*Journal of Low Temperature Physics, Vol. 106, Nos. 3/4, 1997*

# Photoinduced enhancement of the Josephson effect in YBaCuO grain boundary junctions

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*Experiments of persistent photoinduced enhancement of the Josephson effect in YBaCuO junctions are reviewed in this paper. These experiments show that the critical current and the conductivity of these Josephson junctions can be increased after illumination. This effect is due to photodoping of the oxygen depleted region in the weak link.*

*PACS numbers: 73.50.Pz, 74.50.+r, 74.72.Bk.*

## 1. INTRODUCTION

Enhancement of conductivity and/or superconductivity has been found in $YBa_2Cu_3O_x$ thin films after illumination with visible light.[1–4] This persistent photoinduced conductivity (PPC) and photoinduced superconductivity (PPS) is maximum for deoxygenated samples and an insulating $YBa_2Cu_3O_x$ thin film can even become superconducting by illumination.[3]

In bicrystal grain boundary Josephson junctions, the grain boundary forming the weak link, is an $YBa_2Cu_3O_x$ oxygen depleted region between two $YBa_2Cu_3O_7$ banks. If these Josephson junctions are illuminated, the oxygen deficient region shows an enhancement of conductivity similar to $YBa_2Cu_3O_x$ thin films. Thus, by photodoping, it is possible to change the weak coupling present in these Josephson junctions.

This paper is devoted to a review of the effect of illumination on



0022-2291/97/0200-0255$12.50/0 

YBaCuO Josephson junctions. For an understanding of this effect it is necessary to start with a brief summary of the role of oxygen and a short description of PPC and PPS in oxygen deficient $YBa_2Cu_3O_x$ thin films.

## 2. ILLUMINATION OF OXYGEN DEFICIENT $YBa_2Cu_3O_x$ THIN FILMS

### 2.1. The importance of oxygen content

The transport properties of a YBaCuO sample are essentially due to the $CuO_2$ layers which play a major role in the mechanism of superconductivity. The CuO chains, arranged along the b-axis, act as reservoirs which supply the $CuO_2$ planes with charge carriers.

By decreasing the oxygen content $x$ of $YBa_2Cu_3O_x$ samples, oxygen atoms are removed from the chain. The CuO chains are infinitely long in the fully oxygenated case ($x = 7$). As the oxygen content decreases from $x = 7$ to $x = 6$, the number of vacancies in the CuO chains increase. At an oxygen deficiency $x \simeq 6.4$ the sample undergoes an orthorhombic-tetragonal structural transition where the a- and b-axes become equivalent. In the $x = 6$ tetragonal phase, there are no oxygen atoms in the chain planes. Thus, by decreasing the oxygen content, the CuO chains shorten, their effectiveness as charge reservoir decreases and therefore the charge density of the $CuO_2$ planes decreases, diminishing drastically the superconducting properties of the $YBa_2Cu_3O_x$ sample. Thus, the critical temperature $T_c$ of $YBa_2Cu_3O_x$ thin films decreases with oxygen content $x$ from $T_c$ =90 K for $x = 7$, to a semiconducting behavior ($T_c$ = 0 K) for $x \leq 6.4$.

### 2.2. Illumination of oxygen deficient $YBa_2Cu_3O_x$ thin films

Light has an unusual effect on the transport properties of oxygen deficient $YBa_2Cu_3O_x$ thin films. After long time illumination, the critical temperature and the conductivity show large increases. The relative change of conductivity after illumination can be of several orders of magnitude depending upon the oxygen content. Kudinov *et al.*[2] first studied the decrease of the resistivity of a film during the illumination with a laser. Nieva *et al.*[3] discovered an increase in the $T_c$ of a film after illumination. For instance, figure 1 shows the resistivity as a function of temperature for two typical oxygen deficient films $YBa_2Cu_3O_{6.4}$ and $YBa_2Cu_3O_{6.87}$ before (upper curve) and after 8 hours of illumination (lower curve) with a halogen lamp (total photon dose of $3 \times 10^{23}$ ph/cm$^2$). Both the conductivity and the $T_c$ increased after illumination and the enhancement is more pronounced for oxygen deficient films. This excited state is persistent if the sample is

