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Micron scale stacked structures fabricated from BSCCO 2212 single crystal whiskers

Yu.I. Latyshev[a], V.N. Pavlenko[a], J.E. Nevelskaya[a], P. Monceau[b,*]

[a]Institute of Radio-Engineering and Electronics, 11 Mokhovaya St., Moscow 103907, Russia

[b]Centre de Recherches sur les Très Basses Températures, associé à l'UJF, CNRS, 25 Av. des Martyrs, BP 166, 38042 Grenoble-Cedex 9, France

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 stacked junctions fabricated from perfect single crystal $Bi_2Sr_2CaCu_2O_8$ whiskers with in plane size L less than 20 μm. For large values of L a dimensional crossover to monotonous size independent behaviour of $I_c(H)$ is observed. Overlap stacked analogues of long Josephson junctions have also been developed. Flux–flow steps on current voltage characteristics (IVC) of those junctions have been found in high parallel magnetic fields due to a collective motion of the Josephson vortex lattice.

Keywords: $Bi_2Sr_2CaCu_2O_8$ single crystal whiskers; Stacked structures; Intrinsic Josephson effect; Flux flow

1. Introduction

Layered high-T_c superconductors such as $Bi_2Sr_2CaCu_2O_8$ (BSCCO) or $Tl_2Ba_2Ca_2Cu_3O_{10}$ (TBCCO) are known to be considered as a stack of 2D-superconducting layers linked by Josephson coupling which leads to the possibility of the direct observation of DC and AC intrinsic Josephson effects on naturally layered crystal structures when the current is driven across the layers [1].

2. Theory

However, pure Josephson behaviour is predicted theoretically [2] only for rather small junctions with in-plane size L_{ab} smaller than the Josephson penetration depth λ_j given by $s\lambda_c/\lambda_{ab}$, where s is the spacing between the elementary superconducting CuO layers and λ_c, λ_{ab} are the anisotropic London penetration lengths. The critical current across the layers as a function of the magnetic field H parallel to the layers exhibits a Fraunhofer behaviour such as:

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

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 $J_c(0)$:

$$J_c(0) = c\phi_0/(8\pi^2 s\lambda_c^2) \quad (2)$$

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 $H > H_{c_1}$. The value of L, L_m, for which $H_{c_1} > H_1$ is defined as the maximum junction size at which the oscillatory behaviour of $I_c(H)$ is observed. For BSCCO, L_m is estimated to be ~10 μm.

In the case of $L > \lambda_j$, a recent calculation [3] predicts an universal size independent decrease of $I_c(H)$

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

with H_0 a constant field characterizing the layered superconductor, $H_0 = \phi_0\lambda_{ab}/\pi^2 s^2\lambda_c$.

Calculations [3] have been made for fields $H < H_0$ for the case of pinned Josephson vortex lattice. Hence $J_c(0)$ was supposed to be the same as in (1): $I_c(0) = SJ_c(0)$. Previous experiments [1,4] have not clearly demonstrated the two regimes and the crossover between them, when L is varied.

The limit of high parallel magnetic fields $H \gg H_0$ in large junctions $L > \lambda_j$ have been recently calculated in [5].

*Corresponding author. Tel.: 76 88 10 21; Fax: 76 88 12 30; e-mail: directbt@labs.polycnrs-gre.fr

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The dense Josephson vortex lattice was shown to move as a whole, providing a resonance peak on IV characteristics. This phenomenon has not yet been experimentally studied.

