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Photodoping of YBaCuO Grain Boundary Josephson Junctions

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1. INTRODUCTION

Since the discovery of High T_c Superconductivity at the end of 1986 [1], great attention has been paid to the investigation of the action of light on High T_c Superconductors (HTSC). Besides their high transition temperature, the HTSC show unusual physical properties. Some of these are persistent photoconductivity (PPC) and persistent photoinduced superconductivity (PPS). The superconducting properties of an oxygen deficient superconducting $YBa_2Cu_3O_x$ thin film increase with illumination and persist after the light is switched off if the sample is kept at low temperatures (typically smaller than 100 K). This effect, called persistent photoinduced superconductivity (PPS), is more pronounced for oxygen deficient thin film and vanishes for $YBa_2Cu_3O_7$. When the $YBa_2Cu_3O_x$ thin film is semiconducting or insulating, light has also an unusual effect on their transport properties: the conductivity is increased by light leading also to a persistent photoinduced conductivity (PPC). An insulating $YBa_2Cu_3O_x$ thin film taken just below the Metal-Insulator transition ($x \approx 6.4$) can even become superconducting only by illumination. These enhanced superconducting or photoconducting properties relax towards the original properties when the temperature of the sample is risen back to room temperature. The PPC and PPS effects are more pronounced in the UV or visible range and vanish in the IR range.

This photodoping effect can be used also in YBaCuO grain boundary Josephson junctions (GBJJ) as an optical method to change the Josephson coupling. In these GBJJ, the grain boundary which constitutes the barrier is a weak superconducting region which is oxygen deficient and/or disordered. Then, illumination of such junctions will change the transport properties of the oxygen deficient barrier like in the thin films and thus change the Josephson coupling. The PPS will result in a dc Josephson current increased and the voltage positions of the Fiske resonances (ac Josephson properties) shifted. The PPC will induce a decrease of the normal state resistance of the junction.

2. EXPERIMENTS OF ILLUMINATION OF OXYGEN DEFICIENT YBaCuO THIN FILMS

The enhancement of conductivity or superconductivity has been found in $YBa_2Cu_3O_x$ thin films after a long time of illumination by Kudinov *et al.* [2] and Kirilyuk *et al.* [3] and studied by different groups. For a review article on the PPC and PPS effects on $REBa_2Cu_3O_x$ thin films see, for example, Hoffmann *et al.* [4]. For instance for $YBa_2Cu_3O_{6.4}$ the critical temperature T_c which is around 16 K increases by ΔT_c as high as ≈ 10 K. Thus the critical temperature and the conductivity can show an increase which is not a weak effect. The maximum relative change of conductivity after illumination can be as large as a few hundred of percent depending upon the oxygen content. This excited state is stable if the sample is kept at low temperatures (< 100 K).

The excited state due to the persistent photoinduced phenomena is correlated with an increase of the Hall number [5,6]. This correlation strongly suggests that, upon illumination, the carrier density increases, which results in a decrease in resistivity.

To explain these PPC and PPS effects, several models have been proposed but up to now, the exact

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mechanism of these effects is not absolutely clarified. Kudinov *et al.* [2] suggest that the sample illumination results in a photoexcitation of electron-hole pairs across the YBaCuO band gap. In this semiconductor-like picture, electrons are subsequently trapped by defects. These defects are the localized oxygen vacancies in CuO chains where normally an Oxygen ion would be located in a fully oxygenated sample. This capture process creates excess mobile holes transferred into extended states in the CuO_2 planes. The increase of carriers in the CuO_2 planes enhance the transport properties of YBaCuO. This effect is more pronounced for oxygen deficient films because more electrons can be trapped by more oxygen vacant sites. This photoinduced vacancy capture mechanism based on the necessity of oxygen vacancies present in the chain layers seems to be the model that probably describes better the PPC and PPS phenomena [7].

3. ILLUMINATION OF YBaCuO JOSEPHSON JUNCTIONS

The first investigation of the effect of photoinduced hole doping on grain boundary Josephson junctions (GBJJ) as well as step edge junctions (SEJ) have been made by Tanabe *et al.* [8]. They have shown an increase of the critical current I_c of approximately 20–40% and a decrease of the normal state resistance R_n. Such behavior of photoinduced hole doping YBaCuO grain boundary junction indicates that the grain boundary is a low oxygenated barrier. Such an enhancement of the critical current I_c and a decrease of the normal state resistance of GBJJ have been shown also by Hoffmann *et al.* [9] and by Elly *et al.* [10]. Even after illumination, the critical current I_c is again modulated by an applied magnetic field and in good agreement with the theoretical curve $\sin \pi\phi/\pi\phi$ where ϕ is the normalized flux $\phi = \Phi/\Phi_0$ flowing perpendicularly through the junction barrier, in units of flux quantum $\Phi_0 = h/2e$.