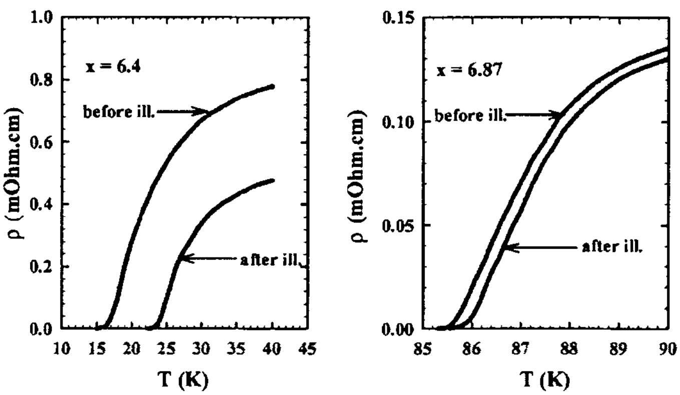


Fig. 1. Temperature dependence of the resistivity of oxygen deficient $YBa_2Cu_3O_x$ thin films before and after illumination (from ref. 4).

kept at low temperatures ($\leq$ 150 K). It slowly relaxes back to its original state if the temperature of the sample is increased to high temperatures. For example, at 300 K after several hours (typically 24 hours) the original state is recovered. In addition to the conductivity and superconductivity enhancement an increase of the Hall number, a slight enhancement of the carrier mobility and a small contraction of the c-axis lattice parameter have also been found.[3,5-7]

To explain these phenomena in $YBa_2Cu_3O_x$ films, several models have been proposed. One of the mechanism invoked, relies on the creation of an electron-hole pair, with transfer of the excited electron to the CuO chain where it is trapped by a localized oxygen vacancy, while the hole enters the $CuO_2$ plane. The increase of carriers in the $CuO_2$ plane enhances the transport properties of YBaCuO and this effect is more pronounced for oxygen deficient films.[8] This photoinduced vacancy capture mechanism[9] based on the presence of oxygen vacancies in the chain layers seems to be the model that probably describes best the PPC and PPS. Another mechanism[10] which has been invoked to describe the effect in samples with relatively high oxygen contents, is photoinduced oxygen ordering. However, this seems to be ruled out by recent experiments, which find an enhancement of PPC down to $x = 6$.[9]

## 3. ILLUMINATION OF $YBa_2Cu_3O_x$ JOSEPHSON JUNCTIONS

A grain boundary Josephson junction (GBJJ) is made of a narrow constriction ( $\simeq$ 1–10 $\mu$m) on top of a grain boundary on the substrate. Pre-

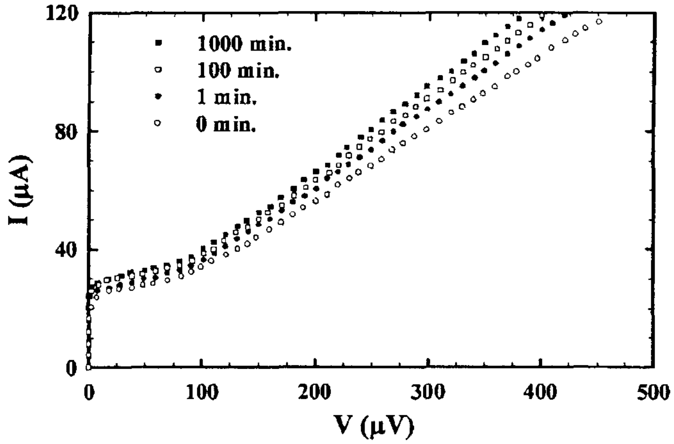


Fig. 2. Time dependence of the $I(V)$ characteristic of a GBJJ at 40 K before and after illumination (1, 100, 1000 minutes) (from ref. 11).

sumably, the grain boundary region is depleted of oxygen although to date no direct evidence exists for this depletion.

