Dimensional Crossover for Intrinsic dc Josephson Effect in $Bi_2Sr_2CaCu_2O_8$ 2212 Single Crystal Whiskers

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The variations of the critical current I_c across the layers as a function of the parallel magnetic field H have been studied on small area stacked junctions fabricated from perfect single crystal $Bi_2Sr_2CaCu_2O_8$ whiskers. Intrinsic dc Josephson effect has been clearly demonstrated on structures with in-plane size L less than 20 μm. With L increases, a dimensional crossover to monotonic size independent behavior of $I_c(H)$ has been observed. $I_c(H)$ decrease in this region is proportional to $\sqrt{H}$ in accordance with the Fistul-Giuliani theory. [S0031-9007(96)00762-4]

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With the coherence length along the c axis much less than the spacing between Cu-O planes, 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 [1,2]. In principle, this leads to the possibility of direct observation of dc and ac intrinsic Josephson effects on naturally layered crystal structures when the current is driven across the layers [3–5].

However, as will be shown, there are some serious limitations to realize this idea. First, oscillatory behavior of the critical current is predicted theoretically [6] 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. In BSCCO λ_j is of the order of a few microns. For junctions with larger size the behavior is disturbed by Josephson vortices entering the junction [7,8].

Another limitation concerns the quality of the single crystals to be studied. To achieve synchronization of all 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 $L \sim 30-100$ μm [9,10]. Microwave experiments [10,11] which were presented to sustain the existence of the intrinsic ac Josephson generation indicated, however, that only a few percent of the total number of elementary junctions has been phase synchronized. Josephson behavior in parallel magnetic fields, namely, the oscillatory dependence of the critical current $I_c(H)$ as a function of the magnetic field, was also not demonstrated satisfactorily.

Recent experiments on epitaxial film [12] and on mesa structures patterned on epitaxial films [13–15] or single crystals [16,17] did not clarify the situation. Namely, no ac or dc intrinsic Josephson effect was observed on small width tilted BSCCO2212 films [12]. Data on small area TBCCO film junctions [14] showed some $I_c(H)$ modulation but the modulation period was considerably inconsistent with the structure lateral size. The results on film structures are very dependent on film quality, i.e., presence of grains, grain boundaries, tension gradient due to mismatch film or substrate, etc.

In the present study we report on a new approach to the problem. We have chosen a single crystal BSCCO2212 whisker as a base material. Recently these whiskers have been characterized [18] as one of the most perfect objects of layered high temperature superconductors. The small transverse dimensions of the whiskers allow us to 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.

For a small naturally layered stacked junction with in-plane size L less than λ_j, theory [6] predicts Fraunhofer behavior of the critical current across the layers in magnetic field H parallel to the layers,

$$I_c(H) = \frac{I_c(0)\sin(\pi sLH/\phi_0)}{\pi sLH/\phi_0}, \quad (1)$$

where ϕ_0 is the flux quantum and L is the junction size perpendicular to the field. Equation (1) implies strong dependence of $I_c(H)$ on L. The first minimum of $I_c(H)$ appears at H_1 corresponding to a magnetic flux density equal to ϕ_0 through elementary junction area,

$$H_1 = \phi_0/sL. \quad (2)$$

For the case $L > \lambda_j$ the behavior described by Eq. (1) can be disturbed by Josephson vortices [8], entering the

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junction at fields $H > H_{c_1}$. Calculation of H_{c_1} for small samples with $L < \lambda_c$ yields [8,19]

$$H_{c_1} \approx \frac{\phi_0}{L^2} \frac{\lambda_c}{\lambda_{ab}} \ln \frac{\lambda_{ab}}{s} . \tag{3}$$