The normal state resistance of the GBJJ vs. illumination time has a sharp decrease at the beginning and saturates after a few hours, behavior analogous of the PPC effect found in YBaCuO thin films. The maximum relative decrease of the resistivity is $\approx 5\%$ for GBJJ with T_c around 90 K. From this time dependent photoconductivity we can compare the PPC of illuminated YBaCuO GBJJ with the PPC of low oxygenated thin films for different concentration x of oxygen content. From this comparison we find an average composition $x \approx 6.6$ of the YBCO weak link for GBJJ with $T_c \approx 90$ K [9,11].

The increase of the critical current is higher than the decrease of the resistance so that the $R_n I_c$ product after illumination has increased by 9% indicating an increase of the superconducting properties of the weak link. These results confirm the results obtained by Tanabe *et al.* and we can conclude that the weak link of GBJJ is an oxygen deficient region.

Not only the critical current I_c at zero voltage is magnetic field dependent but also structures which appear as bumps at some finite voltage and analyzed as Fiske resonances [12]. Due to high damping in these GBJJ, the structures appear as bumps and not as sharp Fiske steps as usually found in Josephson junctions made with classical superconductors.

A Josephson junction can be considered as a transmission line for electromagnetic waves. The electric field is essentially confined within the barrier region of thickness t. The magnetic field fills a larger region of thickness $d = 2\lambda_L + t$ where λ_L is the London penetration depth in the superconducting region. The phase velocity called Swihart velocity c of an electromagnetic wave for such transmission line is given by $c = c_0\ (t/\varepsilon d)^{1/2}$ where c_0 is the light velocity in vacuum and ε the relative dielectric constant of the barrier. As d, the region filled by the magnetic field, is larger than t, the region filled by the electric field, the velocity c is smaller than c_0. In an external magnetic field H, there may be a set of current singularities called Fiske resonances in the $I(V)$ characteristics at voltages [13].

$$V_n = n(h/2e)(c/2W) = n\Phi_0(c/2W) \quad (1)$$

These geometrical resonances occur when the length W of the junction corresponds just to a number n of half wavelength of the Josephson current density wave $j = j_c \sin(\omega t - ky)$ running in the y direction of the length of the junction.

The effect of 30 mn illumination increases the amplitude of the Fiske resonances and shifts their position from 0.8 mV for cumulative illumination time until a maximum position $V_1 = 1.15$ mV which is a 44% change [14]. We have shown also that the maximum voltage position V_1 corresponding to the first mode of the Fiske resonances for GBJJ of different length W before and after illumination is a linear function of $1/W$ as expected from relation (1). From the linear slope we can determine the Swihart velocity and find $c = 4 \times 10^6$ m/s before illumination and $c = 5.6 \times 10^6$ m/s after illumination [14].

After illumination (noted with the index L), the current bump is, for $n = 1$, at a position given by Eq. (1) where $c_L = c_0(t/\varepsilon_L d)^{1/2}$ is the Swihart velocity after illumination corresponding to an effective dielectric constant ε_L. It is thought that the thickness t of the weak link cannot change after illumination because an increase of the Swihart velocity must increase t and an increase of the thickness barrier must increase the normal state resistance and decrease the critical current which is the opposite of what is found in the experiments. From the experimental values of the maximum position of the Fiske resonances before and after illumination we deduce if the barrier thickness is constant:

$$V_L/V = (\varepsilon/\varepsilon_L)^{1/2} = 1.44$$

which gives $\varepsilon_L/\varepsilon \approx 0.48$. The photodoping has an effect of decreasing continuously the relative dielectric constant until a maximum factor of ≈ 2 [14]. This effect is related to photodoping of the oxygen deficient barrier but the mechanism of the decrease of the dielectric constant is not well understood.

4. CONCLUSIONS

We have described the PPC and PPS effects, a remarkable property, shown by oxygen deficient HTCS thin films. Illumination of oxygen deficient $YBa_2Cu_3O_x$ thin film can be interesting because it can be used as a reversible alternative for changing the carrier density of the CuO_2 planes.

More insight in the phase diagram relating the superconducting properties vs. carrier concentration can be obtained with these experiments of illumination. Starting from an underdoped sample, illumination will always increase the superconducting properties if we stay in the underdoped regime. But starting in the overdoped regime, illumination will decrease the superconducting properties. The majority of the experiments have been done in the underdoped regime so until now, no experience in the overdoped regime seems to have shown a reversible decrease of the superconducting properties.

The YBaCuO GBJJ with its oxygen deficient barrier shows also these effects of PPC and PPS. Thus illumination can be used to change the Josephson coupling of YBaCuO GBJJ. These effects can be interesting for adjustment of the same critical current in each junction of a dc SQUID.

A theoretical understanding of the PPC and PPS phenomena is needed because the exact mechanism is not completely understood in particular for other HTCS thin films than YBaCuO for which experiments are also needed.

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