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Physica C 293 (1997) 174–180

PHYSICA C

Intrinsic Josephson effects on stacks fabricated from high quality BSCCO 2212 single crystal whiskers

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Abstract

Measurements of the critical current I_c along the c-axis as a function of the parallel magnetic field H clearly demonstrate the intrinsic DC Josephson effect on small area stacks fabricated from perfect single crystal $Bi_2Sr_2CaCu_2O_8$ whiskers with in-plane size, L, less than 20 μm. Flux-flow steps on current voltage characteristics on overlap stacked analogues of long Josephson junctions have been found due to a collective motion of Josephson vortex lattice. The results on the microwave response of small junctions are also discussed. © 1997 Elsevier Science B.V.

1. Introduction

The ideas of realization of the Josephson effects on natural layered crystalline structure of layered superconductors, i.e. intrinsic Josephson effects (IJE), appeared in early 1970s [1,2] when the first quasi-two-dimensional superconductors were synthesized. Further development of these ideas was stimulated by the discovery of highly anisotropic layered high-T_c materials as BSCCO and TBCCO. It became clear that to realize IJE one needs to have a perfect single crystal stacked structure with very small lateral size L_{ab} compared with Josephson penetration length λ_j [3]. λ_j is defined as $\lambda_j = s\lambda_c/\lambda_{ab}$ with s the spacing between elementary superconducting layers, and λ_c, λ_{ab} are anisotropic London penetration lengths. The estimation of λ_j for BSCCO gives a value ~ 1 μm.

First evidence of IJE was obtained on rather bulk BSCCO single crystals with $L = 30–100$ μm [4,5]. Microwave emission was observed with phase synchronization of only a few percent of the total number of elementary junctions.

Considerable further efforts were directed into fabrication of stacked junctions with smaller sizes [6,7]. Micrometre-scale structures have been developed on epitaxial BSCCO films with tilted c-axis [8] and mesa structures patterned on epitaxial films [9–12]. Recent studies of these structures revealed that observation of IJE is very much dependent on film quality (grain size, epitaxy conditions etc.) and correctly chosen geometry of the experiment.

We have developed a method of fabrication of intrinsic Josephson stacks from single crystal $Bi_2Sr_2CaCu_2O_8$ (2212 BSCCO) whiskers, grown by a Pb-free method [13]. In this paper we will present results of our recent studies on these stacked structures.

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PII S0921-4534(97)01534-7

2. Experimental

Thin 2212 BSCCO whiskers have been characterized [13] as perfect objects. They grow along the [100] direction free of any crucible or substrate and can be entirely free of macroscopic defects and dislocations. We use these whiskers as the basis for fabrication of small *ab*-plane area structures for studies of IJE [14]. The steps of the fabrication process using ion plasma etching are shown in Fig. 1b–e. Junctions have rectangular geometry in the *ab*-plane, the edges being parallel to the *a*- and *b*-axes (see Fig. 1a). Different junctions have been prepared with dimensions L_a, L_b between 200 μm and 5 μm. Along the *c*-axis typically they contain 20–100 elementary junctions. Stacked junctions were mounted onto sapphire substrates and four contacts were prepared with silver paste. The contact resistance ranges from 1 to 5 Ω after annealing in oxygen flow at 450°C.

The critical current density across the layers I_c measured at 4.2 K with a voltage criterion of 1 μV was 5×10^2–2×10^3 A/cm^2 and it did not change significantly with temperature up to $T/T_c \approx 0.75$. This value is about three orders of magnitude smaller than a longitudinal value of 5×10^5 A/cm^2 for samples of the same batch [13].

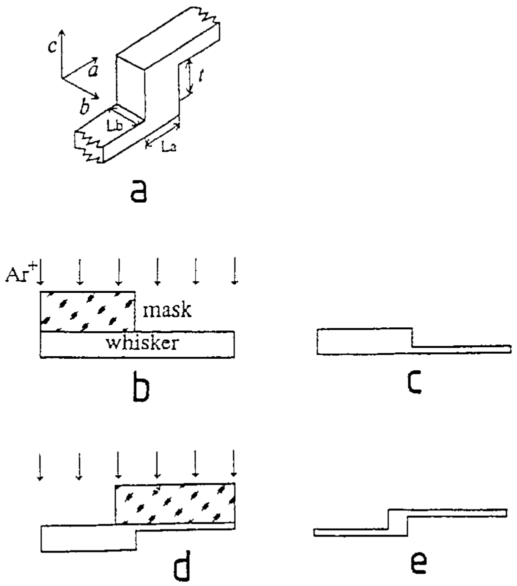

Fig. 1. The stacked structure etched on a $Bi_2Sr_2CaCu_2O_8$ single crystal whisker: (a) crystallographic orientation of the structure, (b)–(e) the steps of the ion etching procedure.

