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Intrinsic Josephson effects on BSCCO 2212 single crystal whiskers

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Micron scale stacked junctions have been fabricated from $Bi_2Sr_2CaCu_2O_8$ whiskers. For in plane size L less than 20 μm 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. For larger values of L a dimensional crossover to monotonic, size independent behaviour of $I_c(H)$ is observed. Flux flow steps on current voltage characteristics of overlap stacks have been found in high parallel magnetic fields, due to the collective motion of Josephson vortex lattice.

1. INTRODUCTION

Layered high T_c superconductors such as $Bi_2Sr_2CaCu_2O_8$ (BSCCO) are known to be considered as a stack of 2D-superconducting layers linked by Josephson coupling [1]. However it was shown [2] that the direct observation of intrinsic Josephson effects (IJE) when the current is driven across the layers can only be revealed for stacked structure with lateral size L_{ab} smaller than the Josephson penetration depth λ_j given by $s\ \lambda_c/\lambda_{ab}$, where s is the spacing between elementary superconducting CuO layers and λ_c, λ_{ab} are the anisotropic London penetration lengths. In BSCCO, λ_j is of the order of a few microns.

First evidence of IJE was obtained on rather large BSCCO single crystals with L ~30-100 μm [1]. A great experimental effort is made for preparation of stack junctions with smaller sizes [3].

We have developed a method of fabrication of micron scale stacked junctions from single crystal $Bi_2Sr_2CaCu_2O_8$ whiskers [4,5]. Hereafter we describe our measurements which clearly demonstrate the existence of the intrinsic Josephson effects.

2. EXPERIMENTAL

Junctions have rectangular geometry in the ab-plane, the edges being parallel to the a- and b-axis (Fig. 1). 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. The critical current density across the layers, I_c, measured at 4.2 K with a voltage criterion of 1 μV was $5 \times 10^2 - 2 \times 10^3$ A/cm^2. This value is about three orders smaller than the longitudinal value of 5×10^5 A/cm^2 in samples from the same batch [4].

3. dc INTRINSIC JOSEPHSON EFFECT

For small junctions with in-plane size L_{ab} smaller than λ_j, I_c across the layers as a function of the magnetic field H parallel to the layers exhibits [2] a Fraunhofer behaviour such as:

$$I_c(H) = I_c(0)\sin(\pi sLH/\phi_0)/(\pi sLH/\phi_0) \qquad (1)$$

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 $J_c(0)$: $J_c(0) = c\phi_0/(8\pi^2 s\lambda_c^2)$. The first minimum of $I_c(H)$ appears at $H_1 = \phi_0/sL$.

For junctions with larger size, the Josephson behavior is disturbed by Josephson vortices entering the junction at fields $H > H_{c_1}$. In the case of $L > \lambda_j$, a recent calculation [6] predicts an universal size independent decrease of $I_c(H)$:

$$I_c(0) - I_c(H)/I_c(0) \approx \sqrt{H/H_0} \qquad (2)$$

with $H_0 = \phi_0\lambda_{ab}/\pi^2 s^2\lambda_c$ and $I_c(0)$ the same as in (1): $I_c(0) = s\ J_c(0)$.

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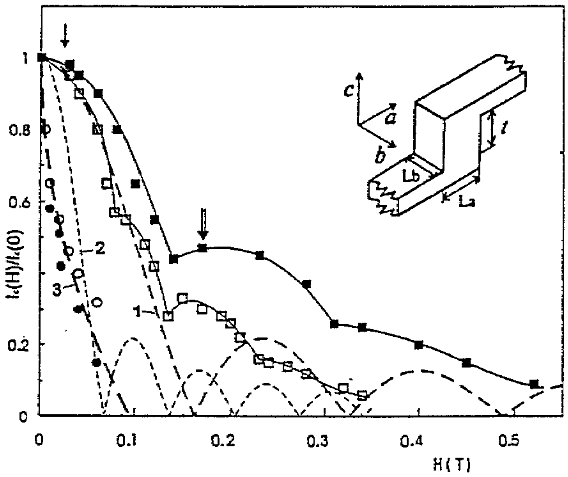

Figure 1. Normalized dependences of critical current of $Bi_2Sr_2CaCu_2O_8$ junctions across the layers $I_c(H)/I_c(0)$ at T =4.2 K with H parallel to the layers for samples of different sizes L: □ 8 μm, □ 20 μm, • 40 μm, ∘ 200 μm. Solid lines are guides for the eyes. Dashed curves 1 and 2 correspond to Eq. 1 for $L = 8$ and 20 μm, respectively. Curve 3 corresponds to Eq. 2 for H_0 = 950 Oe. Insert shows the geometry of the junction.

