Microwave-induced zero-current crossings in $Bi_2Sr_2CaCu_2O_{8+y}$ intrinsic Josephson junctions

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Abstract

Current-voltage characteristics in mesa-structured $Bi_2Sr_2CaCu_2O_{8+y}$ intrinsic junctions under in-plane magnetic fields reveal zero-current crossings (ZCCs) when microwave is applied. From measurements with controlled number of junctions ($N = 5 \sim 14$), we find that the number of ZCCs is just N in total of positive and negative bias sides; half of the $2N$ branches observed without microwave. Unlike Shapiro steps, the voltage step increases with microwave amplitude. Such features can be explained by considering the charging effect of superconducting layers and the pinning of triangular Josephson vortex lattice.

Key words: Intrinsic tunneling; Current-voltage characteristics; Shapiro step; Josephson vortex

1. Introduction

Layered superconductors with large anisotropy naturally contain superconducting / insulating / superconducting layers, which consists Josephson junctions. Such intrinsic junctions provide a wide variety of new fundamental physics such as collective Josephson plasma excitations and also open ways for various technological applications. The most studied is $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO) high temperature superconductor, whose current-voltage characteristics along the c axis shows unambiguous Josephson effects.

Recently, current-voltage (I-V) characteristics in the intrinsic junctions of BSCCO revealed anomalous microwave-induced steps, which cross the zero-current line [1,2]. Such zero-current crossing (ZCC) step voltages are orders of magnitude larger than the expected voltages of the conventional Shapiro steps, which are observed in the THz frequency range [3]. This novel ZCC has been attributed to the phase-locking fluxon motion in the junctions [1]. However, since the measurements have been done on the crystals containing hundreds of junctions, the understanding of this phenomenon remains far from being established. Here we explore detailed studies of the ZCCs under parallel applied field in BSCCO mesas with controlled number of junctions, and propose a new model to explain the ZCC.

2. Experimental

The mesas were carved out of cleaved BSCCO crystals by ion milling. The number of junctions N was controlled by the milling time and was experimentally determined from the number of branches in the zero-field I-V characteristics. In this study we used 4 samples containing 5 to 14 junctions. Magnetic fields up to 9 T were applied nearly parallel to the planes. Microwave up to 20 GHz is applied through a coaxial cable connected to one of the contacts.

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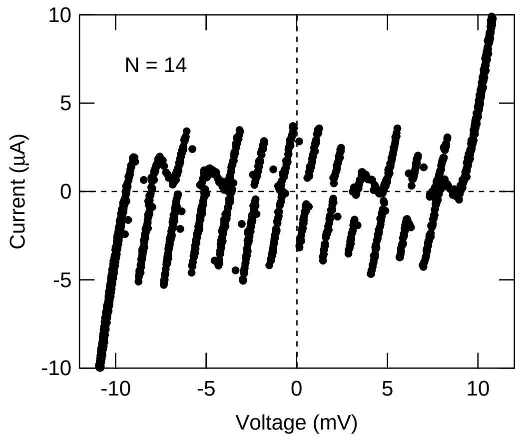

Fig. 1. I-V characteristics of a BSCCO mesa containing 14 junctions at 10 K. Magnetic field of 0.8 T is applied almost parallel to the planes and 9.33 GHz microwave is irradiated.

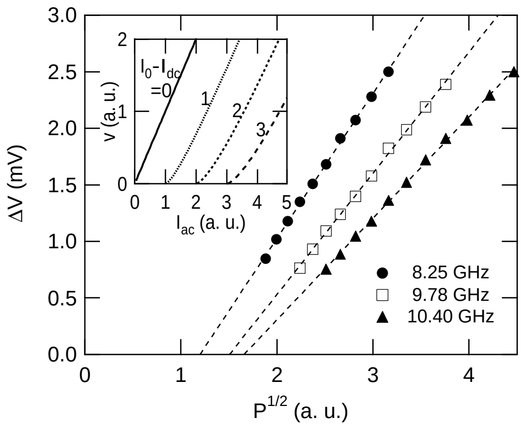

Fig. 2. Step voltage ΔV as a function of microwave amplitude $P^{1/2}$ at fixed frequencies. The mesa contains 10 junctions and magnetic field is 1.3 T. The inset shows Josephson vortex velocity v as a function of microwave current I_{ac} in the simple pinning model.

3. Results and Discussion

Figure 1 shows a typical I-V result in the sample with 14 junctions. In this sample ($N = 14$) we observed 7 ZCC steps in the positive bias side, the number of which is just a half of the number of branches without microwave (or the number of junctions N). Such a feature is observed in all the samples measured in this study. The number of steps does not change in the frequency range we measured. In contrast, the step voltage ΔV does depend on frequency and microwave power P. In Fig. 2 we plot ΔV as a function of microwave amplitude ($\propto P^{1/2}$) at different frequencies. The ZCC step voltage depends linearly on microwave amplitude, and the lines extrapolate not to the zero amplitude but to a finite amplitude. This indicates that there is some critical microwave amplitude beyond which ZCC steps are induced.

The voltage across Josephson junctions is closely related to the net velocity v of the Josephson vortices (JVs) moving along the junctions. In our model, the pinning of JVs plays an essential role; only when the total current I_{total} flowing across each junctions exceeds a critical value I_0, JV starts to move. Such pinning can occur when the field direction is not exactly parallel to the planes, since in that case we have both JVs and pancake vortices (PVs) [4] and PVs can pin the JVs owing to their attractive interactions. If we assume that the net force is proportional to $I_{total} - I_0$ and $I_{ac} \leq I_0 + I_{dc}$, v is found to be proportional to

$$I_{ac} \sin\left[\cos^{-1}\left(\frac{I_0 - I_{dc}}{I_{ac}}\right)\right] - (I_0 - I_{dc})\cos^{-1}\left(\frac{I_0 - I_{dc}}{I_{ac}}\right),$$

where I_{ac} is the microwave current amplitude and I_{dc} is the dc current flowing across the junctions. A typical result of the calculated v as a function of I_{ac} with several $I_0 - I_{dc}$ values is shown in the inset of Fig. 2. This simple model naturally explains the observed critical amplitude and the linear amplitude dependence of ΔV.

Finally, the number of steps can be explained by the structure of the JV triangular lattice. At zero field without microwave, we have N branches in the I-V curve when N junctions have the same quality. This has been understood by the inhomogeneous current distribution along the c axis due to the charging effect of superconducting planes [5]. Now in our case the symmetry is lowered by the triangular JV lattice and each two neighboring junctions have lower phase coherence. In this case, the effective number of the same-quality junctions can be considered as $N/2$, which may lead to $N/2$ steps as observed in our experiments.

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