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INFRARED DETECTION BY Tl-Ba-Ca-Cu-O SUPERCONDUCTING FILMS

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The response of polycrystalline Tl-Ba-Ca-Cu-O superconducting thin films on short laser pulses has been investigated for radiation between 10 μm and 500 μm wavelength. Fast signals with time constants less than 1 ns were observed for wavelengths longer than about 100 μm whereas for shorter wavelengths only a bolometric signal could be detected.

Key words: High-T_c superconductors, infrared detection.

A very promising application of high temperature superconductors is the use of these materials as broadband optical and infrared detectors. In previous investigations on thin films operated in a biased mode like a photoconductor slow bolometric signals and high-speed non-thermal response has been observed[1,2] covering an extremely wide spectral range from uv to far-infrared (FIR). Additionally photovoltaic voltage signals due to a Nernst effect were found in samples subjected to a moderate external magnetic field.[3,4]

The bolometric response is simply due to a change of the biased resistance by irradiation heating. The signal strength follows approximately the derivative of the resistance temperature relation assuming a maximum around the transition temperature. The time constant is determined by the heat capacity and the cooling time of the irradiated sample.

Non-thermal fast response is attributed to an optically induced destruction of the wave function coherence in a random network of weak links or Josephson junctions.[5,6,7] The basic physical mechanisms, however, are not yet well understood. The model of phase slip in superconducting grains coupled by weak links favours optically thin granular films to observe high-speed response.[8] Most of the investigated superconducting films met this requirement. An early measurement carried out on epitaxial films did not yield evidence of a high speed response.[2] Nevertheless, non-thermal signals were also detected in non-granular crystalline films.[9] Furthermore very different variations of the fast response with temperature were reported. Kwok et al. observed an almost constant signal which rapidly vanishes at T_c.[8] On the other hand Culbertson et al. found in strongly granular material a distinct peak at the temperature where the entire film becomes superconducting.[7] This phenomenon was interpreted in terms of a Kosterlitz-Thouless phase transition which was concluded from the characteristic increase of the film resistance with rising temperature and the nonlinear dependence of the signal as function of the bias current.

Extremely short time constants, in the subnanosecond region, were anticipated[10] and experimentally demonstrated in the near infrared spectral range. Actually in non-granular Y-Ba-Cu-O films an upper limit of the response time of 1 ns could be established[9] similarly to the low T_c perovskite-type material $BaPb_{0.7}Bi_{0.3}O_3$.[5] In the FIR a time constant of about 20 ns was measured with Y-Ba-Cu-O films in contrast to the subnanosecond response found in a film consisting of low T_c NbN grains imbedded in a BN matrix.[6]

In the present contribution we report on first investigations of the response of Tl-based granular superconducting films in the FIR. The response of the resistance to short laser pulses was analyzed as function of temperature and for various irradiation intensities in the range between 10 μm and 500 μm. For all applied laser lines a bolometric signal has been obtained. A fast response, however, could be detected only in the FIR for wavelengths longer than about 66 μm. For radiation at 10 μm and 66 μm no evidence of a non-thermal response has been found. From the modulation of the signal due to mode beating spikes of the laser emission an upper limit of the time constant of 1 ns was deduced for the long wavelength radiation. The temporal structure of the fast signals was very similar to that observed with NbN/BN films.[6] The characteristics of the sample resistance and the observed photoresponse support the Kosterlitz-Thouless phase transition model proposed by Culbertson et al.[7] The measurements were carried out on polycrystalline Tl-Ba-Ca-Cu-O superconducting films of about 1 μm thickness showing transition temperatures near 100 K. The film preparation procedures and details of the morphology of the films were described elsewhere.[12,13] The films reported here were deposited on $10 \times 10 \times 2$ mm^3 $SrTiO_3$ substrates in form of narrow strips. Electric contacts were made by silver epoxy. In Fig. 1 the resistance as function of temperature T is plotted for 10 mA bias current which was applied in the measurements of the optical response. The insert in Fig. 1 shows the resistance fitted to the relation $R/R_n = a \cdot \exp(-(b/\tau)^{\frac{1}{2}})$. This temperature dependence is expected for a two dimensional vortex-antivortex pairing transition to superconductivity[14] and has previously observed for YBaCuO.[7] In this relation $\tau = (T - T_c)/(T_{c0} - T)$ is a reduced temperature where T_c and T_{c0} are the transition temperatures to the resistive current flow due to the appearance of unpaired vortices and to the normal conducting state, respectively. The parameters a and b are constants and R_n is the resistance in the normal conducting state just above T_{c0}. The best fit was obtained with $T_c = 42$ K, $T_{c0} = 105$ K, $a = 0.05$ and $b = 0.4$.

