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MAGNETIC FIELD DEPENDENCE OF JOSEPHSON PHOTORESPONSE IN HIGH-T_c SUPERCONDUCTOR THIN FILMS

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The Josephson photoresponse of granular high-T_c superconductor films to pulsed far infrared laser radiation has been investigated in magnetic fields of up to 3 T. Its value is strongly influenced by fields less than 50 mT and shows a pronounced hysteresis here. At low bias current densities, $j_b < 10\,A/cm^2$, an applied field stimulates the photoresponse, while for $j_b > 100\,A/cm^2$ the photoresponse is depressed. All changes have occured by a field of $B < 50\,mT$: for higher fields the photoresponse remains constant. This dependence is interpreted to arise from micrometre sized grain boundary junctions with a strongly inhomogenous critical current distribution on a sub-nanometre scale.

A topic of great current interest is the study of the intergranular interfaces in high T_c superconductors, as the weak links betweek grains determine the materials critical current density j_c and most probably its surface resistance. Conventional experimental techniques, such as a.c. susceptibility [1] and transport critical current measurements [2], have been used to study the effects of external magnetic fields on j_c. Typically, a magnetic field dependence is observed for $B < 50\,mT$ while for larger B a field indepent plateau is reported [2,3]. Additionally, a residual microwave [4,5] and far infrared absorption [6] is found in the superconducting state. These effects are explained by the existence of weak links [4,5], by magnetic flux penetrating at low fields only into the intergranular material [2] and by the effect of intragrain flux pinning on the intergrain flux density [1].

We present a novel technique to study the microscopic structure of weak links, utilising the far infrared Josephson photoresponse of granular thin films. Such an effect, observed in current biased $YBa_2Cu_3O_{7-\delta}$ [7] Tl-Ba-Ca-Cu-O [8] and $Bi_2Sr_2CaCu_2O_8$ [9] samples, is due to the depression of the critical current I_c by far infrared induced high frequency currents I_ω. It can be described in the framework of the resisitively shunted Josephson junction (RSJ) model [9,10]. The advantage of the Josephson photoresponse technique is that it probes exclusively the properties of the weak links. To date photoresponse studies have mainly been used at frequencies $\omega > 2\Delta$ to investigate pair-breaking effects and quasiparticle recombination times [11]. We extend the range of these studies to lower frequencies ($\omega < 2\Delta$), extracting structural information about the superconductor. Here we report the effect of applying a magnetic field on the far infrared response of a $Bi_2Sr_2CaCu_2O_8$ film: depending on the current bias the field may either initially enhance or suppress the photoresponse signal. For higher fields, $50\,mT < B < 3\,T$, the signal remains constant. This behaviour is interpreted in terms of Josephson detection arising from junctions of micrometre size and from much stronger links with sub-nanometre dimensions.

The measurements reported below have been performed with a granular, 300 nm thick, c-axis oriented $Bi_2Sr_2CaCu_2O_8$ film with grain dimensions of some μm, deposited on an MgO substrate. The film was patterned by excimer laser ablation into a stripe 100 μm wide and 2 mm long. All granular $Bi_2Sr_2CaCu_2O_8$ and Tl-Ba-Ca-Cu-O films investigated (200 nm to 1 μm thick, produced by different techniques) exhibited qualitatively the same behaviour. Low field measurements were performed in a closed cycle He refrigerator with

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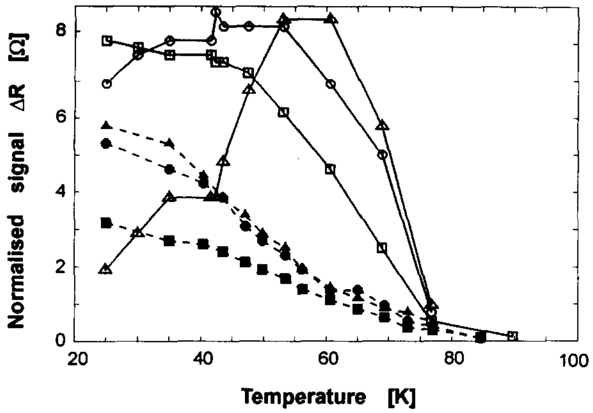

Fig. 1: Temperature dependence of the bias current normalised photoresponse for $B = 0$ (open symbols) and for $B = 50\,\mathrm{mT}$ (filled symbols) for different bias currents: $40\,\mu\mathrm{A}$ (squares), $20\,\mu\mathrm{A}$ (circles) and $4\,\mu\mathrm{A}$ (triangles).