3. DC intrinsic Josephson effect

The pure DC IJE is theoretically predicted [3] only for small junctions with in-plane size L_{ab} smaller than λ_j. In that case I_c as a function of the magnetic field H parallel to the layers exhibits a Fraunhofer behaviour such as:

$$I_c(H) = I_c(0)\left|\sin(\pi sLH/\phi_0)/(\pi sLH/\phi_0)\right|, \tag{1}$$

with ϕ_0 the flux quantum, L the junction size perpendicular to H. $I_c(0)$ is the maximum Josephson current across the layers which is defined by current density $J_c(0)$:

$$J_c(0) = c\phi_0/\left(8\pi^2 s\lambda_c^2\right). \tag{2}$$

The first minimum of $I_c(H)$ appears at $H_1 = \phi_0/sL$.

For junctions with larger size, the Josephson behaviour is disturbed by Josephson vortices entering the junction [15].

In the case of $L > \lambda_j$, a recent calculation [16] predicts an universal size independent decrease of $I_c(H)$

$$\frac{I_c(0) - I_c(H)}{I_c(0)} \approx \sqrt{H/H_0}, \tag{3}$$

with H_0 a constant field characterizing the layered superconductor, $H_0 = \phi_0\lambda_{ab}/\pi^2 s^2\lambda_c$, and the same $I_c(0)$ as in Eq. (1). Previous experiments [5–7] have not clearly demonstrated the two regimes and the crossover between them, when L is varied.

We have studied the $I_c(H)$ behaviour for a number of stacks with different lateral sizes. For large junctions with 40 μm $< L <$ 200 μm, we have observed a rapid monotonous drop of $I_c(H)$, independent of the junction size. The data follow the expected $\sqrt{H/H_0}$ law with $H_0 \sim$ 700–800 Oe. Using the theoretical expression for H_0, we deduce $\gamma = \lambda_c/\lambda_{ab} \sim 1300$. Using this value for γ we estimated the value of maximum Josephson current density (Eq. (2)) for our junctions. We used $\lambda_{ab} = 0.3$ μm, $s = 15$ Å. It gives $J_c(0) \sim 1.5 \times 10^3$ A/cm^2 which is quite consistent with our experimental values.

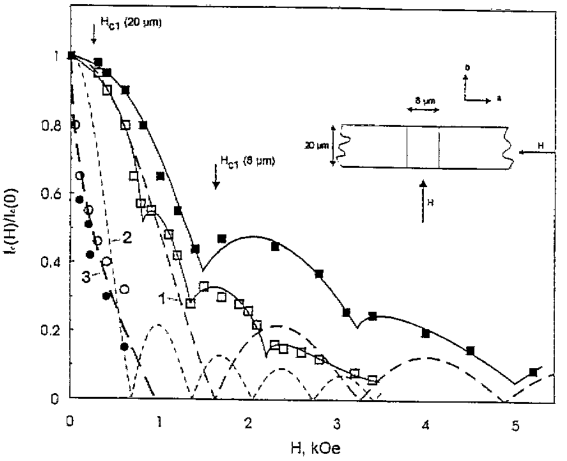

Fig. 2. Normalized dependencies of critical current of $Bi_2Sr_2CaCu_2O_8$ junctions across the layers $I_c(H)/I_c(0)$ at $T = 4.2$ K on magnetic field H parallel to the layers for samples of different sizes L: ■ 8 μm, □ 20 μm, ● 40 μm, ○ 200 μm. Solid lines are guides to the eyes. Dashed curves 1 and 2 correspond to Eq. (1) for $L = 8$ and 20 μm, respectively. Curve 3 corresponds to Eq. (3) for $H_0 = 950$ Oe. H_{c1} indicates the field above which Josephson vortices penetrate the junction. Insert shows the geometry of the junction for which H has been rotated and applied ||a and ||b respectively.