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. 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 for our junctions. It gives $J_c(0) \sim 1.5 \times 10^3$ A/cm^2 which is quite consistent with our experimental values.

With $L <$ 30 μm, oscillations in $I_c(H)$ begin to appear. For the junction with $L = 8$ μm, we observed three oscillations with a period of 0.15 T. The period of oscillations decreases with an increase of 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. 1). Our data for junctions with a size smaller than 20 μm prove the predicted Josephson behaviour of $I_c(H)$ [2]. When L is increased above 20 μm, a crossover occurs to the behaviour predicted in [6]. This crossover is illustrated in Fig. 2 where the dependence of the magnetic field, H^*, which suppresses I_c to half its value at zero field $I_c(0)$ is plotted as a function of the junction size [7].

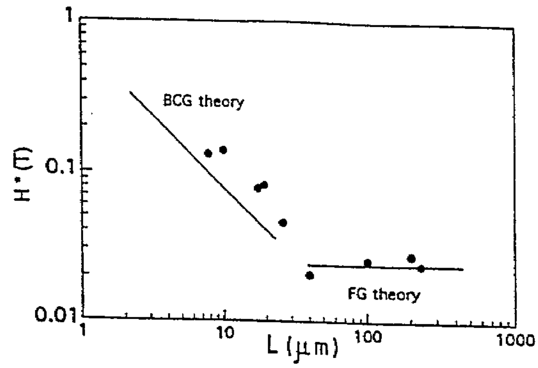

Figure 2. Dependence of the characteristic magnetic field H^*, as a function of the junction size L. Straight lines correspond to theories [refs. 2 and 6] calculated from Eq. 1 and Eq. 2.

The current voltage characteristics (IVC) of stacked junctions at low temperatures are known to have hysteresis and a multiple branch structure [1]. With current increase the voltage jumps to higher and higher branches until all the elementary junctions become resistive. This limiting quasiparticle branch should correspond to the voltage $2\Delta \cdot N$, with 2Δ the energy gap and N the total number of elementary junctions. Usually this value is 30-50% smaller [1] due to the gap suppression by heating effects [8] or quasiparticle injection [9]. Both effects often manifest themselves as a S-shaped form of the quasiparticle branch. Our experiments showed that S-shaping of the IVC can be essentially eliminated with a decrease of the overlap length L_a of the junction to 6-4 μm (overlap type junction). The IVC of the overlap junction with $L_a = 4$ μm is shown in Fig. 3. It has no S-shaped branch at high dissipation levels. We consider that a decrease of the overlap length leads to a better junction thermocoupling with the rest of the crystal.

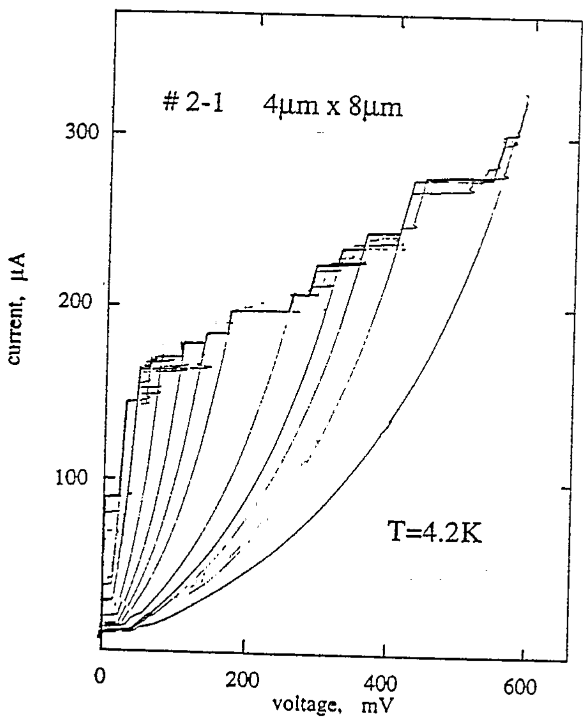

Figure 3. I-V curves of a 4 μm $\times$ 8 μm BSCCO stack junction at 4.2 K.

