Persistent photoconductivity in high T_c grain boundary Josephson junctions

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We observed persistent photoconductivity in $YBa_2Cu_3O_x$ bicrystal grain boundary Josephson junctions. Upon illumination of these grain boundary Josephson junctions, the normal state resistance decreases and the critical current increases. This strongly suggests that the grain boundary in these films consists of oxygen depleted $YBa_2Cu_3O_x$. A comparison with the persistent photoconductivity in oxygen depleted $YBa_2Cu_3O_x$ thin films implies an average oxygen content of $x=6.6\pm0.1$ for the grain boundary. The spectral dependence has a lower threshold for persistent photoconductivity in the junctions (≈ 1.2 eV) than in thin films. © *1997 American Institute of Physics.* [S0003-6951(97)02718-6]

A remarkable property of oxygen deficient $YBa_2Cu_3O_x$ thin films is that they show persistent photoconductivity (PPC)[1] and persistent photoinduced superconductivity (PPS).[2] After illumination with light of an oxygen deficient $YBa_2Cu_3O_x$ thin film, its resistivity decreases and, if the film is superconducting, its superconducting transition temperature increases substantially. This effect is persistent below temperatures of 100 K, and relaxes typically within a day at room temperature.

It has been shown, that PPC is only observed in oxygen deficient $YBa_2Cu_3O_x$.[3] Furthermore the magnitude of these effects depends strongly on the oxygen content[2,4,5] and is maximized for fully deoxygenated $YBa_2Cu_3O_6$.[6] This can be explained by a model, which assumes that oxygen vacancies in the Cu–O chain layers trap photoexcited electrons.[6] This model is further supported by recent photoluminescence measurements[7] and measurements of the PPC spectral dependence.[8]

Weak links made of $YBa_2Cu_3O_x$ bicrystal grain boundary junctions exhibit Josephson behavior with a well developed Fraunhofer pattern[9,10] and Shapiro steps.[11] However, the exact mechanism for the formation of a weak link in these grain boundary junctions is not well understood. A weakening of the superconductivity at length scales comparable to the coherence length is necessary. Clearly, depletion of oxygen is an obvious candidate, although to date the oxygen stoichiometry in the grain boundary has not been obtained.

Following the results of the optical response of a single grain boundary Josephson junction (GBJJ) in a $YBa_2Cu_3O_x$ thin film microbridge,[12] Tanabe *et al.*[13] have shown that $YBa_2Cu_3O_x$ bicrystal GBJJs as well as step-edge junctions exhibit PPC similar to oxygen deficient $YBa_2Cu_3O_x$ thin films. These junctions show upon illumination an increase of the critical current I_c and a decrease of the normal state resistance R_n. This behavior indicates, that the grain boundary consists of oxygen deficient $YBa_2Cu_3O_x$. Here we compare the PPC of $YBa_2Cu_3O_x$ GBJJs with the PPC of oxygen depleted $YBa_2Cu_3O_x$ thin films for various oxygen concentrations x. This allows us to determine the oxygen concentration within the grain boundary of the junction. Furthermore we measured the spectral dependence of the PPC in these junctions.

The GBJJs and dc-SQUIDs used in this study were made of $YBa_2Cu_3O_x$ thin films grown epitaxially by excimer laser ablation on a $SrTiO_3$ (100) bicrystal substrate. The 24° tilt angle of the bicrystal creates the weak link region in the $YBa_2Cu_3O_x$ film. The film is patterned in order to prepare several well defined GBJJs with a length of 8–20 μm and a thickness of 0.1 μm. This planar geometry of the junctions is well suited for illumination experiments. Some of the junctions were patterned to form a dc-SQUID. The critical temperature of the grain boundary junctions is $T_c=86$ K.

Transport measurements were done in a He flow cryostat equipped with optical quartz windows. For the illumination of the sample we used a 1000 W Hg–Xe arc lamp with a spectrum ranging from the UV to IR. A liquid water filter was used to reduce IR radiation and thus to protect sample and optics from excessive heat. For measuring the spectral dependence, we selected a specific wavelength in the range of 255–1100 nm (4.8–1.1 eV) by using interference bandpass filters with a bandwidth of 10 nm. The light intensity at the sample surface was 0.03–28 mW/cm^2 depending on the particular measurement. After illumination the sample was relaxed at room temperature for more than 10 h until the GBJJ (dc-SQUID) recovered its properties before illumination.