With $L < 30$ μm, oscillations in $I_c(H)$ begin to appear. For the junction with $L = 8$ μm, we have observed three oscillations with a period of 1.5 kOe. The period of oscillations decreases with an increase in the sample size as directly demonstrated on a junction with $L_a = 8$ μm and $L_b = 20$ μm by rotating H in the ab-plane (Fig. 2).

From the minima fields in the oscillations of $I_c(H)$ it is possible to deduce the value of s such as $s = \phi_0 n / L H_n$. Our data yield exactly the value of 15 Å (with a dispersion less than 10%) corresponding to a half of the lattice constant along the c-axis.

Our data for junctions with a size smaller than 20 μm prove the predicted Josephson behaviour of $I_c(H)$ [3]. When L is increased above 20 μm, a crossover occurs to the behaviour predicted in [16].

4. AC intrinsic Josephson effect

The AC Josephson effect in layered structures can be identified in different ways, for instance for short stacks with $L < \lambda_j$, by observation of constant voltage steps (Shapiro steps) in current–voltage characteristics (IVC). For a single junction the voltage of the m-th step, V_m, and the microwave frequency ν are related by the Josephson equation: $V_m = m(h/2e)\nu$ were h is the Plank constant and e is the electron charge. For layered stacks containing N elementary junctions in series this relation is modified as:

$$V_m = Nm(h/2e)\nu. \qquad (4)$$

For longer junctions the AC Josephson effect can be associated with fluxon motion when H is applied parallel to the junction. Fluxons can be moved by a current flowing through the junction and their motion leads to electromagnetic radiation. The frequency of radiation ν is given by the Josephson relation:

$$\nu = (2e/h)V = cV/\phi_0, \qquad (5)$$

where V is the DC voltage induced by the fluxon motion. Different modes of coherent fluxon motion can be realized in a long junction. We consider here flux-flow regime which is manifested by a flux-flow step in the IVC.

Below, we will consider our experiments on flux-flow mode in long stacks and then describe the experiments on shorter stacks in a microwave field.

4.1. Flux-flow mode in parallel magnetic field

In flux-flow regime, fluxons are created at one boundary of the junction and annihilate at the other boundary. The radiation frequency ν is determined by the fluxon velocity v and the spacing between moving fluxons Λ as $\nu = v/\Lambda$. Combining that with Eq. (5) we get the voltage corresponding to the flux-flow mode:

$$V = (v/c)(\phi_0/\Lambda). \qquad (6)$$

A resonance occurs when v becomes equal to the velocity of the electromagnetic field propagation in the junction, $\bar{c}$: Swihart velocity (see [17]).

Similar phenomenon can be expected in layered superconductors in high enough parallel magnetic fields. Recently it was deduced [18] that in a parallel field a triangular lattice of Josephson vortices should be formed. In field $H > \phi_0/\gamma s^2$ the non-linear regions of vortices overlap strongly because the intervortex distance Λ along the ab-plane becomes smaller than λ_j. All the interlayer spacings become filled by vortices forming a triangular lattice. Such a dense lattice was shown to be rigid enough to move as a whole [19] when the current is driven across the layers. The resonance can appear when the lattice velocity $\bar{v}$ is equal to $\bar{c}/2$, where $\bar{c}$ is the Swihart velocity for layered materials:

$$\bar{c} = cs/\left(\lambda_{ab}\sqrt{\varepsilon_c}\right), \tag{7}$$

where ε_c is the dielectric constant between conducting layers.

