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Intrinsic dc Josephson effect in naturally layered stacked structures based on BSCCO 2212 single crystal whiskers

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The dependences of the critical current I_c across the layers on a parallel magnetic field H have been studied on small area stacked junctions fabricated from perfect single crystal whiskers. The intrinsic dc Josephson effect has been clearly demonstrated on structures with in-plane size L less than 20 μm. A dimensional crossover to monotonic size-independent behavior of $I_c(H)$ has been observed with increase in L. The decrease of $I_c(H)$ in this region is proportional to $\sqrt{H}$ in accordance with Fistul—Guliani theory [5].

Introduction

Layered high-T_c superconductors (BSCCO, TBCCO) are known to be considered as a stack of $2D$ superconducting layers linked by Josephson coupling [1,2]. In principle, this leads to the possibility of the direct observation of dc and ac intrinsic Josephson effects on naturally layered crystal structure when current is driven across the layers.

However, as will be shown later, there are some serious limitations on the realization of this idea. First of all, theory [3] predicted pure Josephson behavior only for rather small junctions with in-plane size L_{ab} smaller than Josephson penetration depth L_j, which is of the order of a few microns in BSCCO. For junctions of larger size, the Josephson behavior is disturbed by Josephson vortices entering the junction [4,5].

Another limitation concerns the quality of the single crystals to be studied. To achieve synchronization of all the elementary layers, the single crystal should be of very high quality, free of impurities, dislocations, inclusions of other phases etc.

The first experiments have been carried out on rather large single crystals with size $L \sim 30$–$100\,\mu$m [6,7]. Microwave experiments [7,8] which claimed to prove the existence of the intrinsic ac Josephson generation indicated, however, that only a small percentage of the total number of the elementary junctions have been synchronized. Josephson behavior in parallel magnetic fields was also not demonstrated satisfactorily.

In the present study we report on a new approach to the problem. We choose a single crystal BSCCO 2212 whisker as a base material. Recently these have been characterized as one of the most perfect objects of layered high-temperature superconductors (HTCSs) [9]. The small transverse dimensions of the whiskers let us fabricate stacked junctions with lateral sizes as small as 5 μm. Measurements made on these junctions show new features which prove the existence of the intrinsic dc Josephson effect.

Theoretical background

For a small naturally-layered stacked junction with in-plane size L less than λ_j, theory [3] predicts Fraunhofer behavior of the critical current across the layers I_c in magnetic field parallel to the layers H:

$$I_c \propto \sin(\pi s L H/\Phi_0)/(\pi s L H/\Phi_0) , \qquad (1)$$

where s is the spacing between elementary superconducting layers: Φ_0 is the flux quantum; L is the junction size perpendicular to the field. Equation (1) implies strong dependence of $I_c(H)$ on L. One can see that the first minimum of $I_c(H)$ appears at H_1 corresponding to a magnetic flux density Φ_0 through the elementary junction area:

$$H_1 = \Phi_0/sL . \qquad (2)$$

For the case $L > \lambda_j$ behavior of the sort of Eq. (1) can be disturbed by Josephson vortices [5], entering the system at fields $H > H_{c1}$. Calculation of H_{c1} for small samples with $L < \lambda_c$ [5,10] yields

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$$H_{c1} \approx \frac{\Phi_0}{L^2}\frac{\lambda_c}{\lambda_{ab}} \ln\frac{\lambda_{ab}}{s} . \qquad (3)$$

This value turns out to be $(\lambda_c / L)^2$ times as large as that for an infinite sample. Note also that with decrease in L H_{c1} increases more rapidly (as $1/L^2$), than H_1 . ıd can exceed it at some value L_m . This value can be defined as the maximum junction size at which to observe oscillatory behavior of $I_c(H)$ [11]:

$$L_m = \frac{s\lambda_c}{\lambda_{ab}} \ln\frac{\lambda_{ab}}{s} . \qquad (4)$$

For typical BSCCO parameters ($\lambda_c = 100\,\mu$m, $\lambda_{ab} = 0.3\,\mu$m, $s = 15$ Å) L_m is estimated to be $\sim 10\,\mu$m.

The opposite limit, when vortices penetrate the structure of rather large size $\lambda_j < L < \lambda_c$ and form a pinned lattice, has been considered in [5] . Some universal, size independent, behavior of $I_c(H)$ has been predicted in this case:

$$[I_c(H) - I_c(0)]/I_c(0) \propto \sqrt{H/H_0} , \qquad (5)$$

where H_0 is a constant characterizing the layered superconductor,

$$H_0 = \frac{\Phi_0\lambda_{ab}}{\pi^2 s^2 \lambda_c} . \qquad (6)$$

For typical BSCCO parameters H_0 can be estimated as $H_0 \approx 1$ kOe.

Following the analysis above one can expect a crossover from a sizeindependent monotonic drop of $I_c(H)$ in the field of scale of 1 kOe for large samples ($L = 20$–$100\,\mu$m) to oscillating, size-dependent, $I_c(H)$ behavior of the sort of Eq. (1) for small samples ($L < 10$–$20\,\mu$m).

In previous experiments [6–8] the behaviors predicted by Eqs. (1) and (5) as well as a crossover from (5) to (1) have not yet been clearly demonstrated.

