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Effect of light irradiation on Fiske resonances and the Josephson effect in high-T_c junctions

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We have performed photoexcitation experiments in high T_c $YBa_2Cu_3O_x$ grain-boundary Josephson junctions. While the Josephson critical current is substantially enhanced, the normal state resistance decreases, and the positions of the extreme in the Fraunhofer diffraction pattern remain unchanged. These measurements show that the magnetic field penetration depth is not affected by light irradiation. On the other hand, the position and intensity of Fiske steps due to electromagnetic resonances increase substantially, which implies that the ratio of the thickness barrier to the dielectric constant changes by a factor of 2. [S0163-1829(97)50938-6]

Under illumination with visible light, oxygen deficient $YBa_2Cu_3O_x$ thin films show persistent enhancement of conductivity (PPC)[1] or photoinduced superconductivity (PPS).[2] These effects increase with decreasing oxygen deficiency and Hall effect measurements imply an increase in the carrier density with photodoping.[3] The frequency dependence shows at 4.1 eV a well-defined enhancement[4] and thickness dependent measurements imply that the effect only penetrates a few hundred Ångstroms from the surface.[5] Two competing classes of theories have been advanced; photoinduced ordering of oxygen atoms[6] or photocreation of electron-hole pairs with trapping of electrons in the O vacancies.[7] However, the oxygen ordering model seems to be ruled out by recent experiments which find down to $x=6$ an enhancement of PPC.[8]

$YBa_2Cu_3O_x$ bicrystal grain boundary Josephson junctions (GBJJ), show an enhancement of the superconducting properties together with a decrease of the normal state resistance with visible or UV light.[9–12] This photoinduced effect implies that the grain boundary is oxygen depleted, and from a comparison with the PPC of oxygen depleted $YBa_2Cu_3O_x$ thin films,[10,12] an oxygen concentration of $x\approx 6.6$ near the metal-insulator transition is estimated. However, this is an average concentration through the barrier. The oxygen concentration decreases from $x=7$ in the banks down to values lower than 6.6 in the grain boundary. Thus the GBJJ is a rather complicated weak link which can be modeled as a superconductor-semiconductor-superconductor (S-Sc-S) junction or even a more complex structure like S-N-Sc-N-S junction, where N is a normal metal. The temperature dependence of the critical current in such structures has been shown to reflect such complicated structure.[13]

So far no changes have been found of the Fraunhofer diffraction pattern due to illumination.[9,11] In this work, we have illuminated GBJJ which show both dc (Fraunhofer pattern) and ac Josephson properties (Fiske steps). We show clearly that illumination increases the critical current without changing the periodicity of the Fraunhofer pattern, enhances the amplitude of the Fiske steps and shifts their positions to higher voltages. This implies that the magnetic field penetration depth remains constant, whereas the ratio t/ϵ of the barrier thickness t to the dielectric constant ϵ changes with photoexcitation. In this paper we report on the effect of photodoping on the ac Josephson properties.

Details of the fabrication of the GBJJ can be found elsewhere.[14] $YBa_2Cu_3O_x$ epitaxial thin films were deposited on a bicrystal $SrTiO_3$ (100) substrate using an excimer laser ablation process. 24° tilt angles of the bicrystals create the weak link region (length $W\approx 5$ μm) on the $YBa_2Cu_3O_7$ film (thickness $\approx$200–300 nm). The critical temperature of the GBJJ is $T_c=84$ K and the normal state resistance of the GBJJ is $R_n\approx 6$ Ω. The planar geometry (of the GBJJ) is well suited for illumination. The current-voltage characteristics were measured down to 10 K, before and after illumination, and for different small applied magnetic fields. The $I(V)$ characteristics (therefore the critical currents and the Fraunhofer patterns) did not change with temperature cycles and were stable for several months. No trapped magnetic flux was observed for magnetic fields below a few Gauss. Light irradiation was provided by a 70 W Hg-Xe lamp which illuminates the samples through a window of the optical cryostat. The irradiation experiments [$I(V)$ curves and Fraunhofer patterns] were perfectly reproducible. After 8 hours relaxation at room temperature in darkness, the illuminated GBJJ recovered the original properties before illumination.