After the first investigation of the optical response of YBaCuO films, investigations of the effect of light on YBaCuO GBJJ as well as step-edge junctions (SEJ) have been made.[11] In these experiments GBJJ were illuminated ($\approx$ 1000 min) with visible light using a He-Ne laser (power density $\approx$ 100 W/cm$^2$) coupled to a multi-mode optical fiber with a core of 50 $\mu$m. The illumination-induced temperature rise is estimated to be less than 0.5 K, so the sample heating is not expected to have a substantial influence. Figure 2 shows typical $I(V)$ characteristics for three different illumination times of a 10 $\mu$m wide bicrystal junction illuminated at 40 K. The increase of the critical current $I_c$ and the decrease of the normal state resistance $R_n$ depends of the illumination time as shown in Fig. 3. The increase of $I_c$ is 25% for SEJ and 40% for GBJJ. The product $R_nI_c$ increases, indicating an increase of the superconducting properties in the grain boundary. Such behavior of photoinduced hole doping of YBaCuO GBJJ, indicates that the grain boundary is oxygen depleted. Figure 4 shows the magnetic field dependence of $I_c$ before and after 1000 minutes illumination at 30 K for the same junction. The curves before and after illumination are typical for a GBJJ without substantial changes in their shape indicating that Josephson tunneling is maintained after illumination, although with an enhanced intensity.

Adam *et al.*[12] have reported permanent laser-induced changes of the critical current and normal resistance of $YBa_2Cu_3O_x$ SEJ. In these experiments the junctions are illuminated at 50 K with a focused Ar-ion laser beam

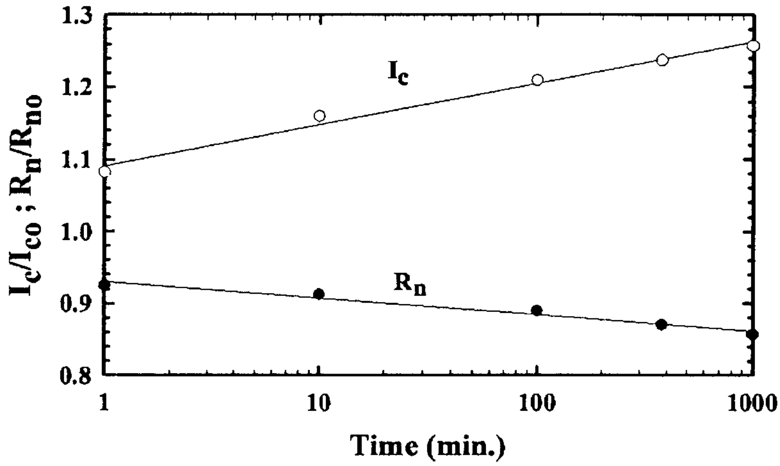


Fig. 3. Dependence of $I_c$ and $R_n$ of a GBJJ on the illumination time (from ref. 11).

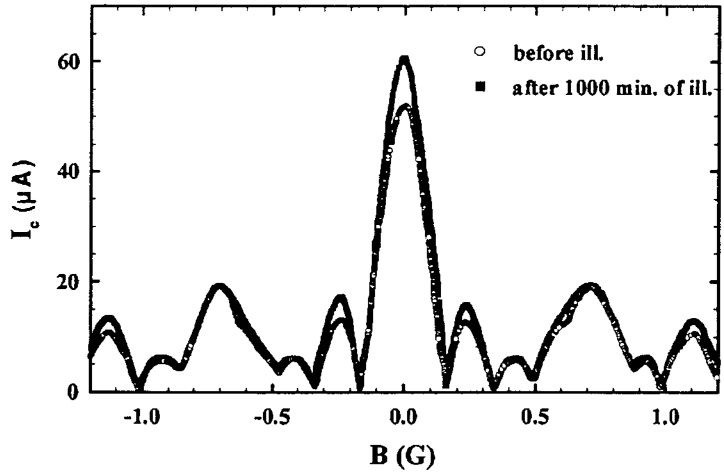


Fig. 4. Magnetic field dependence of the critical current of a GBJJ at 30 K before and after 1000 minutes of illumination (from ref. 11).