4. FLUX-FLOW MODE IN PARALLEL MAGNETIC FIELD

For long junctions with $L > \lambda_j$ the ac Josephson effect can be associated with the 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 Josephson relation: $\nu = (2e/h)V = cV/\Phi_0$, where V is a dc voltage induced by the fluxon motion. 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 $\nu = v/\Lambda$. The voltage corresponding to the flux-flow mode is then:

$$V = (v/c)(\Phi_0/\Lambda). \quad (3)$$

For layered superconductors it was recently shown [10] that in high enough parallel field a triangle lattice of Josephson vortices is formed. For $H > \phi_0/\gamma s^2$ the non-linear regions of vortices overlap strongly because Λ along the ab-plane becomes smaller than λ_j. Such a dense lattice was shown to be rigid enough to move as a whole [11] when the current is driven across the layers. A resonance can appear when the lattice velocity $\bar{v}$ is equal to $\bar{c}/2$, where $\bar{c}$ is the Swihart velocity given in [11] as:

$$\bar{c} = cs/(\lambda_{ab}\sqrt{\epsilon_c}) \quad (4)$$

where ϵ_c is the dielectric constant between superconducting layers.

We have searched such an effect in our overlap structures with $L_a = 8$ μm, $L_b = 20$ μm and with $H \parallel a$. H was varied up to 1.5 T. That is about twice the characteristic field $\phi_0/\gamma s^2$. For $H \approx 0.5$ T, $I_c(H)$ becomes negligibly small, $I_c(H)/I_c(0) \sim 0.5\%$, and a step of low differential resistance appears on the IVC. With the increase of H the step moves to higher voltages (Fig. 4). With current increase the step changes its curvature. The step is hysteresisless. It means that all the elementary junctions are synchronized at this state. With further current increase, IVC instabilities appear and then the stack comes to the multiple branch, hysteretic state, which is similar to the one observed above I_c at zero magnetic field. We associate the observed step as the flux-flow step for collective motion of the Josephson vortex lattice [11]. The maximum voltage of the step position varies approximately proportionally to H (see inset Fig. 4). Using Eq. 3 and taking into account that $v = \bar{c}/2$, $\Lambda = \phi_0/Hs$, the resonance peak voltage V_r is obtained as:

$$V_r = \frac{1}{2}N\frac{\bar{c}}{c}sH \quad (5)$$

with N the number of the layers of the moving lattice. Exactly the same expression has been deduced in [11] where the resonance electric field across the layers E_0 was found 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, $\epsilon_c = 10$. Using that value and $N = 30$, $H = 1.14$ T, we get from Eq. 5 $V_r = 20$ mV which is in agreement with the experimental value, $V_0 = 24$ mV.

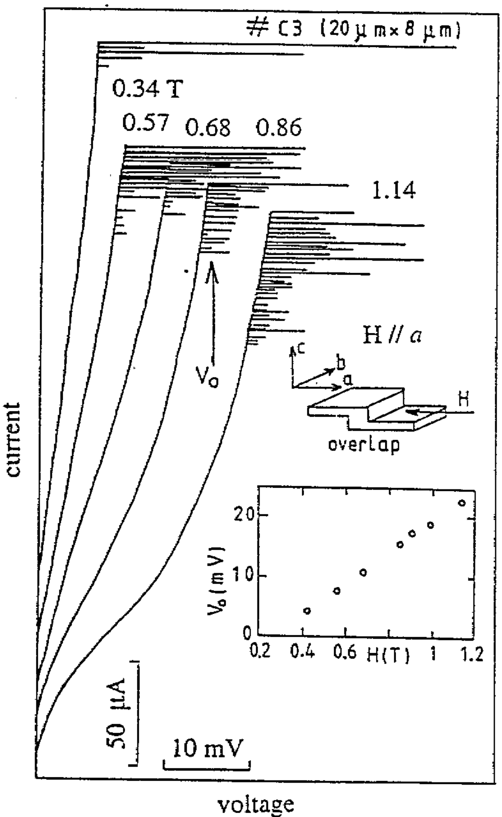

Figure 4. Series of I-V curves of BSCCO 8 μm $\times$ 20 μm overlap stacked structure in various magnetic fields $H \parallel a$ at 4.2 K. Inset shows the dependence of the maximum step voltage V_0 as a function of H.

The value of the Swihart velocity $\bar{c}$ in BSCCO stacks can be directly extracted from the experiment using Eq. 5. We found 9×10^7 cm/s at 4.2 K. Because the Swihart velocity is rather high, we can expect generation of the high frequency electromagnetic field near $V = V_0$. The generation frequency can be estimated as: $\nu \approx \bar{c}sH/2\phi_0$ which gives $\nu = 0.3$ TGz 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.

5. CONCLUSIONS

We have developed micron scale stacked structures from BSCCO 2212 single crystal whiskers. We have shown a dimensional crossover for intrinsic dc Josephson effect for a junction size of $\sim 20 - 30$ μm. Steps in the current voltage characteristics under a parallel magnetic field on overlap stacked analogues of long Josephson junctions have been found to be due to a collective motion of a Josephson vortex lattice.

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