3. Experimental

Micron scale stacked junctions have been fabricated from selected single phase (2212) whiskers [6]. Recently thin BSCCO whiskers have been identified [6] as one of the most perfect objects among layered high-T_c materials. They grow along the [100] direction free of any crucibles or substrates and may be entirely free of macroscopic defects and dislocations. We use these whiskers as the base objects for fabrication of small *ab*-plane area structures for studies of the intrinsic Josephson effect [7]. The steps b–e of the fabrication process are shown in the inset of Fig. 1. A low discharge voltage (<1 kV) has been chosen for ion plasma etching to avoid degradation of the superconducting parameters. Junctions have rectangular geometry in the *ab*-plane, the edges being parallel to the *a*- and *b*-axis (see Fig. 1(a)). Different junctions have been prepared with dimensions L_a, L_b between 200 μm down to 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 Ohm after annealing in oxygen at 450 °C.

The critical current density across the layers 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 significantly change with temperature increase up to $T/T_c \approx 0.75$. This value is about three orders of magnitude smaller when compared with a longitudinal value of 5×10^5 A cm^{-2} in samples from the same batch [6].

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 of H_0, we deduce $\gamma = \lambda_c/\lambda_{ab} \sim 1300$.

Using this value for γ we estimated the value of the maximum Josephson current density (Eq. (2)) for our junctions. We used $\lambda_{ab} = 0.3$ μm, $s = 15$ Å. It gives $J_c(0) \sim 1.5\times10^3$ 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 have observed three oscillations with a period of 1.5 kOe. 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. 2). For H perpendicular to the smaller size $I_c(H)$ drops more slowly and with a larger period of modulation. The appropriate theoretical dependencies are shown in Fig. 2 as dashed lines.

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

Our data for junctions with a size smaller than 20 μm prove the Josephson behaviour of $I_c(H)$ predicted by Bulaevskii, Clem and Glazman [2]. When L is increased

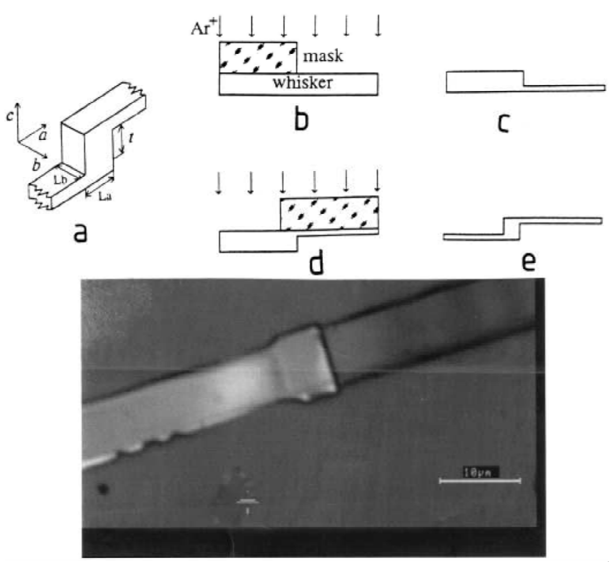

Fig. 1. Microphotograph of the stacked structure etched on a $Bi_2Sr_2CaCu_2O_8$ single crystal whisker. The inset shows: (a) crystallographic orientation of the structure, (b)–(e) the steps of the ion etching procedure.