Typical $I(V)$ characteristics for $T=12$ K, in zero magnetic field ($H=0$), for which I_c is maximum, and for $H=0.56$ Gauss, where I_c is near a minimum of the Fraunhofer pattern are shown in Figs. 1 and 2, respectively. The critical current is well described by a Fraunhofer pattern [Fig. 3(a)] $|\sin\pi\phi/\pi\phi|$, where $\phi=\Phi/\Phi_0$ is the normalized flux flowing perpendicularly through the junction barrier (or in normalized magnetic fields H/H_0).[15] GBJJ without illumination, also exhibit electromagnetic or Fiske resonances which appear as ''bumps'' at a finite voltage in the $I(V)$ characteristics.[16–18] Such a bump is seen in Fig. 2 at a volt-

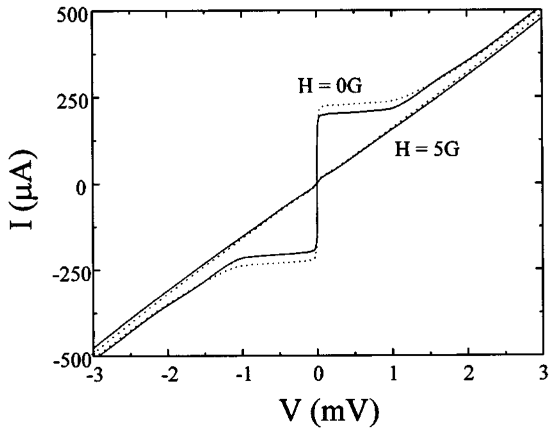

FIG. 1. $I(V)$ characteristics of a $YBa_2Cu_3O_x$ GBJJ before (solid line) and after illumination (dotted line) without applied magnetic field at $T=12$ K. The normal state resistance is shown before (solid line) and after illumination (dotted line) for an applied magnetic field of 5 G.

age of 0.8 mV in the $I(V)$ curve and emphasized by substracting the background produced by the $I(V)$ characteristics (inset Fig. 2). These bumps in the $I(V)$ characteristics are electromagnetic (Fiske) resonances between the Josephson currents and electromagnetic cavity modes of the junction.[15] The ac Josephson current density $J=J_c\sin(\omega\tau-ky+\alpha)$ generates electromagnetic fields of frequency $\omega/2\pi$ propagating through the barrier along its length with velocity c. Here $k=2\pi dB/\Phi_0$ with $d=2\lambda+t$, where t is the thickness of the barrier and λ the London penetration depth. The Swihart velocity c, is given by $c=c_0\sqrt{t/\epsilon d}$ where c_0 is the vacuum light velocity and ϵ the relative dielectric constant of the barrier.[15] When the Josephson frequency $\omega/2\pi=2eV/h$ matches the frequency of one of the junction modes, an additional zero frequency current appears, leading to excess current bumps in the $I(V)$ curves at voltages

$$V_n=n\left(\frac{h}{2e}\right)\frac{c}{2W}=n\Phi_0\frac{c}{2W}. \tag{1}$$

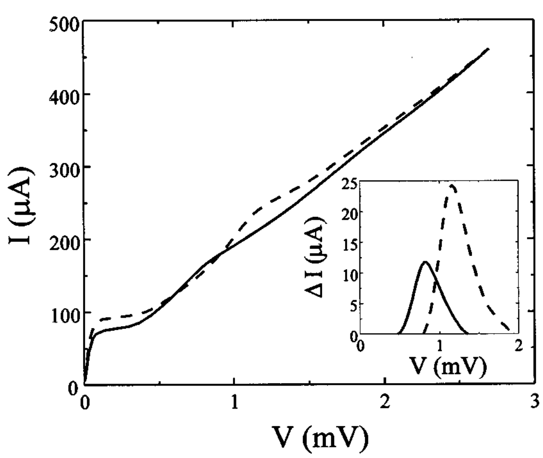

FIG. 2. $I(V)$ characteristics of a $YBa_2Cu_3O_x$ GBJJ before (solid line) and after illumination (dotted line) for an applied magnetic field of $H=0.56$ G at $T=12$ K. The inset shows the Fiske step before (solid line) and after illumination (dotted line) when the background is subtracted.

