Tuning the Current-Voltage Characteristics of Josephson Junctions by Strong Microwave Fields

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Abstract. We observe some unusual resonance-like structures on the current-voltage characteristics (CVC) of thin film ramp-edge Josephson junctions between YBCO and Nb when applying strong microwave fields (MW). The unusual resonances have their voltage position on the CVC dependent on the MW power rather than the MW frequency, while their amplitude is largely unaffected by an increase in the MW power. Such behaviour indicates an intriguing Josephson dynamics associated with the switching from a parametric excitation regime induced by the magnetic field of the MW via oscillations of the Josephson critical current to an ac-current excitation regime triggered by the electric field of the MW. We propose a model, which describes the experimentally observed features on the CVC in terms of MW-induced multiple switching between running and locked solutions of sine-Gordon equation. Such tuning of the CVC via MW could be used to optimize the output of THz emitters.

1. Introduction

Recently a growing interest to the studies of dynamics of the Josephson junctions (JJ) was stimulated by proposals [1-3] and realizations [4-6] of several novel THz devices based on layered superconductors (like Bi2212), which can be modelled as a stack of identical intrinsic JJs. A remarkable step toward the realization of superconducting THz electronics was the observation [5] of tunable THz radiation from mesa Bi2212 samples achieved for a proper choice of the applied dc current, $I_{dc}$: that is, radiation was detected only at certain operating points of current-voltage characteristics (CVC). For a single JJ, as well as for a stack of identical junctions as in the experiments [5], with increasing $I_{dc}$, the CVC curve describes the so called zero-voltage branch (where the voltage $V$ is almost zero) up to the critical current $I_c$ followed by a sudden jump to the resistive branch where $V$ is proportional to $I_{dc}$. When decreasing $I_{dc}$, the voltage smoothly decreases and drops to zero when the dc current becomes smaller than a so-called return current $I_r < I_c$ [7]. For currents in the interval $I_r < I_{dc} < I_c$, the CVC is characterized by a hysteresis, i.e., the CVC has two solutions. Interestingly, the strong radiation from the Bi2212 mesa was observed only at the resistive branch of the CVC, which

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was associated to a special matching condition between the wave-length of the THz radiation and the sample size [5]. Thus, to achieve a strong radiation from JJs we need to develop an approach allowing us to tune the CVC until resonance conditions are met. In this work we show experimentally that the control of the CVC can be achieved if a strong microwave signal (MW) is applied to a JJ. We observe that the hysteresis on the CVC is completely suppressed and that several shallow resonance-like structures are clearly visible on the CVC. As the MW power is increased the voltage position of such resonances increases monotonically. Such a behaviour is in striking contrast to another MW-induced effect, namely the appearance of Shapiro-steps [7] on the CVC, also observed in these junctions [8]. Indeed, the Shapiro current resonances appear at voltages that are independent on the MW power and are solely related to the MW frequency. Then, the amplitude of Shapiro-steps is strongly affected by the MW power, in contrast to the case of the observed shallow resonances. To understand Shapiro-steps it is enough to assume that the MW produces an alternating electric field of the same frequency across the junction which in turn induces an alternating current. To explain the formation of the observed unusual resonances, we assume instead that the MW produces both an alternating electric field E and an alternating magnetic field H. The significance of H is that it induces oscillations of the Josephson critical current. That triggers an intriguing Josephson dynamics associated with the switching from a parametric excitation regime induced by the magnetic field of the MW via oscillations of the Josephson critical current to an ac-current excitation regime triggered by the electric field of the MW. The model describes experimentally the observed features on the CVC and could be used to optimize the output of THz emitters.

2. Experiments

We prepared thin film ramp-edge junctions between 170 nm untwinned YBa$_2$Cu$_3$O$_{7-x}$ and 150 nm Nb using a 30 nm Au barrier. In this work we are considering junctions for which tunnelling occur in the ab plane either in the [010] or [100] direction. A total of 8 junctions have been measured, all being 4 µm wide. So far, there have been several reports on these junctions that address junction fabrication [9], superconducting order parameter issues [10], Andreev bound states-induced zero-bias anomaly in the quasiparticle tunnelling [11], and microwave-induced Shapiro steps [8].