This value turns out to be $(\lambda_c/L)^2$ times larger than that of an infinite sample. Note also that as L decreases H_{c_1} increases more rapidly, as $(1/L^2)$, than H_1 and can exceed it at some value L_m. This value can be defined as a maximum junction size to observe oscillatory behavior of $I_c(H)$,

$$L_m = \frac{s\lambda_c}{\lambda_{ab}} \ln \frac{\lambda_{ab}}{s} . \tag{4}$$

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

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 Ref. [8]. Some universal, size independent, behavior of $I_c(H)$ is predicted in this case,

$$\frac{I_c(0) - I_c(H)}{I_c(0)} \approx \sqrt{H/H_0} , \tag{5}$$

where H_0 is a constant field characterizing the layered superconductor,

$$H_0 = \frac{\phi_0 \lambda_{ab}}{\pi^2 s^2 \lambda_c} . \tag{6}$$

For typical BSCCO parameters H_0 can be estimated as $H_0 \approx 0.1$ T.

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

In previous experiments [9–11,18–21] the behavior predicted by Eqs. (1) and (5) as well as a crossover between these two regimes have not yet been demonstrated clearly.

Micron scale stacked junctions have been fabricated from selected single phase (2212) whiskers [21]. 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* axes. 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 $\sim$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 at 450 °C.

The critical current density across the layers measured at 4.2 K with a voltage criterion of 1 μV was 3×10^2 – 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 3 orders smaller to be compared with a longitudinal value of 5×10^5 A/cm^2 in samples from the same batch [18]. Then, the junction geometry is quite convenient for the four probe technique since the long parts can be used for preparing current and potential leads. The long parts remain superconducting up to currents about 2 or 3 orders exceeding the critical current of the stacked structure.

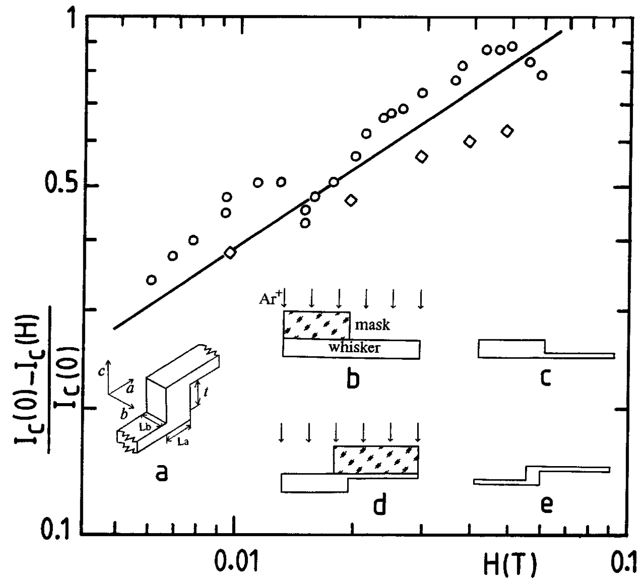

FIG. 1. Variation of the normalized critical current $[I_c(0) - I_c(H)]/I_c(0)$ at $T = 4.2$ K along the c axis as a function of the magnetic field H applied in the a-b plane for $Bi_2Sr_2CaCu_2O_8$ junctions with different sizes in the a-b plane: ◇, 200 μm × 200 μm (from [9]) and ∘, 30 μm × 30 μm. The straight line is the universal $H^{1/2}$ dependence predicted by the Fistul-Giuliani theory [8] for large junctions. The inset shows 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.

For large junctions with lateral size L of the order of 100 μm we have observed a rapid monotonous drop of I_c in rather weak parallel magnetic field H of scale of 0.1 T. The $I_c(H)$ dependences in this field range do not essentially change with L variation from 40 to 200 μm. Similar, size independent behavior of $I_c(H)$ has been predicted by the Fistul-Giuliani theory [8]. Figure 1 shows the fit of experimental data for two samples following the theoretical dependence given by Eq. (5). The data follow relatively well the expected $(H/H_0)^{1/2}$ law. Note that the sizes of the samples differ by a factor of 5. The characteristic field H_0 obtained from the fit has a value $(7 - 8) \times 10^{-2}$ T. The $I_c(H)$ measurements have been performed mostly at 4.2 K. However, several measurements showed that the variation of $I_c(H)$ and the value of H_0 were not substantially changed within the temperature interval between 4.2 and

30 K. Using the theoretical expression for H_0 [Eq. (6)], we can estimate the anisotropy parameter $\gamma = \lambda_c/\lambda_{ab}$ and the Josephson penetration depth $\lambda_j = \gamma s$ for our samples. This estimation gives $\gamma = 1000$ and $\lambda_j = 1.5$ μm, that is, consistent with estimations [11] made from direct measurements of λ_c and λ_{ab}.

