Fast nonlinear photoresponse of current biased thin-film $Bi_2Sr_2CaCu_2O_8$ to pulsed far-infrared radiation

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The response of a polycrystalline thin-film $Bi_2Sr_2CaCu_2O_8$ superconducting stripe to short-pulse far-infrared ($\lambda = 447$ μm) radiation is reported. Under constant current bias, a photosignal is generated when the maximum zero voltage current is exceeded. Measurements of the sensitivity as a function of temperature, bias current, and intensity reveal the signal source to be nonbolometric. The response is found to obey a $(\text{power})^{1/2}$ law over more than 2 orders of magnitude. We believe the detection mechanism arises from the interaction of grain boundary Josephson junctions with radiation induced screening currents.

The application of current biased superconducting NbN/BN thin films as fast detectors for far-infrared (FIR) radiation was first reported by Leung *et al.*[1] Previously Bertin and Rose[2] observed an "enhanced mode" of microwave detection in evaporated Sn films. The origin of the photosignal in both these cases is nonbolometric: peak responsivity is found at temperatures much lower than the maximum of the temperature derivative of the sample resistance.

Since the expansion of high T_c superconductor research a fast FIR photoresponse has been found in granular films of $YBa_2Cu_3O_{7-\delta}$[3] and Tl-Ba-Ca-Cu-O.[4] We have established that a similar phenomenon exists in $Bi_2Sr_2CaCu_2O_8$ and, more importantly, have observed a square root dependence of the photosignal on power, in agreement with the response of constant current biased Josephson junctions. For a signal to be observed, the film must be biased into a partially resistive state, i.e., full Josephson coupling between the grains is destroyed. We find that although the sample sensitivity varies strongly with temperature and bias current, no FIR bolometric response is observed.

Measurements were made on thin-film (0.5 μm thickness) $Bi_2Sr_2CaCu_2O_8$ deposited by excimer laser sputtering on (100)MgO with subsequent annealing.[5] The film was patterned, with KrF excimer laser radiation, to produce a bridge 1900 μm by 75 μm which linked two 4×4 mm^2 pads. Two Au contacts were sputtered onto each pad. Bias and signal connections, made with 50 Ω cable, were arranged as for a four point conductivity measurement. The substrate was thermally anchored to the cold finger of a closed cycle He refrigerator. The system base temperature was 15 K with an estimated accuracy of temperature measurement of ± 2 K. Upon cooling the sample resistance dropped smoothly from 3.1 kΩ at 300 K to 2 kΩ at 100 K. Below 100 K a superconducting transition with a midpoint of 85 K is observed; this had a 90%–10% transition width of 10 K for currents of 10 μA or less.

Our radiation source is fully described elsewhere.[6] It comprises a FIR laser optically pumped by a *Q*-switched CO_2 laser with a pulse repetition rate of 165 Hz. Smooth stable pulses with a full width at half maximum (FWHM) of 65 ns with $\lambda = 447$ μm are obtained from CH_3I vapor. Average laser output power was measured with a calibrated Golay cell. Using a 300 MHz bandwidth Schottky diode detector to obtain the temporal pulse profile, peak powers can be calculated. A typical pulse is shown in Fig. 1.

The laser radiation was focused onto the superconducting stripe using a 10 cm focal length lens. With a $1/e^2$ beam diameter of 2.4 mm (measured by translating a pyroelectric detector across the focal region) 50 mW peak power was incident on the stripe. Positive voltage pulses, obtained for bias currents between 2 μA and 200 μA, were amplified in a 50 Ω amplifier and recorded with a 50 MHz storage oscilloscope. A pulse obtained at 17 K and 100 μA bias, is displayed in Fig. 1. This signal has a FWHM of 100 ns, slightly broader than the Schottky diode pulse due to the nonlinear film response.

Signal height is shown as a function of temperature in Fig. 2 for different bias currents. Also displayed are resistance versus temperature curves for four values of current. Interpretation of the signal variation with current and temperature is difficult because of the varying detector resistance compared with the amplifier impedance. However the following observations are made: The sample must be biased so as to destroy full superconductivity for a signal to be seen and the temperature of maximum response decreases with increasing bias current. The responsivity drops towards zero at the point of the maximum slope of the resistance-temperature characteristics, where bolometric response is expected to peak. Finally, the maximum value of signal per unit current is independent of bias for currents up to 200 μA.

Intensity dependence measurements were made at 17 and 60 K by placing paper attenuators in the FIR beam. For a reference signal part of the beam was diverted with a 50 μm Mylar sheet into the Golay cell. Plots of the square of the superconductor detector signal height (100 μA bias) vs the input power are shown in Fig. 3. The lines are drawn

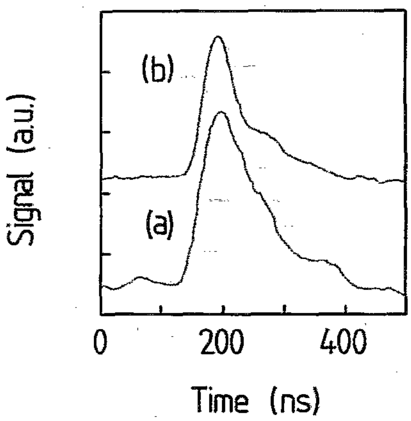

FIG. 1. Single laser pulse ($\lambda = 447\ \mu$m) response of (a) $Bi_2Sr_2CaCu_2O_8$ film at $T = 17$ K and 200 μA bias compared with (b) the time resolved Schottky diode detector signal.