We have undertaken a search for this effect in our overlap structures with $L_a = 8$ μm, $L_b = 20$ μm and $H \| a$. The value of H was varied up to 1.5 T. That is about twice as large as the characteristic field $\phi_0/\gamma s^2$ for our case. At fields ≈ 0.5 T, the critical current $I_c(H)$ becomes negligibly small, $I_c(H)/I_c(0) \sim 0.5\%$, and a step of low differential resistance appears in the IVC. With increases in H, the step moves to higher voltages. The step at $H = 1.14$ T is shown in Fig. 3. As the current is increased, the step changes its curvature. The step has no hysteresis. It means that all the elementary junctions are synchronized at this state. With a further increase in current, IVC instabilities appear and the system is driven to the multiple branch, hysteretic state, which is similar to the one observed above I_c at zero magnetic field. It is reasonable to associate the observed step to the flux-flow step for collective motion of the Josephson vortex lattice. First, the theory [19] indeed predicts a similar change in the IVC curvature as in our experiment. Second, the maximum voltage of the step position varies approximately proportionally to H (see inset Fig. 3). The resonance peak voltage V_r can be obtained using Eq. (6) and taking into account that $v = \bar{c}/2$, $\Lambda = \phi_0/Hs$ as:

$$V_r = \frac{1}{2}N\frac{\bar{c}}{c}sH, \tag{8}$$

with N the number of the layers of the moving lattice. Exactly the same expression has been deduced in Ref. [19]. The authors found the resonance electric field across the layers E_0 as $E_0 = H\bar{c}/2c$. The ratio $\bar{c}/c$ can be estimated as 2.8×10^{-3} for $\lambda_{ab} = 1700$ Å, $s = 15$ Å, $\varepsilon_c = 10$. Using this value of $\bar{c}/c$ and $N = 30$, $H = 1.14$ T, we get from Eq. (8) $V_r = 20$ mV which is not far from the experimental value, $V_0 = 24$ mV. Thus we conclude that the observed step of low differential resistance in IVC can be identified as the flux-flow step due to collective coherent motion of the Josephson vortex lattice.

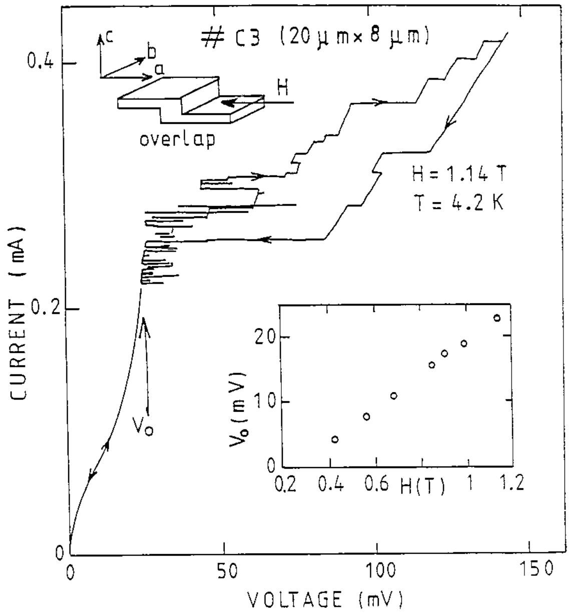

Fig. 3. Large scale $I-V$ characteristic of BSCCO $L_a = 8$ μm × $L_b = 20$ μm overlap structure in magnetic field $H \| a$, $H = 1.14$ T at 4.2 K. Insert shows a dependence of the maximum step voltage, V_0, on the magnetic field.

Note that the value of Swihart velocity $\bar{c}$ in BSCCO stacks can be directly extracted from the experiment with the use of Eq. (8). On the other hand, for known values of $\bar{c}$ and N one can calculate the value of s from such kind of experiment as well as from the experiments on DC intrinsic Josephson effect.

The value of $\bar{c}$ is found to be 9×10^7 cm/s at 4.2 K. That is consistent with the value 4×10^7 cm/s extracted from the flux-flow experiment [20] carried out at low H limit at 77 K. The factor of 2 difference appears to be due to the variation of λ_{ab} with temperature (see Eq. (7)). Because the Swihart velocity is rather high we can expect generation of a high frequency electromagnetic field near $V = V_0$. The generation frequency can be estimated as:

$$\nu \approx \frac{\bar{c}sH}{2\phi_0}, \tag{9}$$

which gives $\nu = 0.3$ THz for $H = 1$ T. It points out the ability of the overlap stacks to be used as high frequency local oscillators in various devices of superconducting electronics.

4.2. Microwave experiments

We have studied the effect of microwave on IVC of two small junctions with lateral sizes 4×8 μm and 5×10 μm at frequencies 10–12 GHz. We searched for the coherent response like Shapiro steps. The experiments were carried out mostly at 4.2 K.