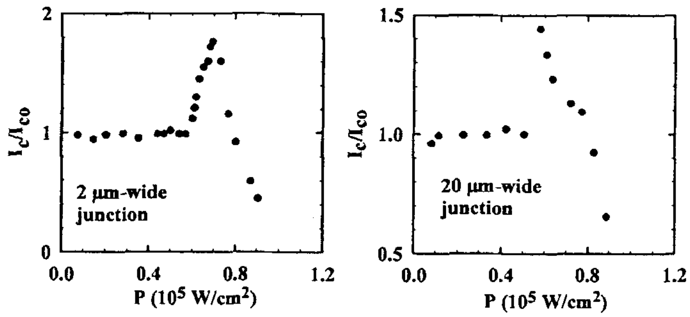


Fig. 5. Dependence of the critical current on optical power (from ref. 12).

of various intensities. After illumination with $6 \times 10^4$ W/cm$^2$, enhancements of $I_c$ and $R_n I_c$ are obtained without a measurable change in the junction critical temperature. However, depending on the illumination power density, either increase or decrease of $I_c$ is observed. Figure 5 shows the dependence of the critical current of SEJ versus laser beam power density $P$. The junction properties remain practically unchanged for light power densities below $6 \times 10^4$ W/cm$^2$, and a significant increase of $I_c$ is observed only above this threshold. Further increase of the illumination power results in a gradual decrease of $I_c$. The increase of $I_c$ can be as large as 75 % (and 25 % for the $R_n I_c$ product). These effects are different from the photoinduced changes observed by Tanabe *et al.*[11] since they are irreversible at room temperature and probably caused by structural changes within the SEJ due to the very high light intensity.

It is difficult to compare the illumination effects in SEJ and GBJJ because for the different experiments the optical power and the wavelength varied. Moreover in a SEJ there are two grain boundaries and the effect can be additive. Even for GBJJ the comparison is difficult because there are many important parameters which influence the PPC like the substrate or bicrystal angle.

Our experiments were performed on single junctions and SQUIDs made of YBaCuO GBJJ prepared by pulsed laser deposition[13] (thickness $\approx$ 120 nm) on $SrTiO_3$ 36.8° bicrystal substrates. Microbridges with widths ranging between 5 and 12 $\mu$m were illuminated with different type of sources. In the experiments performed at UCSD a 1000 W mercury-xenon arc lamp, with a spectrum ranging from UV to IR was used. To protect the sample and the optical elements from excessive heating, far infra-red wavelengths were filtered using a liquid water filter. The power density at the sample surface was during all experiments below 100 mW/cm$^2$ in order to avoid any effects of thermal heating or permanent structural changes. Irradiation

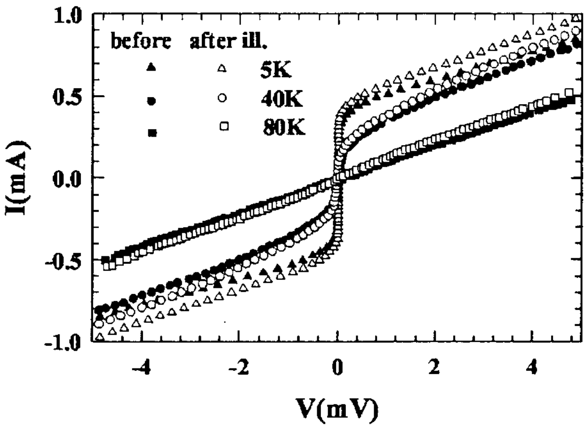


Fig. 6. $I(V)$ curves of a GBJJ-SQUID before and after 1 hour of illumination for different temperatures (UCSD).

