Spectral dependence of nonbolometric far-infrared detection with thin-film $Bi_2Sr_2CaCu_2O_8$

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The photoresponse of granular current biased thin-film $Bi_2Sr_2CaCu_2O_8$ superconductor to short pulse far infrared radiation has been measured for 16 laser lines, with frequencies between 10 and 1000 cm^{-1}. A strong dependence of the signal on the frequency ω, approximately proportional to $\omega^{-2.3}$, is observed. It is shown, by calculations based on the resistively shunted junction model, that this photosignal can be understood to arise from the ac Josephson effect at grain boundary weak links.

A fast nonbolometric response to far-infrared (FIR) irradiation has been established in thin films of high T_c superconductors,[1–3] similar to that observed from superconducting grains of NbN embedded in a BN matrix.[4] Nonepitaxial films of high T_c superconductors show granular properties without special preparation techniques, due to the short coherence length. Response times of the order of 1 ns and sensitivities approaching 1 V/W have been measured.

Physical mechanisms such as the ac Josephson effect at grain boundaries,[1] electron heating,[5] hot spots,[6,7] or radiation-induced vortex-antivortex depairing[6] have been suggested to explain this response. Observations of the intensity and magnetic field dependencies of laser pulse induced signals in $Bi_2Sr_2CaCu_2O_8$ films (with grain sizes larger than the optical penetration depth) support the Josephson effect explanation.[3,8] This mechanism will show a characteristic frequency dependence, in contrast to that expected from electron heating and hot spots. We report here, for the first time, quantitative measurements of the spectral dependence of the nonbolometric responsivity of $Bi_2Sr_2CaCu_2O_8$, in the range from 10 to 1000 cm^{-1}. These results agree with the frequency dependence calculated from the resistively shunted Josephson junction (RSJ) model and thus further support this effect as a basic nonthermal response mechanism.

The sample investigated was produced on an MgO substrate by excimer laser sputtering and post-annealing. Electron micrographs show the film to be 0.3 μm thick and to consist of an irregular array of tile-shaped grains, between 1 and 15 μm across. X-ray diffraction reveals the film to be single phased and c-axis oriented. The film was patterned by excimer laser radiation into a bridge measuring 1900 μm by 75 μm. 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 bias currents $I_b < 10$ μA.

Our radiation source comprises of a commercial far-infrared (FIR) oversized waveguide laser pumped by a Q-switched CO_2 laser:[9] 15 laser lines were available in the range from 10 to 100 cm^{-1}. The FIR laser radiation was focused either onto the superconducting sample using a 10-cm focal length TPX (4-methyl pentene-1) lens or into a Golay cell for an energy measurement. A Schottky diode detector was used to obtain the pulse profiles. The full width at half maximum height varied between 65 and 150 ns while peak incident powers lay between 10 μW and 10 mW.

Alternatively the CO_2 laser radiation ($\omega = 939$ cm^{-1}) could be diverted directly into the cryostat. Its intensity at the site of the sample was varied by translating a ZnS lens, thus defocusing the beam. The pulse incident on the $Bi_2Sr_2CaCu_2O_8$ bridge was measured with a pyroelectric detector. Such pulses have durations of 200 ns and peak powers of several watts.

The sample was biased with several currents 2 μA $< I_b < 400$ μA and the positive voltage pulse appearing across the stripe upon irradiation was recorded and averaged with a 50-MHz bandwidth storage oscilloscope. The temperature dependencies of the observed photoresponses (PR) are displayed in Fig. 1. The FIR response, Fig. 1(a), is purely nonbolometric, with a maximum at temperatures slightly above the onset of resistivity for a given current. It has been shown[2,3] that the signal has a response time of less than 4 ns, its maximum is proportional to the bias current and it has a $\sqrt{\text{power}}$ dependence in the range between 0.3 and 30 mW at $\omega = 22.4$ cm^{-1}.