Basically, the microwave field begins to suppress I_c and the currents of interbranch jumps at very low power levels (~ 1 μW for $f = 10$ GHz). We can estimate volt–watt sensitivity at this power level to be $\sim 10^{-5}$ V/W. In contrast the quasi-particle branches are not affected by the microwave power until it reaches ~ 10 mW.

For a power level $W \gtrsim 20$ μW, microwave suppresses I_c to zero and a resistive branch appears in IVC (Fig. 4). This branch looks like a step of low differential resistance. As in the case of flux-flow step, the microwave induced step is without hysteresis until the current exceeds some value. Above this current the stack switches to the multibranch hysteretic state. With an increase in W, the step moves to higher voltages proportional to $W^{1/2}$, see insert in Fig. 4. The current amplitude of this step is not considerably changed being about 0.1 of $I_c(W = 0)$. The step was observed up to a voltage ~ 500 mV which is about half of the maximum voltage of the limiting quasi-particle branch and then gradually disappeared.

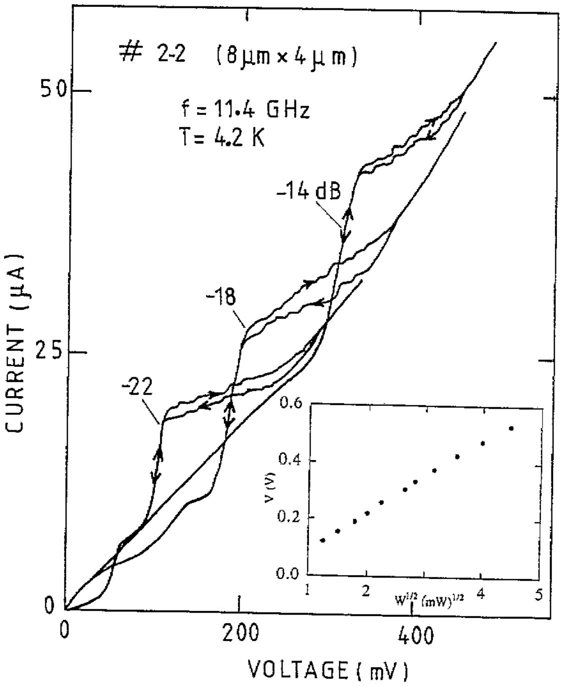

Fig. 4. $I-V$ characteristics of a $L_a = 4$ μm × $L_b = 8$ μm BSCCO stack junction under 11.45 GHz microwave irradiation of various power levels. Zero attenuation corresponds to input power 200 mW. $T = 4.2$ K.

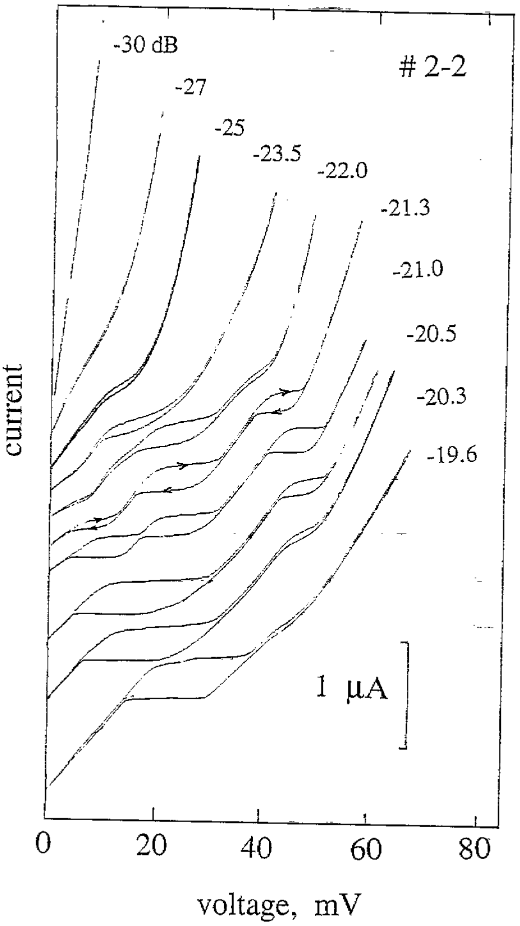

Fig. 5. Microwave induced steps of constant differential resistance on the $I-V$ characteristics of 4×8 μm BSCCO stack. $T = 4.2$ K. 0 dB corresponds to the input power 200 mW. Microwave frequency $f = 11.45$ GHz. The curves are shifted along the vertical direction. A zero voltage for each curve corresponds to zero current.