were performed at 80 K through optical quartz windows. After one night of relaxation at room temperature in darkness, the illuminated GBJJ recovers its original properties. For the experiments done at UNSA, the source is an ordinary halogen lamp. Figure 6 shows typical $I(V)$ characteristics of a GBJJ-SQUID before and after 1 hour of illumination at 5, 40, and 80 K (UCSD) and figure 7 a typical $I(V)$ curve at 30 K after 5 hours of illumination (UNSA). The main differences between illuminated and non-illuminated $I(V)$ curves are an enhancement of the critical current and a decrease of the normal state resistance at high voltage. These results confirm the results obtained by Tanabe *et al.*[11] and we can conclude that the weak link of GBJJ is oxygen deficient. Fig. 8 shows the time dependence of the junction resistance at several bias current for the experiments done at UCSD. The resistance has a sharp decrease initially which saturates after a few hours. The relative decrease is of the order of 5–10 %.

A comparison of the PPC in illuminated YBaCuO GBJJ with the effect in oxygen deficient thin films[9] allows a determination of the oxygen deficiency $x$ in the weak link area. Fig. 9 shows the relative conductivity change of oxygen deficient YBaCuO thin films as a function of $x$. The relative changes obtained in the GBJJ imply $x \simeq 6.6$ for the sample used at UCSD and $x \simeq 6.4$ for those used at UNSA. For the experiments of Tanabe *et al.*[11] and Adam *et al.*[12] we find $x \simeq 6.5$ and $x \simeq 6.4$ respectively. Atomic Force Microscopy, coupled with quantitative high resolution electron microscopy, on YBaCuO grain boundaries indicate an oxygen content variation from 6.4 to 6.8 in the vicinity of the grain boundary.[14]

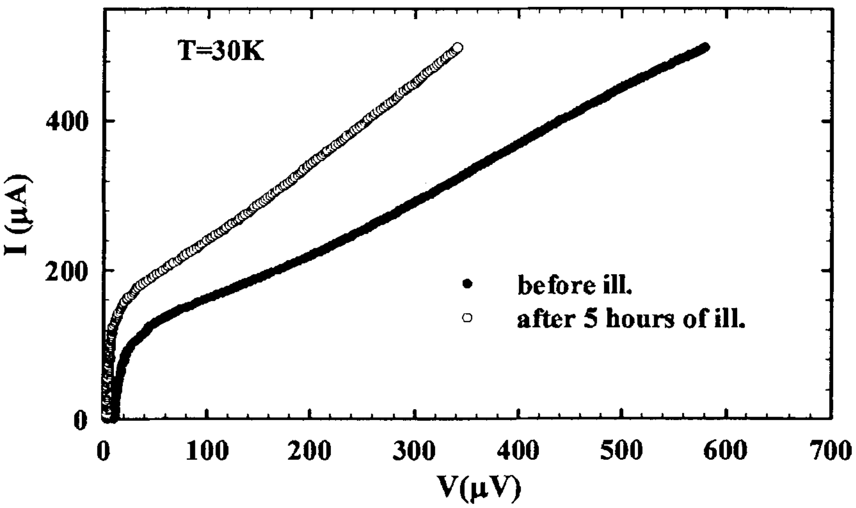


Fig. 7. $I(V)$ curves of a GBJJ before and after 5 hours of illumination (UNSA).