We are going to focus on a single representative junction only for which tunneling occurs along [010] direction (for more details see [12]). Two qualitatively different behaviours are observed. First behaviour is for a frequency f of the applied MW in the range 0.01 < f/f$_J$ < 0.1 in which case Shapiro steps appear at integer n multiples of the voltage V$_n$, satisfying the Josephson voltage-frequency relation f/V$_n$ = 0.486 GHz/µV. Here f$_J$ = ω/2π = (eI$_C$/2πC)${0.5}$ is the characteristic (Josephson) plasma frequency of the junction (typically of about 100 GHz) and C is the capacity of the contact. This behaviour is well understood [7] and it will not be the subject of further investigation in this work. It has to be added, however, that no trace of half-integer Shapiro steps at multiples of V$_{2/2}$ were observed strongly suggesting a purely sinusoidal current-phase relation for the Josephson junctions [8]. The latter observation allows us to apply the usual sine-Gordon equation for the analysis of CVC in our samples. A second MW-induced behaviour can be summarized as follows. With increasing the MW power, the CVC of the junction changes drastically (see Fig. 1a): the hysteresis is strongly suppressed, and some intriguing structures that includes sharp changes in the CVC slope appear (which are reminiscent of shallow resonances). In contrast to the case of Shapiro-steps which are located at equidistant voltages that are independent on the amplitude of the MW power, the voltage position of the obtained structures on the CVC monotonically increases with the MW power (see Fig. 2). Thus, as MW power increases the peak position of the first resonant-like structure shifts in the direction indicated by the big arrows in Fig.1a. Then, as shown by the vertical arrows in Fig.1a the peak voltage position of the second resonance-like structure shifts toward higher values as well. These resonance-like structures are very robust against a change in f in the range 0.001 < f/f$_J$ < 0.1 and are most pronounced at lower frequencies in the range 0.001 < f/f$_J$ < 0.01 where Shapiro steps are not observed anymore. To our knowledge, such structures on CVC have never been investigated so far.
3. Theory

To model the CVC of the junctions measured, we assume that the magnetic field of the MW, \( H(t) = H \sin(2\pi ft) \) induces an ac current in the sample and the amplitude of this current \( I_{ac} = kH \). The coupling constant \( k \) is determined by the circuit parameters and depends, in general, on \( f, I_{dc} \) and \( H \). So, the current flowing through the junction is the sum \( I(t) = I_{dc} + I_{ac}(t) \). To compute the CVC of the junction \( V = V(I_{dc}) \) we first solve numerically the following equation for the JJ phase difference \( \psi \) ( [12] ) :

\[
\psi + \psi / \sqrt{\beta} + J(\tau) \sin \psi = i(\tau).
\]

Here \( i(\tau) = I(\tau)/I_c \) with \( I(\tau) \) being the total current flowing through the JJ, \( \tau = \omega t \) is the normalized time, and the dots above the variable represent the time derivative. \( J(\tau) \) can be interpreted as a dimensionless critical current modulated by \( H \) (for more details see [12]). Then we calculate \( V = \Phi_0 \omega t \langle d\psi / d\tau \rangle \) (here \( \langle ... \rangle \) means time average) for every dc bias current \( I_{dc} \), so that finally the CVC is obtained. Some results of the simulations are shown in Fig. 1b. In the calculations the values of all the sample parameters are determined from the measurements. However, the coupling constant \( k \) and numerical value of the MW field amplitude \( H \) could not be found accurately so that they are used as fitting parameters. The relative values of \( H \) for different CVCs are kept as in the experiments. Our simulations reproduce the characteristic features of the experimental curves including the very delicate crossings of CVC curves at different amplitudes. Comparing the experimental and theoretical curves in Fig.1, we can see a good agreement: the hysteresis is suppressed by the MW radiation, the curves intersect each other and the resonance-like structures are shifted towards higher voltages with increasing MW power.

Figure 1: The CVC for a [010] junction (\( I(0) = 82 \mu A, f_J = 108 \) GHz, and \( R = 4 \) Ohm) at different applied MW power. With increasing MW power of frequency 0.5 GHz the peak position of the first resonant-like structure shifts in the direction indicated by the big arrows. Vertical arrows show the peak voltage position of the second resonance-like structure.

(a) Experimental curves. MW power increases by 1 db from -5 to 10 db.
(b) Calculated CVC: (1) -10 db and \( k = 0.02 \), (2) 0 db and \( k = 0.02 \), (3) 4 db and \( k = 0.02 \), (4) 7 db and \( k = 0.1 \), (5) 10 db and \( k = 0.1 \), dashed line 20 db and \( k = 0.1 \).
4. Conclusions
We experimentally observed some unusual MW-induced resonant-like structures on the dc CVC of thin film ramp-edge Josephson junctions made between YBCO and Nb. As we increase the MW power the voltage position of the resonances increases monotonically. However, the amplitude of the resonances is largely unaffected by that. This behaviour can be qualitatively described within a modified sine-Gordon model by assuming that the applied MW has both an electric field component producing an MW current and a magnetic field component suppressing the Josephson critical current. The obtained results suggest a way to control the shape of the CVC, allowing us to reach voltages within a considerable wide range at a given dc bias current. This control can be potentially useful for the recently proposed and realized THz emitters to fit necessary resonance conditions.

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