As L decreases below 30 μm, the experimental normalized dependences $I_c(H)/I_c(0)$ start to deviate from the universal Fistul-Giuliani dependence as shown in Fig. 2. $I_c(H)$ begins to drop more slowly and oscillations appear. For a junction with $L = 8$ μm we have observed oscillations of $I_c(H)$ with a period of 0.15 T. Three oscillations can be defined, though the field H_{c_1} calculated from Eq. (3) only slightly exceeds the field of the first minimum (see Fig. 2). The period of oscillations decreases with an increase of the sample size [Fig. 3(a)]. This has been directly demonstrated on a junction with different sizes L_a (8 μm) and L_b (20 μm) by rotating H in the a-b plane ($H \parallel a$ and $H \parallel b$; see inset of Fig. 2). For the H orientation perpendicular to the smaller size, $I_c(H)$ drops slower and with a larger period of modulation (Fig. 2) in a good qualitative agreement with Eq. (1). The appropriate theoretical dependences are shown as dashed lines.

The magnetic field H_n, corresponding to the minima of the Fraunhoffer pattern of $I_c(H)$, is plotted in Fig. 3(a) for junctions of different sizes. It shows that the period does not depend on the position of oscillation, n, and that it is inversely proportional to the sample size L in accordance with Eq. (1). Consequently it is possible to deduce the value of s, the spacing between elementary superconducting layers such as $s = \phi_0 n/LH_n$. Figure 3(b) shows that for three different sizes and different magnetic fields (i.e., different n) the ratio $\phi_0 n/LH_n$ exactly yields the value 15 Å, corresponding to half of the lattice constant along the c axis. With a dispersion which does not exceed 10%.

All the data considered above for junctions with a size smaller than 20 μm prove the Josephson behavior of $I_c(H)$ predicted by the theoretical work of Bulaevskii, Clem, and Glazman (BCG theory). When L is increased above 20 μm, a crossover occurs to the behavior predicted by Fistul and Giuliani (FG theory). This crossover is illustrated in Fig. 4 where the dependence of the characteristic magnetic field which suppresses I_c to half its value at zero field $I_c(0)$ is plotted as a function of the junction size. The straight lines correspond to the calculated BCG and FG limits. The points correspond to our experimental data. The picture shows that a crossover from FG to BCG regime occurs within a size interval of 20–30 μm.

In summary, a method of fabricating micron-scale stacked BSCCO junctions of high quality has been developed. Intrinsic dc Josephson behavior has been clearly demonstrated on these samples. The variation of the critical current along the c axis as a function of a parallel magnetic field exhibits a dimensional crossover from an oscillatory behavior to a monotonic size independent behavior when the in-plane junction size is increased.