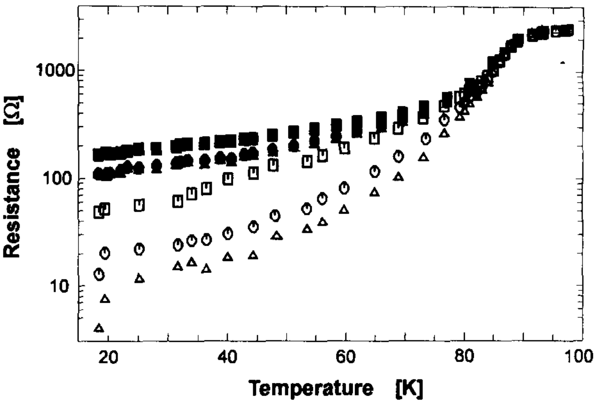

Fig. 2: Temperature dependence of the resistance for $B = 0$ (open symbols) and $B = 50\,\mathrm{mT}$ (filled symbols) and bias currents of $100\,\mu\mathrm{A}$ (squares), $40\,\mu\mathrm{A}$ (circles) and $10\,\mu\mathrm{A}$ (triangles). Resistance values for $I_b \leq 10\,\mu\mathrm{A}$ coincide in both cases.

optical access in a calibrated external magnetic field of up to 50 mT, which was applied perpendicular to the film surface. For $B \geq 20\,\mathrm{mT}$ a bath cryostat was used and the sample was mounted in a temperature variable insert in the bore of a superconducting solenoid. Far infrared laser radiation with a pulse duration of 80 ns at a wavelength of 0.5 mm was focussed on the stripe. Peak incident power was 10 mW. A constant current was applied to the sample and the photoresponse signal voltage ΔV, developing across the irradiated stripe, was observed with a digital storage oscilloscope.

The photoresponse normalised by the bias current, $\Delta R = \Delta V/I_b$, is displayed in Fig 1 without magnetic field and in a field of 50 mT. Without field and for small bias currents only a small signal can be observed at low temperatures. This increases with temperature and bias current to show a maximum in ΔR (at $\approx 58\,\mathrm{K}$ for $I_b = 4\,\mu\mathrm{A}$), which shifts to lower temperatures with increasing bias current (e.g. to 37 K for $I_b = 20\,\mu\mathrm{A}$) For $I_b \geq 40\,\mu\mathrm{A}$ the maximum has disappeared and only the decrease of the response is seen. Applying a magnetic field the maximum of ΔR also shifts to lower temperatures (e.g. for I_b=4 μA to 50 K at 1 mT, to 33 K at 4.1 mT and to 20 K at 5.7mT) and for sufficiently large fields, here displayed for $B = 50\,\mathrm{mT}$, only the decrease at the maximum's right hand side is observable. The signals can easily be distinguished from a bolometric response which should be proportional to $\frac{1}{c(T)}\frac{dR}{dT}$ where c is the heat capacity of the film and which should show a time constant of $\approx 100\,\mathrm{ns}$ for our film [12].

Fig. 2 shows the $R(T)$ characteristics of the sample without field and in a field of $B = 50\,\mathrm{mT}$ for various bias currents. A long resistive tail at temperatures $T < 80\,\mathrm{K}$ is observed. This is strongly enhanced by the magnetic field indicating a large number of grain boundary weak links in the current path. It can also be seen that the relative increase of the resistance with increasing current is much smaller in the magnetic field. This shows that many junctions have already been driven into a resistive state by the field.

The observations of resistance and response can be linked and understood qualitatively by considering the film as an array of RSJ-type weak links. For a single junction of normal state resistance R_n the IV-characteristics is given by:

$$V = \begin{cases} R_n\sqrt{I_b^2 - I_c(I_\omega, B, T)^2} & \text{if } I_c \leq I_b \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

Irradiating this junction leads to a depression of I_c by the value ΔI_c and the potential $\Delta V = V(I_\omega) - V(I_\omega{=}0)$ will manifest itself as the photoresponse signal [10,11]. For $I_b < I_c$ the junction is in the zero resistance state and therefore no photoresponse is expected as long as $I_b < I_c - \Delta I_c$. Increasing B, T, or I_b, the resistance will rise and a photoresponse will be generated. The latter will peak for $I_b = I_c$ and decrease for further increasing $\frac{I_b}{I_c}$ because $(\frac{dV}{dI_c})_{I_b}$ decreases. The film's net response is then obtained by taking an average over the single junction voltages. This approach has successfully been applied to explain the resistance as a function of I_b, B and T [13] as well as the photoresponse [9,10] of granular films. Sharp structures from single junctions, as for instance at $I_b = I_c$, are rounded and their average will indicate the behaviour of the "typical" junction.