Figure 1(b) shows the temperature dependence of the response to 939 cm^{-1} CO_2 laser pulses. Two signal components may be distinguished: a bolometric component which peaks at the maximum of the temperature derivative of the resistance dR/dT (indicated by the lines) and a nonbolometric signal occurring at lower temperatures, where dR/dT approaches zero. It can be seen, from the FIR measurements, that no nonbolometric component is expected at temperatures of 90 K and above. It is therefore possible to calculate the radiation-induced temperature shift (and to estimate the absorbed energy) assuming that the 939 cm^{-1} response at 90 K is purely bolometric. Taking into account the temperature dependence of the specific heat,[10] the maximum temperature shift at 17 K is then calculated to be less than 5 K. Consideration of the resistance-temperature curve shows that any bolometric contri-

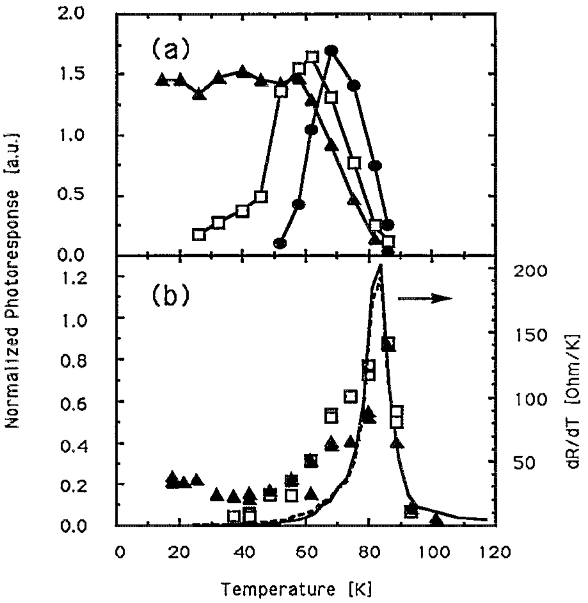

FIG. 1. Dependence of photoresponse/bias current for currents of 10 μA (circles), 40 μA (squares), and 100 μA (triangles) at (a) $\omega = 22.4$ cm^{-1} and (b) 939 cm^{-1}. For $T \approx T_c$ the 939 cm^{-1} photoresponse follows approximately dR/dR, shown as solid (40 μA) and dashed (100 μA) lines. At lower temperatures considerable deviation can be seen, indicating a nonbolometric component similar to the FIR response.

bution to the photosignal at this temperature would be less than 1%. It is worth noting that the measured power dependencies of both the bolometric and nonbolometric component are linear for incident powers $P_{\rm inc} < 1$ W.

To establish a wavelength dependence of the nonbolometric signal, incident radiation peak powers were measured along with the corresponding photosignals. As the laser power varied considerably with wavelength all signals were normalized to an average incident power, $P_{\rm inc}$, of 2.2 mW (the power of the 19.7 cm^{-1} laser line), taking into account the known intensity dependence of the PR. This is PR $\sim \sqrt{P_{\rm inc}}$ for $\omega < \Delta_{\rm BCS} \approx 100$ cm^{-1} (Ref. 3) and PR$\sim P_{\rm inc}$ as measured for $\omega = 939$ cm^{-1}. The normalized PR is shown by the squares in Fig. 2. It can be seen that

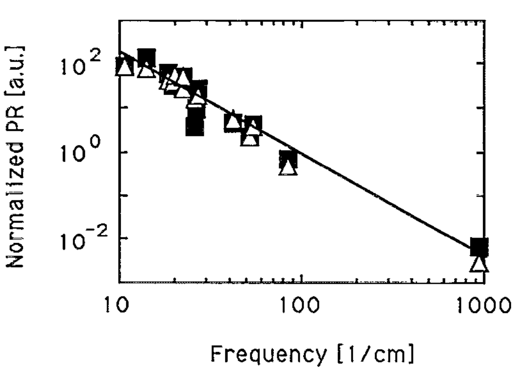

FIG. 2. Frequency dependencies of observed (solid squares) and calculated photoresponses (open triangles), both normalized to a power of 2.2 mW. The solid line indicates a slope of -2.3

this signal decreases approximately proportional to $\omega^{-2.3}$, as indicated by the solid line.