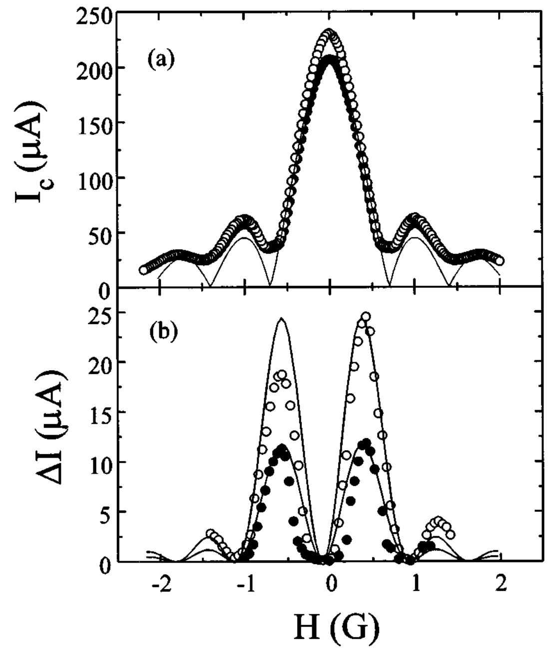

FIG. 3. Magnetic field dependence of the Fiske step (b) before (black dots) and after illumination (white dots) as compared to the Fraunhofer pattern (a). The solid lines in (b) are the theoretical curves F_1^2 (see Eq. 3) and in (a) are $|\sin\pi\phi/\pi\phi|$.

We will only analyze the $n=1$ structure since it is the only one clearly observed, while the higher order ones are too small to be analyzed. It is interesting to notice though, that the first resonance at 1.6 mV observed at $H=0$ Gauss (Fig. 1) is actually the second-order mode. Even though the amplitude of the Fiske resonance should vanish at zero field, there is still a bump caused by the high current, which in turn induces a field in the junction.

The additional dc current $\Delta I(\phi)$, of these resonances as a function of the magnetic flux ϕ through the junction, is given theoretically by[15]

$$\Delta I(\phi)=I_cQ\left(\frac{W}{2\pi\lambda_J}\right)^2F_1^2, \tag{2}$$

with

$$F_1^2=\left[\frac{2\phi}{\phi+\frac{1}{2}}\right]^2\left[\frac{\sin\left(\pi\phi-\frac{\pi}{2}\right)}{\pi\phi-\frac{\pi}{2}}\right]^2, \tag{3}$$

where $\lambda_J=\sqrt{\Phi_0/(2\pi\mu_0 dJ_c)}$ is the Josephson penetration length, J_c the critical current density, and Q the quality factor. The theoretical function F_1^2 plotted in Fig. 3(b) is in qualitative agreement with the experimental results. Comparing the magnetic field periodicity of the Fiske step [Fig. 3(b)] with that of the Fraunhofer pattern [Fig. 3(a)] shows that the maxima and minima found experimentally are in agreement with theoretical values.[15] The first maximum of the amplitude of the Fiske step is at $0.7\Phi_0$, the second maximum is at $1.5\Phi_0$ and the first minimum is at Φ_0.

The maximum amplitude of the Fiske step is given for $n=1$ by

$$\Delta I^{max}=1.2 I_c Q\left(\frac{W}{2\pi\lambda_J}\right)^2. \quad (4)$$

Using Eq. (1), we determine the Swihart velocity, $c=4\times10^6$ m/s, which implies $t/\epsilon=0.05$ nm giving a capacitance of the junction $C_J\approx120$ fF. Using the experimental value $\Delta I^{max}=11\mu A$ (Fig. 2 inset), an estimated value of $2\lambda_{ab}(12\ K)\approx280$ nm, which gives $\lambda_J\approx2.6\ \mu m$, and Eq. (4) we find $Q\approx0.5$. To summarize the results without illumination, the GBJJ used in this study exhibit all the standard phenomena predicted and observed for conventional Josephson junctions,[15] with reasonable values for the various junction parameters.