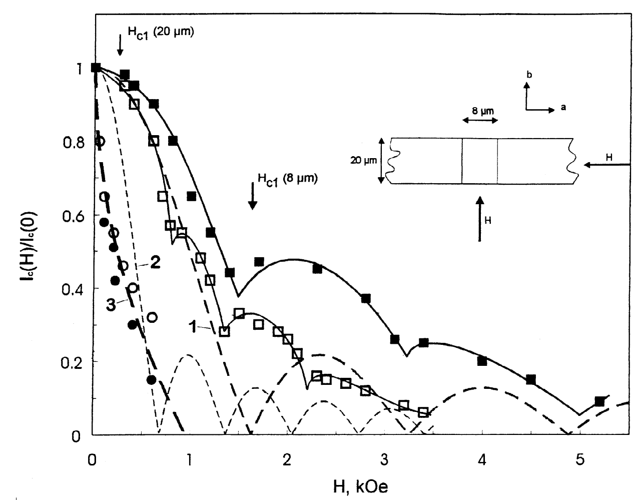

Fig. 2. Normalized dependencies of critical currents of $Bi_2Sr_2CaCu_2O_8$ junctions across the layers $I_c(H)/I_c(0)$ at $T=4.2$ K on magnetic field H parallel to the layers for samples of different sizes L: ■ 8 μm, □ 20 μm, ● 40 μm, ○ 200 μm. Solid lines are guides for eyes. Dashed curves 1 and 2 correspond to Eq. (1) for $L=8$ μm and 20 μm respectively. Curve 3 corresponds to Eq. (3) for $H_0=950$ Oe. H_{c_1} indicates the field above which Josephson vortices penetrate the junction. Inset shows the geometry of the junctions for which H has been rotated and applied $\|a$ and $\|b$ respectively.

above 20 μm, a crossover occurs to the behaviour predicted by Fistul and Giuliani [3].

The current voltage characteristics (IVC) of stacked junctions at low temperatures are known to have hysteresis and a multiple branch structure [1,4]. With current increase the voltage jumps to higher and higher branches (Fig. 3) 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 [4,8] due to the gap suppression by heating effects [8,9] or quasiparticle injection [8,9]. The heating effect is often demonstrated itself as a S-shaped form of the quasiparticle branch (Fig. 3(b)). Our experiments showed that heating effects may be essentially suppressed with a decrease of the overlap length L_a of the junction to 6–4 μm (overlap type junction). The *IV* characteristics of the overlap junction are shown in Fig. 3(a). They have no S-shaped branch at high dissipation levels. The better junction thermocoupling with the rest of the crystal occurs because the overlap length becomes smaller than the thermalization healing length L_T, $L_a < 2L_T$. It gives an estimation for L_T in BSCCO of about a few microns. The overlap structures of that type may be considered as good candidates for high frequency Josephson effect applications where a high bias voltage is usually required.

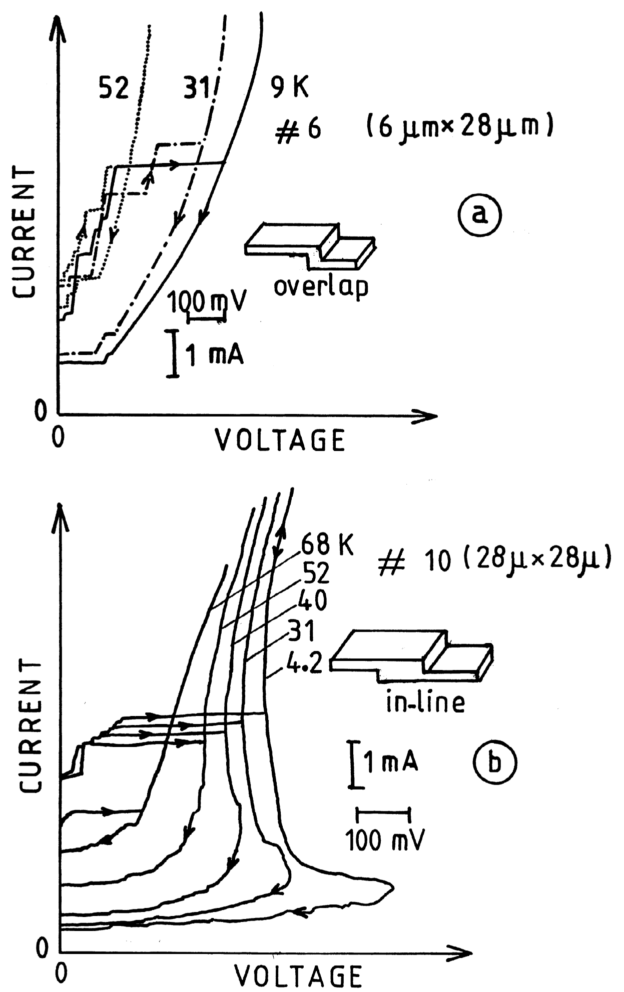

Fig. 3. Current voltage characteristics of the two stacked $Bi_2Sr_2CaCu_2O_8$ structures of the same width, L_b, but different overlap length, L_a: (a) $L_a = 6$ μm, (b) $L_a = 28$ μm.