Figure 1 shows typical $I(V)$ characteristics of a GBJJ at different temperatures before and after white light illumination at 80 K. The main difference between the $I(V)$ curves before and after illumination, is an enhancement of I_c and a decrease of R_n in agreement with earlier results by Tanabe *et al.*[13] Figure 2(a) shows the time dependence during white light illumination of the GBJJ resistance at 70 K taken at

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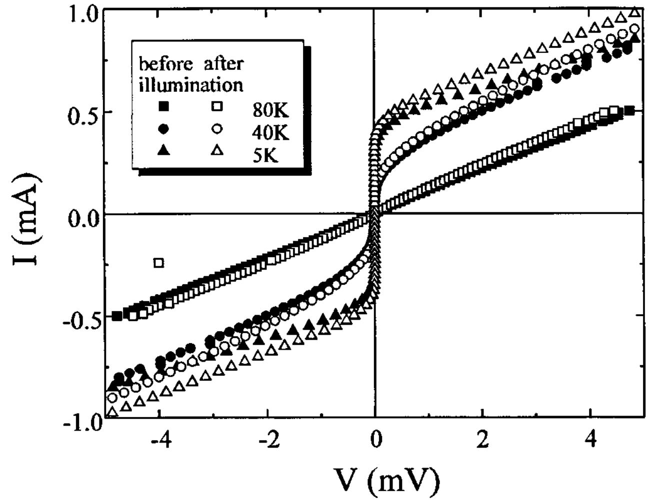

FIG. 1. $I(V)$ characteristics of the dc-SQUID before and after white light illumination for several different temperatures. Notice the decrease of the normal state resistance R_n and the increase of the critical current I_c.

different current biases. The resistance decreases sharply at the beginning of the illumination and saturates after a few hours. The relative decrease of the resistance is always 5%–10%. The time dependence can be fitted to a stretched exponential:[5]

$$R(n)=R(\infty)+[R(0)-R(\infty)]\exp[-(n/n_c)^{\beta}], \qquad (1)$$

where $R(n)$ is the resistance after a photon dose n (with $n \propto t$, t being the illumination time), $R(\infty)$ is the resistance at saturation, n_c is a critical photon dose, and $0<\beta<1$ is a dispersion parameter, e.g., Fig. 2(b) shows a fit to Eq. (1) for the data taken at $I=500\ \mu$A.

The time dependence of the resistance change varies for different wavelengths. The fit parameters $\Delta R_{max}=R(0)-R(\infty)$, n_c, and β versus the incident photon energy are shown in Fig. 3. The spectral dependence of $1/n_c$ is remarkably different from the one observed in $YBa_2Cu_3O_x$ thin films.[5,8,14] For the GBJJ there is only a weak broad peak around 2.6 eV and an increase in efficiency above 4.0 eV. The peaks at 1.8 and 4.1 eV observed in the $YBa_2Cu_3O_x$ thin films[5,8,14] are absent. Also compared to thin films the onset of PPC is lowered from 1.6 to below 1.2 eV. This can also be seen in the spectral dependence of ΔR_{max}, which slowly increases above 1.2 eV and reaches its maximum at around 2.2 eV, and then stays constant [see Fig. 3(c)]. The decrease of ΔR_{max} above 4.5 eV is most likely not intrinsic, but simply due to the fact that only low intensities of light were available at these wavelengths, and thus it was not possible to reach saturation.

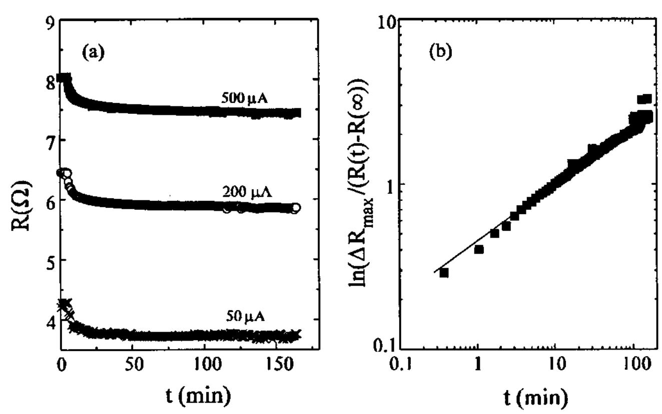

FIG. 2. (a) Time dependence of the dc-SQUID resistance R during illumination at 70 K. R was measured at bias currents of 50, 200, and 500 μA. (b) Fit (solid line) of Eq. (1) to the data taken at 500 μA. The fit parameters are $R(0)=8.03\ \Omega$, $R(\infty)=7.39\ \Omega$, $n_c \propto \tau=10.2$ min, and $\beta=0.34$.