In our film at $T = 25\,K$ a nonvanishing resistance is observed, therefore some of the junctions have to be considered as biased at (or above) their critical current and thus the nonvanishing signal is explained. The response maximum occurs in the range $20\,\mu\mathrm{A} < I_b < 40\,\mu\mathrm{A}$ (Fig. 1) yielding $j_c \approx 10^2\,\mathrm{A/cm^2}$ for the "typical" junction. For further increasing $R(B, T, I_b)$, the condition

$I_c > I_b$ is valid for most junctions and thus ΔR decreases.

To explain the field dependence we consider a homogenous rectangular junction of thickness much smaller than the electromagnetic penetration depth, λ, and of length l in a perpendicular magnetic field B. This shows the dependence

$$I_c(B) = I_c(0) \left| \frac{\sin(\pi \frac{\Phi}{\Phi_0})}{\pi \frac{\Phi}{\Phi_0}} \right| \qquad (2)$$

where $\Phi = Bl2\lambda$ is the magnetic flux through the junction and $\Phi_0 = \frac{h}{2e}$. Due to the distribution of grain and junction sizes the interference pattern will average out and a first rapid decrease for a flux penetration of the order Φ_0 through the typical junction can be expected followed by a slower decrease for larger Φ. A non rectangular shape of the junctions or an inhomogenous j_c distribution on the scale of l will change the explicit form of (2) [2,14], however the monotonic decrease of the average $j_c(B)$ will persist. Considering Eq. (1), this reduction of I_c with B means that a magnetic field can depress the photoresponse if $\frac{I_b}{I_c(B=0)} > 1$, as well as stimulate it, if $\frac{I_b}{I_c(B=0)} < 1$.

Fig. 3 shows the dependence of the photoresponse on magnetic fields at $T = 25\,\mathrm{K}$. Essentially no changes in signal are observed in fields below 1 mT. For $I_b \geq 20\,\mu\mathrm{A}$ (Fig. 3a) a strong decrease with increasing magnetic field is observed, while for $I_b \leq 10\,\mu\mathrm{A}$ (Fig. 3b) a rapid increase, peaking at small values of B, followed by a decrease takes place. For all bias currents the photoresponse levels out at a field of approximately 50 mT, remaining constant up to the maximum applied field of 3 T. Whereas the dependence of the photoresponse for $B < 50\,\mathrm{mT}$ can be understood by the reduction of I_c at a fixed I_b as explained above, the plateau value of ΔV in higher fields is incompatible with the expected monotonic decrease of $I_c(B)$. The fact that a photoresponse signal arises shows that there are weak links present in the current path whose j_c is not influenced by magnetic fields up to 3 T. The decisive difference between the $I_c(I_\omega)$ dependence responsible for the photoresponse and the $I_c(B)$ dependence is that only the latter depends on l. Equ. (2) allows the calculation of l if at least two values of $I_c(B)$ are known.

Considering a bias current of $100\,\mu\mathrm{A} = I_b > I_c$ any depression of I_c will be reflected in a reduction of ΔV. The depression of ΔV has reached its 1/e value in a field of 10 mT. Taking this value as the field needed to depress the average junction's critical current to zero, i.e. for a flux Φ_0 to enter the typical junction, the average junction dimension, l_g, can be estimated as $l_g = \frac{\Phi_0}{2B\lambda} \approx 0.5\,\mu\mathrm{m}$, in agreement with the physical size of the grain boundaries in the film. Of course the choice of $B = 10\,\mathrm{mT}$ is somewhat arbitrary and depends on the distribution of junction sizes, so l_g indicates the order of magnitude of the junctions only.

For $50\,\mathrm{mT} < B < 3\,\mathrm{T}$, ΔV is constant within 10 % experimental uncertainty. Therefore $I_c(3\,\mathrm{T})$ can at most be reduced to $0.9 I_c(0)$. We suggest that this field indepent plateau represents the center of a second $I_c(B)$ Fraunhofer pattern with a much larger period in B than that of the whole grain boundary, due to the microscopic length, l_a, of the junctions involved. From Eq. (2) the length of these junctions can be calculated as $l_a \leq 1\,\mathrm{nm}$. The response plateau is at $\approx 30\,\%$ of the zero field value, thus a considerable current has to pass through these junctions. We thus suggest that the grains are linked by unit cell size microbridges with high critical current densities, responsible for the field independent plateau, which are embeded in the macroscopic grain boundaries with much lower j_c. More detailed calculations of a junction with structural inhomogenities [14,15,16] yield the same order of magnitude for the junction length and its inhomogenities as the picture presented here.