Another microwave induced series of steps has been observed at much smaller currents ~ 1% of $I_c(W=0)$, see Fig. 5. These small steps of approximately constant differential resistance develop with microwave power in a different way. The voltage spacing between steps (~ 10 mV) is independent of microwave power, while their current amplitude is an oscillating function of W (Fig. 6). The steps are hysteretic. They exist at rather low powers and disappear at $W \sim -18$ dB [0 dB = 200 mW].

The microwave induced step of low differential resistance on IVC at a voltage proportional to $W^{1/2}$ has been recently observed on large BSCCO stacks by Irie and Oya [21]. They supposed this step to originate from the microwave induced flux-flow process. When the microwave field exceeds H_{c1} fluxons can enter the junction and be accelerated by microwave and DC current. That gives rise to a flux-flow step. The number of fluxons involved in motion should be proportional to the H-component of microwave which in turn is proportional to $W^{1/2}$. Our experiments show that the microwave induced step looks very similar to the flux-flow step induced by static H (see Figs. 3 and 4). For more detailed analysis the quantitative theory of this model has to be elaborated.

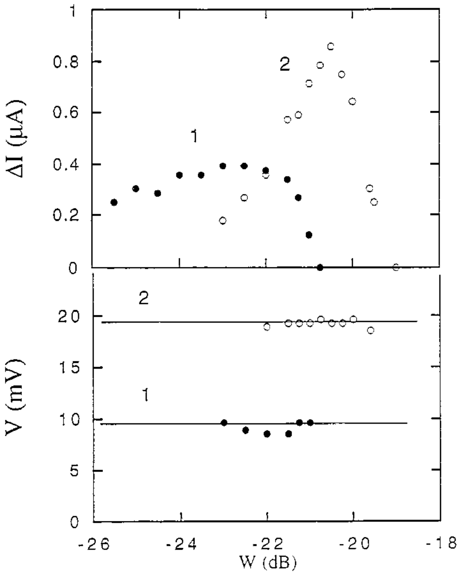

Fig. 6. The amplitude ΔI_c and the voltage spacing V of the microwave induced steps of 4×8 μm BSCCO stack as a function of microwave power W (dB). $f = 11.45$ GHz.

The set of small steps at low current resembles in many aspects to Shapiro steps. The steps are separated by equal voltage which is not dependent on power. The step size (ΔI) oscillates with increasing power, the maximum of the second step corresponds to the minimum of the first one (Fig. 6). However, in contrast to usual Shapiro steps, (i) they are steps of constant differential resistance with a high value of ~ 16 kΩ (not steps of a constant voltage), (ii) the step spacing, 10 mV, is about 5 times larger than expected from Eq. (4) for $N = 80$, the total number of the layers of this particular stack.

We can conclude that for our smallest BSCCO stacks 4×8 μm we did not observe Shapiro steps expected for small junctions with $L < \lambda_j$. All observed features induced by microwave more probably result from interaction between microwave and fluxon motion. We add that 'pure' Shapiro steps have not been observed either in recent studies of TBCCO 7×7 μm stacks [9]. It appears that to observe a reliable Shapiro step response in BSCCO and TBCCO one needs to have much smaller stacks, with $L \sim 1$ μm.

5. Conclusions

A method of fabrication of the micrometre-scale stacked structures from BSCCO 2212 single crystal whiskers has been developed. The structures are shown to be perspective objects for basic research of various aspects of the intrinsic Josephson effect and for possible high frequency applications.

Acknowledgements

We acknowledge fruitful discussions with L.N. Bulaevskii, A.F. Volkov, A. Ustinov. The work has been supported by Russian State Program on HTSC under the project N95028. The Centre de Recherches sur les Très Basses Températures is associated with the Joseph-Fourier University of Grenoble.

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