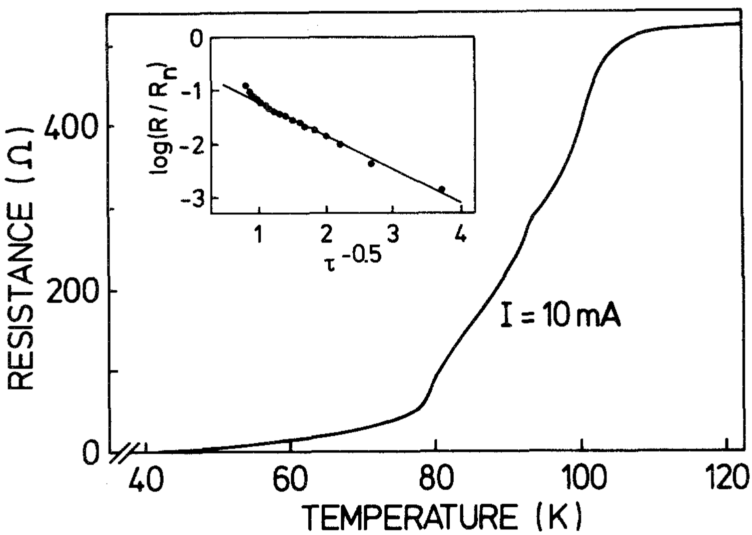

Fig.1 – Resistance as function of temperature for 10 mA bias current. The insert shows a fit to the relation $R = R_n a \cdot \exp(-(b/\tau)^{\frac{1}{2}})$.

The radiation was generated by a multimode CO_2 TEA laser emitting a pulse train due to self mode-locking and an FIR molecular laser using CH_3F and D_2O pumped by the CO_2 laser. Using a GaAs Schottky diode of 800 GHz bandwidth (Farran Technology, Ireland), it was proved that the mode beating structure of the pump laser pulse was also present in the emission of the FIR laser. In total 17 different laser lines were applied at 10 μm, 66 μm and between 119 μm and 496 μm. In order to prevent irradiation of the contacts the contact regions were shielded by a metallic mask leaving free a 1.3×4 mm^2 superconducting bridge. The samples were placed in a temperature variable cryostat with windows of crystalline quartz (FIR) or ZnSe (10 μm). The films were biased in series with a 50 Ω load resistor using a constant current source and the signal voltage across the superconductor was recorded on a Phillips PM 3320 digital oscilloscope with 4 ns sampling intervals.

Recordings of single laser pulses obtained at three different wavelengths are plotted in Fig. 2 for various temperatures. At $\lambda = 231$ μm and for temperatures well below T_{c0} (Fig. 2a) the signal reproduces the temporal structure of the laser pulse. Mode beating spikes can clearly be distinguished as shown on an extended time scale in the insert of Fig. 2a. The resolution is limited by the digitizer imposing an upper limit of the response time of the order of 1 ns. With increasing temperature a long signal tail arises which is of thermal origin. Approaching T_{c0} the fast signal decreases and finally vanishes whereas the slow bolometric response increases and assumes a maximum around T_{c0}. Practically the same temporal structure and temperature dependence was found for all wavelengths in the FIR between 119 μm and 496 μm. In Figs. 2b and c corresponding recordings of single laser pulses are shown for $\lambda = 66$ μm and 10 μm. In both cases no indication of a fast response could be detected. In the temperature range from 4.2 K up to above the transition temperature T_{c0} only slow bolometric signals have been observed with decay times of about 10 μs which is several orders of magnitude larger than the response time of the fast signal in the long wavelength regime. The time dependence of the bolometric signal is determined by the thermal diffusivity of the thin film.

Due to the large difference in time constants of the fast nonthermal response and the bolometric signal, the strength of both signals can easily be separated. In Fig. 3 the responsivity of the fast and the bolometric signal components and the sample resistance are shown as function of the temperature. The measurement was carried out at $\lambda = 385$ μm. The fast signal shows a pronounced maximum around T_c where resistive current flow sets in. The bolometric