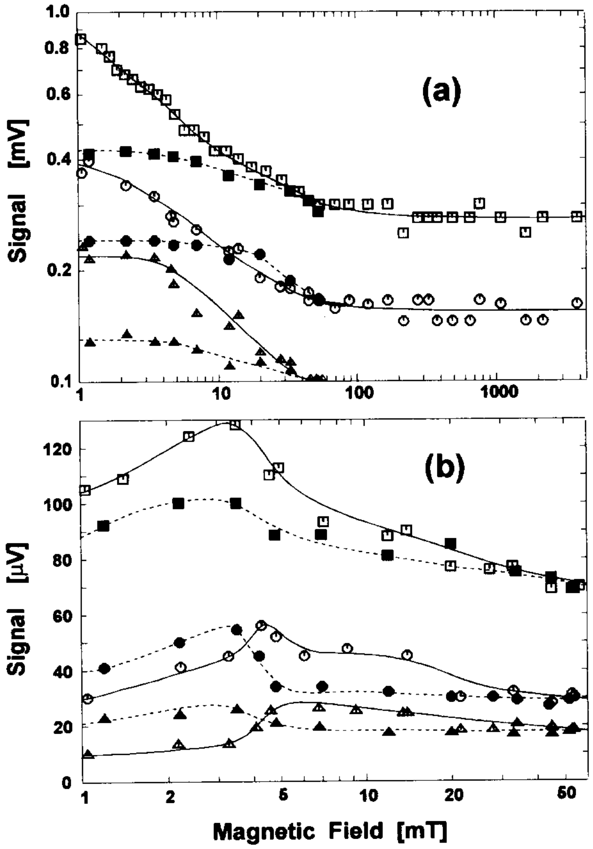

Fig. 3: Magnetic field dependence of the photoresponse at $T = 25\,\mathrm{K}$ for bias currents of a) $100\,\mu\mathrm{A}$ (squares), $40\,\mu\mathrm{A}$ (circles) and $20\,\mu\mathrm{A}$ (triangles) b) $10\,\mu\mathrm{A}$ (squares), $4\,\mu\mathrm{A}$ (circles) and $2\,\mu\mathrm{A}$ (triangles). Open symbols and full lines are for increasing field, filled symbols and dotted lines for a field decreasing from 50 mT. The lines are included to guide the eye. Note the different scales in (a) and (b) on both axis.

It can also be seen from Fig. 3 that the photoresponse does not show the same behaviour for increasing and decreasing fields; a pronounced "memory effect" of the photoresponse on previous magnetisation is observed. After magnetic cycling to 50 mT signal values indicate a remnant magnetisation of some mT. So in a decreasing field and for $I_b \leq 10\,\mu A$ the photoresponse maximum occurs at reduced field values, causing the crossing of the ΔV curves for increasing and decreasing field. For $I_b \geq 20\,\mu A$ the photoresponse remains depressed after removing the external field. This is attributed to flux trapped within the network of grains and grain boundaries, with the high-j_c microbridges forming barriers against flux expulsion when the magnetic field is decreased [17]. The initial photoresponse values could only be restored after heating the film above T_c. Flux trapped in the grains does not contribute significantly to the photoresponse, as this should decrease the intergranular field [1]. This would influence the photoresponse in the opposite way to what is observed. This is further confirmed by the fact that no difference between the responses of field cooled and zero field cooled samples was observed.

The continuation of the plateau to high fields could alternatively be explained by a recently proposed model [3], which considers the reduction of the effective area of a junction by the grain magnetisation. Depending on the intergranular spacing, this model yields a value of 0.1 - 1 T for the first drop of I_c. This field, however, is much bigger than the value observed by us, favouring the explanation given above.

In conclusion, we have found that magnetic fields may stimulate or depress the Josephson photoresponse of a granular thin film superconductor, depending on the bias current applied. The influence of the magnetic field may be used to probe the structure of the grain boundary weak links in thin films. Our results can be understood by assuming the grains to be connected by weak links of strongly inhomogenous current distribution. Sub-nanometre sized regions of high j_c may be responsible for the observation of a photoresponse in fields of up to 3 T and may account for the trapping of flux inside the sample. Such grain boundary sub-structure has been suggested to interpret transport $j_c(B)$ measurements [2,3,15,18] in granular films and single junctions. Our results show that this unusual $j_c(B)$ dependence in granular superconductors actually originates from the weak links.

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