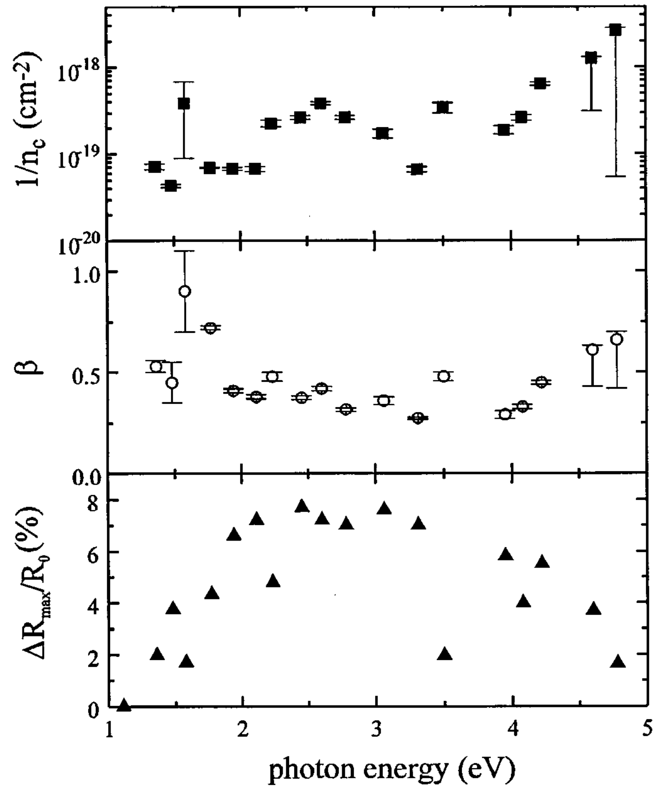

FIG. 3. Spectral dependence of $1/n_c$ (a), β (b), and ΔR_{max} (c) as defined by Eq. 1.

A reason for the PPC below 1.6 eV could be that in the regions of the grain boundary with a higher oxygen content electrons get excited and then diffuse into the oxygen depleted regions. A similar effect has been observed in films with thicknesses larger than the optical penetration depth,[15] and it has been shown that $YBa_2Cu_3O_{6.6}$ thin films still have a very small efficiency for the excitation even below the observed strong onset at 1.6 eV.[16] It is also possible that the lower onset of the PPC reflects a change of the electronic properties due to structural changes in the grain boundary.

The gradual increase of ΔR_{max} in between 1.2 and 2.2 eV could be caused by a distribution of traps, which results in more traps being accessible at higher photon energies. A similar effect has been observed in $Tl_2Ba_2CuO_{6+\delta}$,[17] but not in $YBa_2Cu_3O_x$ thin films.

Figure 4 shows the time dependence of the photoinduced changes of the normal state resistance ΔR_n, compared to the photoinduced changes of the critical current ΔI_c at 5 K. Both ΔR_n and ΔI_c have the same time dependence in agreement with data of Tanabe *et al.*[13] At the same time I_cR_n increases during illumination by 12% (see inset of Fig. 4) indicating an

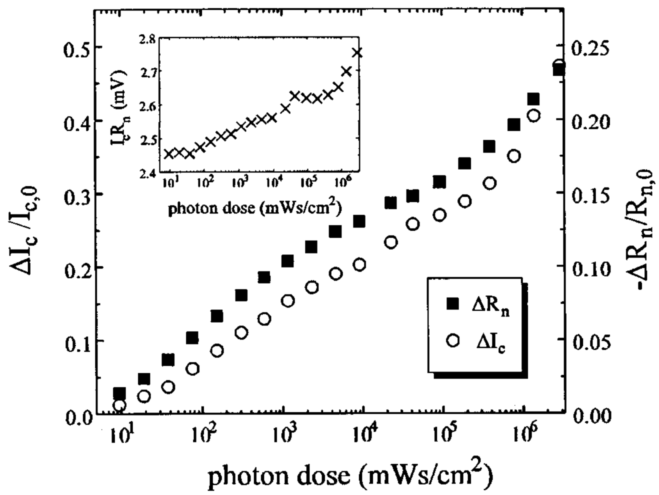

FIG. 4. ΔR_n and ΔI_c vs photon dose at 5 K. R_n was measured at 1 mA. The inset shows the change in I_cR_n.

increase of the superconductivity in the weak link. Note the unusually large I_cR_n product when compared to tunnel junctions.

For $REBa_2Cu_3O_x$ thin films (RE = rare earth or yttrium), the relative change of the conductivity at saturation is a monotonic function of oxygen content x.[6] A comparison of the relative change in the 80 K conductivity $\Delta\sigma/\sigma_i = 5.7 \pm 0.4\%$ of the GBJJ with $\Delta\sigma/\sigma_i$ vs x from Reference 6 gives an average oxygen content of the grain boundary of $x = 6.6 \pm 0.1$. A similar oxygen deficiency ($x \approx 6.5$) is obtained from the data of Tanabe *et al.*[13] on $YBa_2Cu_3O_x$ GBJJs on $SrTiO_3$ bicrystals. Furthermore Ayache *et al.*[18] observed an oxygen content of $x = 6.4$ in similar grain boundaries using high resolution transmission electron microscopy (TEM).

In conclusion, illumination of a GBJJ or a dc-SQUID enhances the critical current.[13] The spectral response shows a significant lower threshold (≈ 1.2 eV) for the excitation than what is observed for $YBa_2Cu_3O_x$ thin films. This might be caused either by structural changes within the grain boundary or by electron diffusion from the fully oxygenated $YBa_2Cu_3O_x$ banks of the GBJJ. A comparison of the saturation change of the conductivity in the $YBa_2Cu_3O_x$ GBJJ with PPC of oxygen deficient $YBa_2Cu_3O_x$ thin films implies that the oxygen content of the grain boundary is $x = 6.6 \pm 0.1$. We believe this is the first determination of the oxygen content in a high T_c GBJJ.

The modified characteristic is stable at low temperature and this technique can be interesting for adjusting and maximizing critical currents in GBJJs or dc-SQUIDs as the value of I_c and R_n can be controlled *in situ* by varying the photon irradiation dose.

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