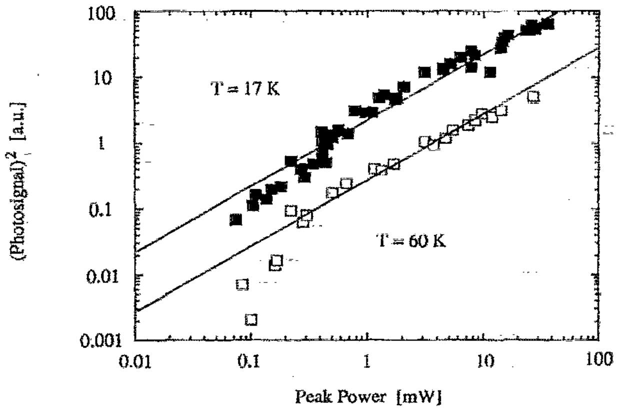

FIG. 3. Intensity dependence of square of photosignal at 17 and 60 K for 100 μA bias current. The solid lines depict a slope of unity. Values at 60 K have been divided by 10 for clarity.

with unity slope to guide the eye. This diagram shows a square root dependence of the photoresponse on the incident power. A similar curve is found for 40 μA bias at 60 K. This square root dependence is in agreement with the microwave response of Sn films[2] but conflicts with recent FIR results on a NbN/BN film.[7] The nonlinear behavior accounts for the broadening of the observed pulse shape, as shown in Fig. 1(a).

At low powers, less than 1 mW, a linear dependence is observed. Here we find a detector sensitivity of 0.6 V/W, giving a noise equivalent power (NEP) $= 5 \times 10^{-9}$ W/$\sqrt{\mathrm{Hz}}$ over a 50 MHz bandwidth. For higher powers, in the regime of square root detection,[8] we obtain a detector sensitivity of 12×10^{-3} V/$\sqrt{\mathrm{W}}$ with a corresponding NEP $= 3 \times 10^{-12}$ W/Hz for the same bandwidth.

To explain the signal origin we regard the film as a network of superconducting grains interconnected via Josephson junctions,[9] where the film response arises from a superposition of individual junction signals. A distribution of single junction critical currents, I_0, exists due to differing physical arrangements of crystallites. Upon irradiation I_0 is depressed to a value I_c and a signal voltage is developed across those boundaries for which the bias current exceeds I_c.[10] The possibility of a direct thermal reduction of I_0, creating a bolometric signal, may be excluded as I_0 is temperature independent below approximately $T_c/3$.[11] Thus, contrary to experimental results, no photosignal should be observable at 17 K.

To extend theoretical models from the response of one junction to that of a film is difficult. However we can show that experimental results agree qualitatively with the photoresponse of a single junction. Computer simulations[12] have shown that for frequencies well below the BCS gap energy ($\hbar\omega \ll 2\Delta$) and $I_\omega/I_0 < 1$ then the maximum zero voltage current, I_c, is given by

$$I_c = I_0[1 - \gamma I_\omega]. \qquad (1)$$

Here $\hbar\omega = 22.4\ \mathrm{cm}^{-1} \ll 200\ \mathrm{cm}^{-1} = 3.5k_bT_c$, γ is a constant and I_ω is the amplitude of the radiation induced current. Thus if the junction is biased to an operating point with differential resistance $\delta V/\delta I = R$ then the signal voltage v satisfies

$$v = \gamma I_0 R I_\omega \qquad (2)$$

or

$$v \propto (\mathrm{Power})^{1/2}. \qquad (3)$$

Additionally, for values of $I_\omega/I_0 \ll 1$ a linear dependence of the signal on power is expected.[10]

It is expected that only those junctions for which $I_0 \approx I_b$ (the bias current) contribute to the photoresponse. Those for which $I_b + I_\omega < I_0$ give no response and if $I_b \gg I_0$ the junction is assumed ohmic. Thus for a given temperature $< T_c$ there exists a value of I_b for which a substantial number of junctions satisfy $I_0 \approx I_b$, explaining the shift of the peak response with bias current and the linear dependence of the maximum signal on I_b.

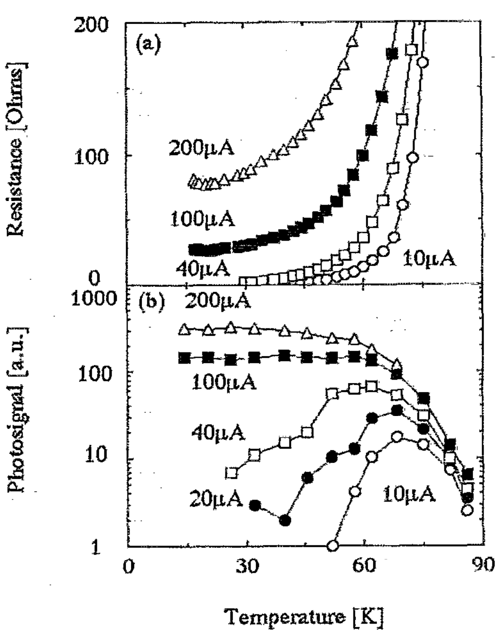

FIG. 2. Temperature dependence of (a) sample resistance and (b) photosignal for different bias currents.

To conclude, we report for the first time the observation of a fast nonbolometric photoresponse in a $Bi_2Sr_2CaCu_2O_8$ thin film. The sensitivity of this film is comparable to that of Tl-Ba-Ca-Cu-O films,[4] and intermediate between the responses of $YBa_2Cu_3O_{7-\delta}$[3] and NbN/BN.[1] An upper bound on the response time of 50 ns is imposed by our laser pulse duration. A square root dependence on incident power is found, consistent with a Josephson junction network.

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