HIGH-SPEED OPTICAL DETECTORS IN YBCO FILMS WITH NON-GRANULAR AND FINE-GRAIN MORPHOLOGIES

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Abstract--Optical detectors based on $YBa_2Cu_3O_{7-\delta}$ thin films have been fabricated, which show a response time of a few ns. Typical dimensions of the active area are $10\times10\mu m^2$. No preamplifier is needed during operation. In this paper, we report on the optical response of detectors having non-granular and fine-grain morphologies to different pulsed laser radiation (e.g., a mode-locked Nd:YLF laser at 1.3μm and a GaAs diode laser at 0.9μm). This study is focused on the detection sensitivity for measuring short optical pulses. It is found that the best NEP obtained with a fine-grain detector is on the order of $10^{-10}W/Hz^{1/2}$, when irradiated by the 65ns-pulse-width diode laser.

I. INTRODUCTION

Much attention has been paid in recent years to the fast optical response of superconducting thin films to pulsed laser radiation [1-6]. Response times in the range of ns to several hundred fs were reported. From a practical point of view, the observed photoresponse can be used to develop a high-speed optical detector in either conventional or high-T_c superconducting (HTS) thin films. The main advantage of such detectors is a broad response spectrum from the visible region to far-infrared (FIR) wavelengths. Therefore, it could provide in the future an alternative liquid-nitrogen cooled photodetector based on an $YBa_2Cu_3O_{7-\delta}$ (YBCO) film for detecting very short (on the order of ns or less) optical pulses of radiation, for example, from free electron lasers [7].

The response time of HTS detectors at different wavelengths (λ) has been examined by many authors. For example, Leung et al. [2] studied the performance of a granular YBCO detector and observed a nonbolometric effect in the optical response to pulsed FIR radiation at temperatures well below the transition temperature (T_c). A response time of 20ns was observed. Frenkel et al. [3] reported a nonbolometric optical response, as fast as 1ns, to a Nd:YAG (λ=1.06μm) laser radiation in non-granular YBCO films at 40K. Using a similar detector, Zheng et al. [4] observed a response time of less than 10ns to a CO_2 laser (λ =10.6μm) at 10K. Furthermore, Carr et al. [5] reported a fast bolometric response (as fast as 4ns) of an YBCO detector to pulsed radiation from FIR to visible light sources. Somewhat discouragingly, however, the detectors with a high speed response always showed a very low responsivity (e.g., 0.01V/W [4] and 0.03V/W [3]), which is far lower than the requirements for practical applications.

In the following, we shall describe two kinds of detectors: a non-granular (NG) YBCO detector and a fine-grain (FG) one. We believe that with an FG morphology the detection sensitivity of HTS detectors can be improved. Possible mechanisms for the improvement in sensitivity can be the following: (1) Films having fine and homogeneous grains can form a high density of boundary weak links. The boundary weak links may contribute coherently to the detected signal, but incoherently to the noise, so that the signal-to-noise (S/N) ratio will be high [1]. (2) It should be noted that, as in the case of BaPbBiO films, the reflection coefficient of polycrystalline films (including FG films) is smaller than that of single-crystal films [1]. Low reflectivity and high absorption will increase the detection efficiency.

II. EXPERIMENTS

The NG, c-axis oriented YBCO thin films, having a thickness of 70nm, were prepared by laser ablation onto MgO (100) or $SrTiO_3$ (100) substrates. The deposition process has been described elsewhere [8]. The films had a zero-resistance T_c of about 86-88K and a critical-current density (J_c) of 10^5-$10^6A/cm^2$ at 77K.