Experimental

Micron scale stacked junctions have been fabricated on the selected single phase (2212) whiskers [12]. The steps of the fabrication process are shown in Fig. 1,*b*,*c*,*d*,*e*. A low discharge voltage (< 1 kV) has been chosen for ion plasma etching to avoid degradation of the superconducting parameters. The microphotograph of one of the junctions is illustrated in Fig. 1,*g*. Junctions have rectangular geometry in the *ab* plane, the edges being parallel to the *a* and *b* axis. Along the *c* axis they contain

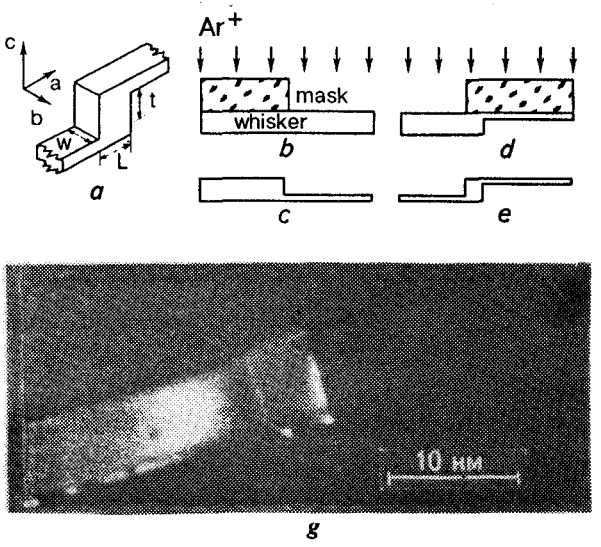

Fig. 1. The stacked structure etched on a $Bi_2Sr_2CaCu_2O_x$ single crystal whisker: a crystallographic orientation of the structure (*a*); the steps of ion etching procedure (*b*–*e*); scanning laser microscope picture of one of the stacked structures (*g*).

~ 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.

Results and discussion

All the junctions studied had in-plane dimensions L smaller than λ_c , which provides uniform current distribution in *ab* plane. The critical current density across the layers measured at 4.2 K with a voltage criterion of 1 μV was $3\cdot10^2$–10^3 A/cm^2 and was not changed appreciably with temperature increase up to $T/T_c \approx 0.75$. This value is about three orders smaller when compared with a longitudinal value of $5\cdot10^5$ A/cm^2 in samples from the same batch [9].

For the junction with $L \approx 8\,\mu$m we have observed oscillatory behavior of $I_c(H)$ with a period 1.5 kOe, in a good agreement with Eq. (1) (see Fig. 2). Direct experiments on one junction with different sizes L_a and L_b demonstrated the different dependences of $I_c(H)$ for $H \parallel a$ and $H \parallel b$, showing an accord with (1) (i.e., for H orientation perpendicular to the smaller size, $I_c(H)$ drops slowly with a larger period of modulation (see Fig. 2). The value of s extracted from the period of $I_c(H)$ modulation in both cases exactly corresponds to 15 Å, the value of the spacing between elementary superconducting layers.

It is shown also that for junctions with $L > 40\,\mu$m, the dependence $I_c(H)$ becomes monotonic and practi-

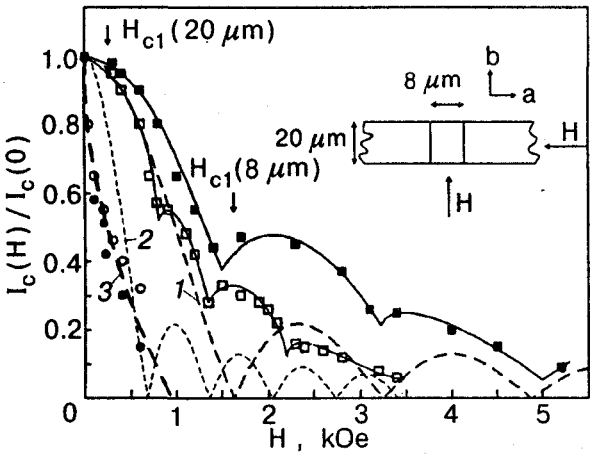

Fig. 2. Normalized dependences of critical currents across the layers $I_c(H)/I_c(0)$ on a magnetic field H parallel to the layers for samples of different sizes L, μm: 8 (■); 20 (□); 40 (●); 200 (○). Solid lines are guides for the eyes. Dashed curves *1*, *2* correspond to Eq. (1) for $L = 8$ and 20 μm, respectively. Curve *3* corresponds to Eq. (5) for $H_0 = 950$ Oe.

cally independent of L over a range of L from 40 to 200 μm. Scaling of the experimental dependences with Eq. (2) gives reasonable value for H_0 (950 Oe) which compares well with the theoretical estimation for BSCCO (1 kOe) [5].

Conclusions

A method of fabricating micron-scale stacked junctions of high quality has been developed. Intrinsic dc Josephson behavior has been clearly demonstrated on these junctions. A dimensional crossover from Josephson behavior to monotonic size-independent behavior of critical current in a parallel magnetic field has been observed with increase in in-plane junction size. Field dependences for larger junctions are in a good agreement with Fistul-Giuliani theory.

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