The effect of 30 min illumination on $I(V)$ is shown in Fig. 1 at $T=12$ K in zero magnetic field, after the light is switched off to avoid heating effects. There is an 11% enhancement of the critical current I_c and a small (1.5%) decrease of the normal state resistance R_N. This small decrease of resistance is seen more clearly when the $I(V)$ curve is measured in a high magnetic field ($H=5$ Gauss) before and after illumination (Fig. 1). The increase of the critical current is higher than the decrease of the resistance so that after illumination $R_N I_c$ increased by 9% indicating an increase of the superconducting properties of the weak link. The increase of the Josephson current and of the normal state conductivity are persistent and stable when the temperature is kept below ≈100 K.

As shown in Fig. 3, the highest I_c enhancement is obtained for zero magnetic field while the magnetic field periodicity is unchanged after illumination. This implies that the magnetic field penetration depth λ_{ab} which governs this periodicity[15] does not change by photodoping. Since this penetration depth is large compared to the width of the grain boundary, i.e., the oxygen depleted region, there is little change of the Fraunhofer pattern with the light.

Figure 2 shows the $I(V)$ curves before and after illumination at 12 K for $H\approx0.56$ Gauss where the Fiske step is maximum. The effect of illumination is better shown in the inset of Fig. 2 where a straight line interpolated background is subtracted from the $I(V)$ curve. Light increases dramatically the amplitude of the Fiske step by a factor of about 2 and shifts it from 0.8 mV to 1.15 mV. The time evolution of this shift can be changed by varying the photon dose. At low optical power, this shift versus time is slow enough to be resolved.[19]

Figure 3 shows the magnetic field dependence of the amplitude of this Fiske step before and after illumination. The Fiske resonance amplitude increases with illumination, however, the minima in field remain almost unchanged (only a small asymmetry is found). This implies that the order n of the Fiske step is unchanged.

After illumination (labeled with the index L), the current bump, for $n=1$, is at a position

$$V_L=\Phi_0\frac{c_L}{2W}, \quad (5)$$

where $c_L=c_0\sqrt{t_L/\epsilon_L d}$ is the Swihart velocity after illumination given by the barrier thickness t_L and the effective dielectric constant ϵ_L.

From the experimental values of the position of the Fiske step before and after illumination we obtain

$$\frac{V_L}{V}=\sqrt{\left(\frac{t_L}{\epsilon_L}\right)\left(\frac{\epsilon}{t}\right)}=1.44. \quad (6)$$

The Swihart velocity increases from 4 to 5.7×10^6 m/s, which gives $(t/\epsilon)/(t_L/\epsilon_L)\approx0.48$. Therefore the photodoping increases t/ϵ by a factor of ≈2.

The ratio of the amplitude ΔI^{max} before and after illumination ΔI_L^{max} is

$$\frac{\Delta I_L^{max}}{\Delta I^{max}}=\frac{I_{C,L}}{I_C}\frac{Q_L}{Q}\left[\frac{\lambda_J}{\lambda_{J,L}}\right]^2=\left[\frac{I_{C,L}}{I_C}\right]^2\frac{Q_L}{Q}. \quad (7)$$

From the experimental values: $I_{C,L}/I_C=1.2$ and $\Delta I_L^{max}/\Delta I^{max}\approx2$ we find $Q_L/Q\approx1.4$. Since $Q\approx RC\omega$ the total capacitance ratio before and after illumination $C_L/C=(Q_L/Q)(R/R_L)(V/V_L)\approx1$ using $R_L/R\approx0.985$ and $\omega_L/\omega=V_L/V$. The total capacitance C includes both the junction capacitance C_J and the stray capacitance C_S of the $SrTiO_3$ substrate. For $SrTiO_3$ substrates, the stray capacitance per unit length has been determined to be about ≈70 fF/μm.[20] This gives $C_S\approx350$ fF for our junction which is larger than C_J. Therefore, the total capacitance is given mainly by the contribution of the stray capacitance and is weakly affected by light.

In summary, the effect of light on the Josephson effect was studied using $YBa_2Cu_3O_x$ grain boundary Josephson junctions which exhibit all the expected properties of conventional junctions. We have shown clearly that the illumination has no effect on the periodicity of the Fraunhofer pattern, implying that the London penetration depth remains unaffected by illumination. Illumination enhances the critical current and decreases the normal state resistance as found earlier,[9,10,12] shifts the Fiske steps to higher voltages and reinforces their amplitude substantially. This effect can be understood as due to a change of the barrier parameters by photodoping.

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