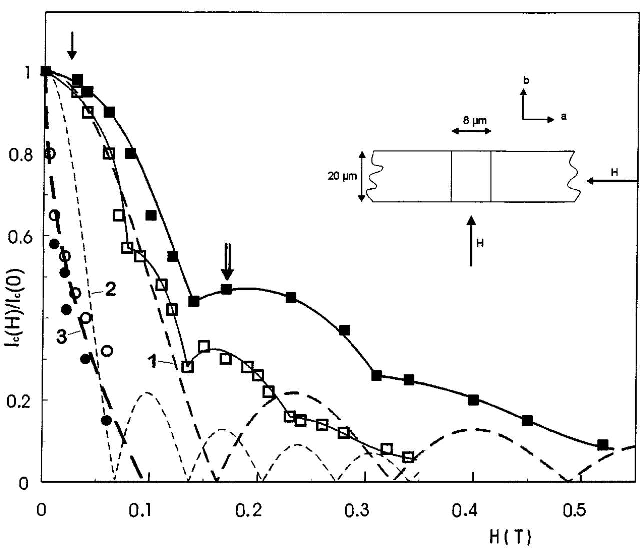

FIG. 2. Normalized dependences of critical currents of $Bi_2Sr_2CaCu_2O_8$ junctions across the layers $I_c(H)/I_c(0)$ at $T = 4.2$ K on magnetic field H parallel to the layers for samples of different sizes L: ■, 8 μm; □, 20 μm; •, 40 μm; and ∘, 200 μm. Solid lines are guides for the eyes. Dashed curves 1 and 2 correspond to Eq. (1) for $L = 8$ and 20 μm, respectively. Curve 3 corresponds to Eq. (5) for $H_0 = 950$ Oe. The arrow (double arrow) indicates H_{c_1}, the field above which Josephson vortices penetrate the 20 μm (8 μm) wide junction. Inset shows the geometry of the junctions for which H has been rotated and applied $\parallel a$ and $\parallel b$, respectively.

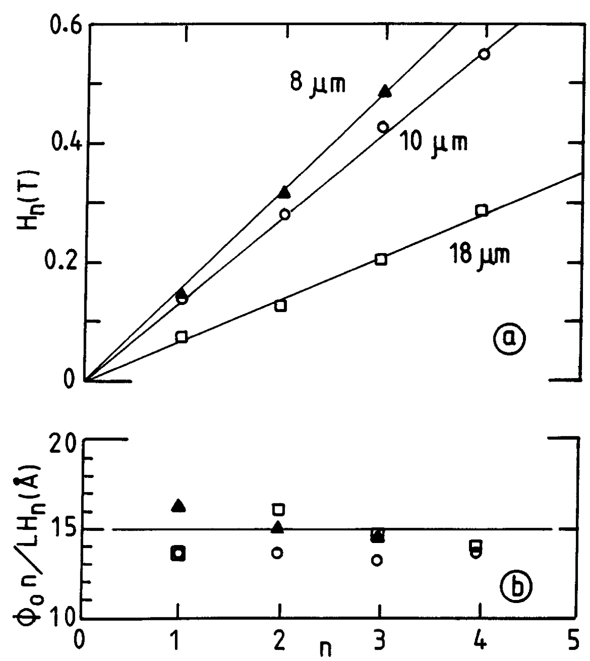

FIG. 3. Dependences of the magnetic fields H_n corresponding to the nth minimum of $I_c(H)$ (a) and the ratio $\phi_0 n/LH_n$ (b) on n for junctions of different sizes L: ▲, 8 μm; ∘, 10 μm; and □, 18 μm.

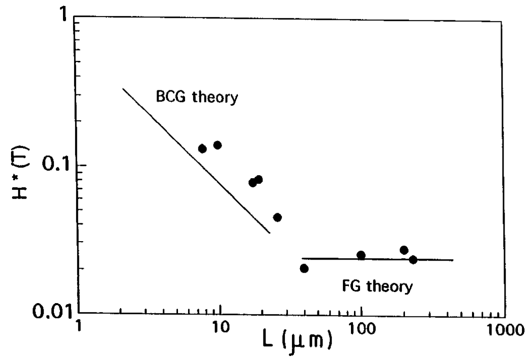

FIG. 4. Dependence of the characteristic magnetic field H^*, which suppresses $I_c(0)$ to the half of its value, as a function of the junction size L. Straight lines correspond to the theories of Bulaevskii, Clem, and Glazman (BCG) and of Fistul and Giuliani (FG), calculated from Eq. (1) and Eq. (5) using the following parameters: $s = 15$ Å, $H_0 = 8 \times 10^{-2}$ T.

Field dependences for larger junctions are in good agreement with the Fistul-Giuliani theory.

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