease in the dissipation coefficient $1/R_N$ (or
damping) with temperature (here $R_N$ is the normal resistance of the Josephson junction). A
similar suppression of the flux-flow with decreasing T has been previously observed (both
theoretically and experimentally) in PAJJs made of niobium low temperature
superconductors [4, 5].
Conclusion

In conclusion, we have shown that an inductive asymmetric loop configuration within the array implemented in our PAJJ leads to a significant difference in the flux-flow for positive current biases relative to negative current biases and consequently to a corresponding different qualitative flux-to-voltage response. To achieve both an enhanced current amplification [11] and an enhanced microwave power generation [12] a PAJJ has to be operated in a regime of enhanced flux-flow, i.e., it should be biased with a positive current. The degree of asymmetry of our design can be further extended to enhance the contrast in the directional flux-flow and to improve PAJJs performances in these applications.

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References


[13] The films were deposited by Theva GmbH.

Figure captions

Fig. 1. Optical micrograph of the PAJJ made of a parallel array of 22 identical sets of 20 JJ. Shown is a small central part of the array consisting of 4 sets of 20 JJ. Within each set all 20 JJ are 3µm wide and are connected via superconducting loops of identical width (3µm) and variable length (logarithmically decreasing from 18µm to 13µm).

Fig. 2. A family of 30 consecutive IVCs recorded at 89K for different values of I_{crt}. The horizontal arrow shows the m=1 flux-flow current resonance’s direction of motion in the IV plane when increasing I_{crt}. The family is shown in 3 sets of 10 IVC’s each. For clarity IVCs 11 to 20 (21 to 30) have been shifted vertically by 0.1 mA (0.2 mA). The first (last) IVC within each set is shown in blue (red). The inset shows the same family of 30 IVCs for negative biases.

Fig. 3. (a) I_c(I_{crt}) and (b) V(I_{crt}) at 89 K for various voltage criteria V_{cr} and bias currents (criteria) I_{cr}, respectively. To obtain I_c(I_{crt}) and V(I_{crt}) one should draw straight lines parallel to the current axis at V_{cr}, and, respectively, parallel to the voltage axis at I_{cr} and consider the points where those lines cross the IVCs.
Fig. 4 (a) A family of 300 consecutive IVCs recorded at 81K for different values of $I_{ctrl}$ in the range (-2.25, 2.25) mA. $I_{ctrl}$ is changed in steps of 15 µA. (b) $V(I_{ctrl})$ for various bias currents $I_{cr}$ in the ranges (-1, -0.4) mA and (0.4, 1) mA.

Fig. 5 (a) A family of 256 consecutive IVCs recorded at 77K for different values of $I_{ctrl}$ in the range (-2.325, 1.5) mA. $I_{ctrl}$ is changed in steps of 15 µA. (b) $V(I_{ctrl})$ for various bias currents $I_{cr}$ in the ranges (-1, -0.5) mA and (0.5, 1) mA.

Fig. 6 (a) A family of 115 consecutive IVCs recorded at 57.5K for different values of $I_{ctrl}$ in the range (0, 4.56) mA. $I_{ctrl}$ is changed in steps of 40 µA. (b) $V(I_{ctrl})$ for various bias currents $I_{cr}$ in the ranges (-3, -1) mA and (1, 3) mA.
Figure 2

Current (mA) vs Voltage (µV) at a temperature of 89K. The data shows IV curves labeled as IVCs, with changes in the control current, $I_{ctrl}$, of 15 µA. The legend indicates different ranges of IVCs: 1-10, 11-20, 21-30.
Figure 3
Figure 4

(a) Voltage, $V$ (µV) vs. Control Current, $I_{\text{ctrl}}$ (mA) at $T=81$K. $I_{\text{ctrl}}$ changes by 15 µA. $I_{\text{ctrl}}$ range: (-2.25, 2.25) mA. Flux-interferometer region and flux-flow resonances region.

(b) Voltage ($V$) vs. Control Current ($I_{\text{ctrl}}$) at $T=81$K. Various $I_{\text{ctrl}}$ values shown with different colors.
Figure 5

(a) Current, $I$ (mA), vs. Voltage, $V$ ($\mu$V) at $T=77$K. The control current $I_{ctrl}$ changes by 15 $\mu$A. The $I_{ctrl}$ range is (-2.325, 1.5) mA. Two regions are highlighted: the flux-flow resonances region and the flux-interferometer region.

(b) Voltage, $V$ ($\mu$V), vs. Control Current, $I_{ctrl}$ (mA) at $T=77$K. The data points are shown for different $I_{ctrl}$ values, indicated by the color bar on the right.
Figure 6

(a) Current, $I$ (mA) vs. Voltage, $V$ ($\mu$V) at $T=57.5$ K. $I_{ctrl}$ changes by 40 $\mu$A, $I_{ctrl}$ range: (0, 4.56) mA.

(b) Voltage, $V$ ($\mu$V) vs. Control Current, $I_{ctrl}$ (mA) at $T=57.5$ K.