We assume the observed signal to arise from laser-induced high-frequency currents, I_ω, flowing across grain boundary weak links and that the overall signal is generated by a linear superposition of the effect of single junctions. For simplicity, we consider the behavior of a single effective junction with a critical current I_c: this junction having the properties of an average over an array of junctions. This concept has been successfully used to explain dissipation in Bi-based thin films.[11]

For numerical calculations we use the actual incident optical powers, estimate the induced currents, and evaluate the PR with RSJ model.[12] The numerical results are then normalized in the same way as the experimental data. At the highest FIR power level ($\omega = 22.4$ cm^{-1}) it is estimated from intensity measurements that $0.1\, I_c < I_\omega < I_c$ (no deviation is observed from PR $\sim \sqrt{P_{\rm inc}}$ in the range 0.01 $P_{\rm max} < P_{\rm inc} < P_{\rm max}$) and the value $I_\omega = 0.8 I_c$ is taken for the calculations. Using other values of I_ω shows that the numerical results are not sensitive to the absolute value of I_ω. The frequency dependence is estimated from the behavior of the conductivity $\sigma(\omega)$ of a BCS superconductor with an applied electric field, E_ω. Here $\sigma(\omega) = \sigma_1 + i\sigma_2$, $\sigma_2 \sim 1/\omega$ and $\sigma_1 \ll \sigma_2$ for $\omega < 2\Delta_{\rm BCS}$. For $\omega \gg 2\Delta_{\rm BCS}$, $\sigma_1 \gg \sigma_2$ and $\sigma_1 \approx \sigma_2(2\Delta_{\rm BCS})$ is valid. This means $|I_\omega| \sim |j| \sim \frac{1}{\omega}|E_\omega|$ for $\omega < 200$ cm^{-1} and $|I_\omega(1000\,{\rm cm}^{-1})| \approx |I_\omega(200\,{\rm cm}^{-1})|$.

The dc voltage V across a single junction of capacitance C, and normal state resistance R_n, is given by the Josephson equation

$$V = \frac{h}{4\pi e}\left\langle \frac{d\varphi}{dt} \right\rangle_t \tag{1}$$

and the phase difference φ across the junction is determined in the RSJ model by

$$\frac{d^2\varphi}{d\tau^2} = -\beta\left(\frac{d\varphi}{d\tau} + \sin(\varphi) - \frac{I_\omega}{I_c}\cos(\Omega\tau) - \frac{I_b}{I_c}\right), \tag{2}$$

where

$$\tau = \frac{4\pi e}{h} I_c R_n t, \quad \Omega = \frac{h}{4\pi e I_c R_n}\omega,$$

and

$$\beta = \frac{h}{4\pi e}\frac{1}{I_c R_n}\frac{1}{R_n C}.$$

These equations were solved numerically for the applied frequencies. Good correspondence to the experimental data is obtained for $\beta = 1$ and $\Omega/\omega = 50 \times 10^{-9}$ s, equivalent to values of $I_c = 100$ μA, $R_n = 50$ Ω, and $C = 1$ fF. The numerical results (triangles) are shown together with the experimental data (squares) in Fig. 2. The calculated values do not lie on a smooth curve because of errors introduced by the power normalization, which is not exactly correct over the range of incident powers (10 μW $< P_{\rm inc} < 10$ mW) applied in the FIR.[3] However the errors are within the uncertainties of the energy measurements and thus justify the normalization of the experimental data.

Our calculation gives an I_cR_n product of 5 mV, which is lower than the value $I_cR_n = \pi\Delta/2e \approx 20$ mV that is expected from Ambegaokar–Baratoff theory using the BCS value for Δ. This may reflect a depressed order parameter Δ_{gb} at insulating grain boundaries created by oxygen deficiency.[13] Our value of Δ_{gb} agrees with the theoretical value for such interfaces[14] and with measurements performed on $YBa_2Cu_3O_7$.[15]

The strong decrease in sensitivity with increasing frequency is consistent with observations made on NbN/BN and Sn films.[16,17] Our results clearly show that electron heating or hot spots (proposed as response mechanisms in very thin films, $d < 100$ nm)[5,6] are not responsible for the detection mechanism in granular films with $d \geqslant 200$ nm: these processes should be linear in absorbed energy and only weakly dependent on frequency, in strong contrast to our measurements.

In conclusion, we have studied, for the first time, the wavelength dependence of nonbolometric FIR detection with granular superconducting films and we observe a $\omega^{-2.3}$ decrease of the sensitivity. Assuming the film to be a network of Josephson junctions and the overall PR to be a linear superposition of the effects of single junctions, this dependence can be explained in the context of the RSJ model.

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