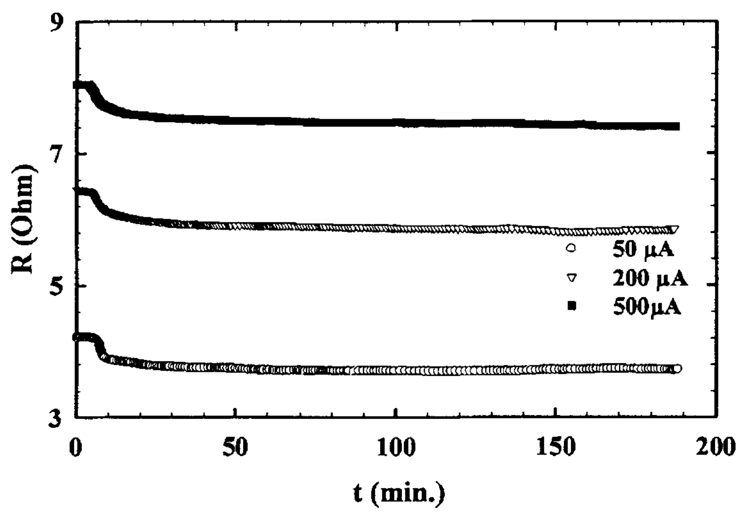


Fig. 8. Time dependence of the resistance for three bias current (50, 200, 500 $\mu$A).

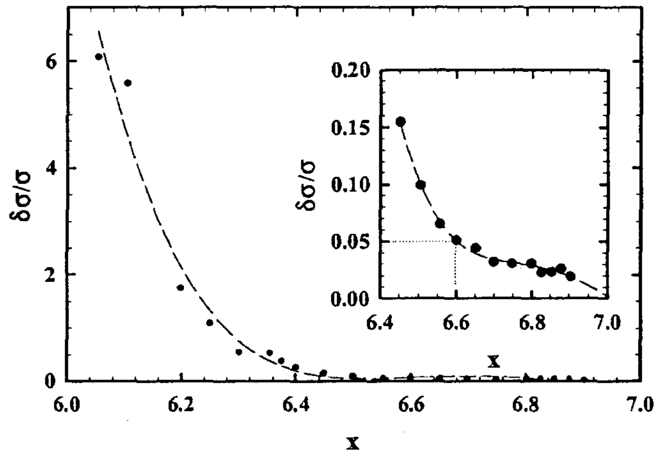


Fig. 9. Dependence of the conductivity of $YBa_2Cu_3O_x$ thin films versus oxygen content $x$ with an enlargement in the insert around $x = 6.4$–$6.8$.

A careful comparison of the decrease $R(t)$ of the illuminated GBJJ and the oxygen deficient thin film reveals an important difference. $R(t)$ is described by a stretched exponential law in YBaCuO thin films while the GBJJ the decrease of $R(t)$ is more pronounced initially (at least two exponentials are needed). A reason for the difference between single films and GBJJ may be that the oxygen deficiency is not uniform across the barrier. The direct determination of the oxygen content concentration profile is difficult since this must be known at length scales comparable to $\xi_{ab}$, the ab-plane coherence length. This is typically of the order of nanometers as it was found from capacitance measurements in the electromagnetic resonances (Fiske steps) of GBJJ.[15,16] Little work has been done to study the oxygen concentration profile in grain boundaries.[14] Moeckly *et al.*[17] have pointed out the importance of chain-site oxygen disorder driven by the elastic strain gradient near a grain boundary.

## 4. CONCLUSIONS

Illumination experiments of YBaCuO GBJJ and SEJ have shown an enhancement of the critical current and a decrease of the normal resistance. These experiments indicate that the weak links in GBJJ or SEJ are oxygen deficient. Comparisons of the relative conductivity change between illuminated YBaCuO GBJJ an SEJ with illuminated YBaCuO thin films with different oxygen content allow an estimate of the oxygen deficiency in the weak link region. From these comparisons, we estimate the oxygen content in the weak links of these Josephson junctions to be between 6.4 and 6.6 close to the metal -insulator transition of 6.4. The modified $I(V)$ characteristic is stable at low temperature and this technique provides an in-situ control for $I_c$ and $R_n$ in GBJJ, SEJ, and SQUIDS.

## ACKNOWLEDGMENTS

Work supported by the Office of Naval Research and international travel supported by NATO, NSF, CNRS and DAAD.

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