We used overlap junctions for studies of the resistive state at high parallel magnetic field ($H \| a$).

It is known that in long Josephson junctions the so-called flux–flow regime can be realized, when the chain of strongly interacted fluxons moves along the junction with the Swihart velocity, $\bar{c}$, the velocity of electromagnetic field propagation in junctions (see e.g. [10]).

Similar phenomenon could be expected in layered superconductors in high parallel magnetic fields. Recently it was deduced [11] that in a parallel field a triangle 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 spacing becomes filled by vortices forming a triangular lattice. Such a dense lattice was shown to be rigid enough to move as a whole [5] 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 in layered material:

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

where ϵ_c is the dielectric constant between conducting layers.

We have undertaken searching for this effect on our overlap structures. The experiments have been carried out on the overlap structure with $L_a = 8$ μm, $L_b = 20$ μm and with $H \| a$. 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 on the IVC. With the increase of H the step moves to higher voltages. The step at $H = 1.14$ T is shown in 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 system comes to the multiple branch, hysteretic state, which is similar to the one observed above I_c at zero magnetic field. It would be reasonable to associate the observed step as the flux–flow step for collective motion of the Josephson vortex lattice. First, the theory [5] indeed predicts the change of the IVC curvature as in our experiment. Second, the maximum voltage of the step position varies approximately proportionately to H (see inset to Fig. 4). The resonance peak voltage V_r can be estimated as [5,10]:

$$V_r = N \cdot d \cdot \frac{\bar{c}}{2c} \cdot H \tag{5}$$

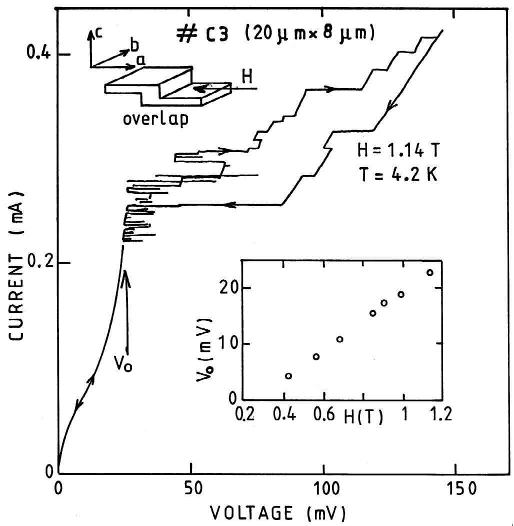

Fig. 4. Current voltage characteristic of overlap stacked structure $Bi_2Sr_2CaCu_2O_8$ in parallel magnetic field. The inset shows the dependence of the maximum voltage at the step, V_o, on the magnetic field H.

with N the number of the layers of the moving lattice, d the total crystal thickness. The ratio $\bar{c}/c$ can be estimated as 2.8×10^{-3} for $\lambda_{ab}=1700$ Å, $c=15$ Å, $\epsilon_c=10$. Using that value and $N=30$, $d=0.4$ μm, $H=1.14$ T, we get from (5) $V_r=19$ mV which is not far from the experimental value, $V_o=24$ 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. Because the Swihart velocity is rather high we can expect generation of the high frequency electromagnetic field near $V=V_o$. The generation frequency can be estimated as:

$$\nu \approx \frac{\bar{c}sH}{2\phi_0} \tag{6}$$

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

4. Conclusions

The method of fabrication of the micron scale stacked structures from BSCCO 2212 single crystal whiskers has been developed. The structures are shown to be perspective objects for basic research into the intrinsic Josephson effect and for its high frequency applications.

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