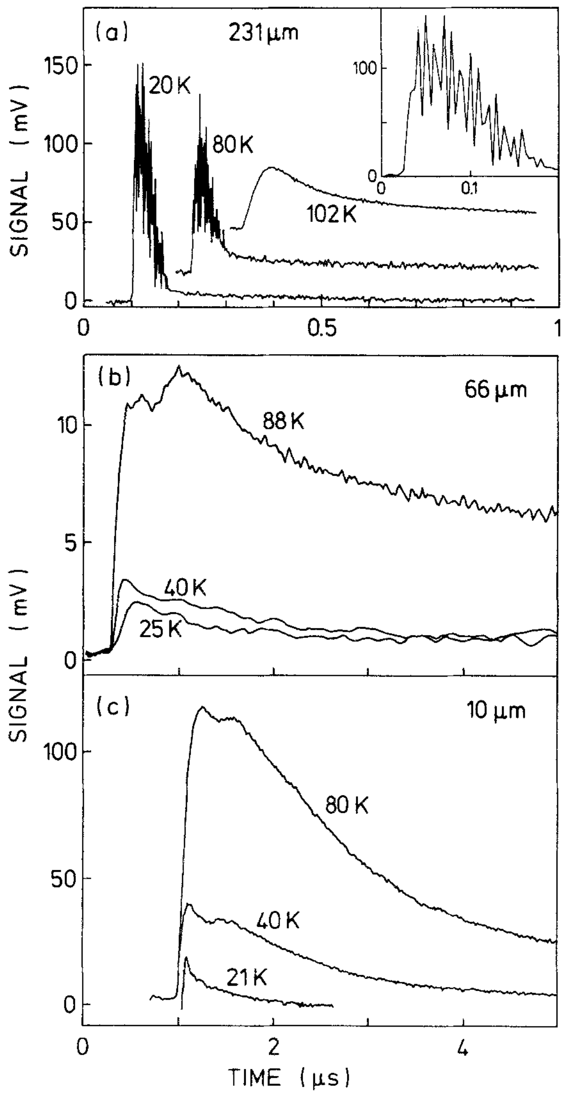

Fig. 2 – Voltage response for various wavelengths and temperatures. (a) $\lambda = 231\ \mu m$. The mode beating structure of the laser pulse, shown with better temporal resolution in the insert, is clearly observed. (b) $\lambda = 66\ \mu m$ and (c) $\lambda = 10\ \mu m$. For both wavelengths no fast response could be detected.

signal, on the other hand, peaks in the vicinity of T_{c0} where the derivative of the resistance is largest. The peak responsivity of the fast component is about ten times larger than that of the bolometric signal. Quantitatively the same results were obtained with all long wavelength laser lines. At 66 μm and 10 μm where the samples did not show a fast response, the peak bolometric responsivity is about twice of that shown in Fig. 3.

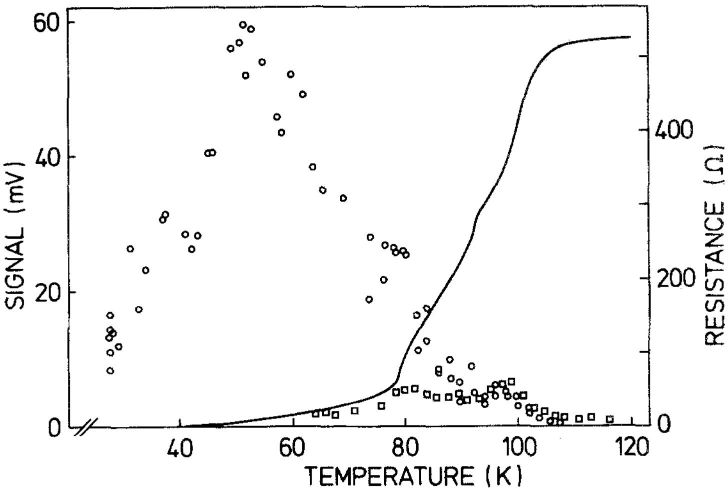

Fig. 3 – Peak voltage signal of the fast and the slow bolometric response (left ordinate scale) versus temperature in comparison to the sample resistance (right ordinate scale). Wavelength $\lambda = 385$ μm.

The experimental results may be understood considering two classes of processes leading to optical response in granular films: processes occuring in weak links at grain boundaries (e.g. Josephson effects) and processes occuring in the whole film surface (breaking of Cooper pairs). For processes at grain boundaries, fast recovery of thermal equilibrium is possible because of small boundary thickness in the order of nm, allowing fast heat transfer into the surrounding grain material. On the other hand, radiation of energy $\hbar\nu > 2\Delta$ can be absorbed in the whole film surface due to pair breaking. In this case, for films of thickness ~ 1 μm, recovery times of μsec are observed due to heat diffusion into the substrate. Rising the temperature, more and more weak links become normal conducting and the energy gap in the grains decreases. Thus, approaching the transition temperature T_{c0} the fast signal vanishes and a slow response appears also at long wavelengths.

In summary, Tl-based granular superconducting thin films represent very fast FIR detectors. The observed responsivity of about 10 mV/W at T_c compares favourably to other high speed FIR detectors. In fact, the nominal sensitivity of GaAs Schottky diodes is about 10 to 100 times higher than the sensitivity of the present sample, however superconducting films of sufficiently large area are in contrast to diodes multimode detectors and may therefore be more efficient.

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