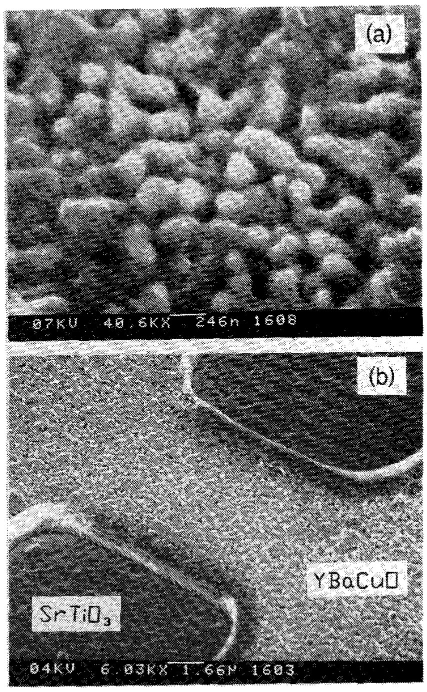

Fig.1 SEM photographs of (a) an FG film and (b) a bridge-type detector.

The FG YBCO thin films with 250nm thickness on $SrTiO_3$ (100) substrates were prepared by metalorganic aerosol deposition [9]. After deposition a post-annealing in oxygen was performed to produce a c-axis oriented film, which showed a good quality, T_c=88-90K and $J_c\geq10^4A/cm^2$

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at 77K. Homogeneous grains with a diameter of about 200nm have been obtained. FG morphology and a 10×10μm^2 bridge are shown in Fig.1. The temperature dependence of J_c for the fine-grain film is shown in Fig.2, which is measured with the aid of the same patterned bridge. The solid line is a guide to the eye.

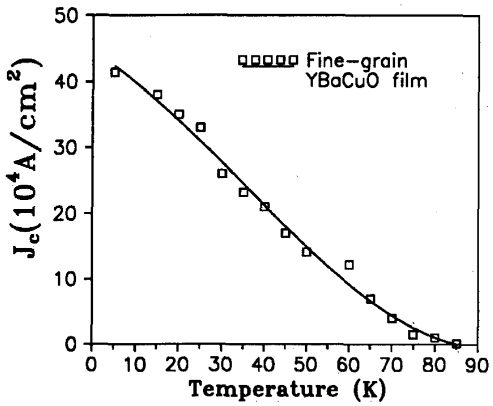

Fig.2 Critical-current density J_c of a fine-grain YBCO film as a function of temperature.

The bridges were fabricated by standard photolithographic technique and Ar ion-beam milling. Afterwards oxygen plasma etching was performed to remove the photoresist. The active area used for this work is 10×10μm^2. The experimental setups of the measurements for cw and pulsed optical sources have been described earlier [10,11]. The optical response was obtained by using a dc bias current (I_B) and measuring the change of voltage across the bridge. A gold (or silver) layer with a thickness of 200nm was evaporated onto YBCO films to make electrical contacts (resistance<1Ω). Several optical radiation sources were used: a mode-locked Nd:YLF laser with a pulse width of 75ps at a repetition rate of 77MHz (λ=1.31μm), or a GaAs diode laser (λ=0.9μm, average power 1-3mW) with a pulse width of 65ns at a repetition rate that can be varied from 10kHz to 30kHz, or a cw HeNe laser (λ=0.63μm) which can be chopped with frequencies up to 4kHz. An optical attenuator and a focus lens were placed at the front of the cryostat window. The laser beam was focused to a spot of approximately 30μm diameter. The average power (=peak power × pulse duty cycle) was measured with a calibrated powermeter (HP 8153A lightwave multimeter).

A fast, computerized sampling oscilloscope (Tektronix CSA803) with an input sampling head (Tektronix SD-26) having a rise time of about 25ps was used to analyse the response behaviour to the Nd:YLF laser. A standard 100MHz oscilloscope was used to display the response to the pulsed GaAs laser. The voltage noise of the detector was measured with a dynamic signal analyzer (HP 3561A).

III. RESULTS

A. Optical response of NG detectors to the Nd:YLF laser

The temperature dependence of the resistance (R-T) for an NG film on a MgO substrate is shown in Fig.3. This measurement has been carried out with a three-probe geometry [11] and shows a finite background resistance which varies slightly with I_B. The inset of Fig.3 shows the same curves in the temperature range between 35K and 80K with an expanded vertical scale in order to examine the details of the transition tails at 1 and 5mA. Our detectors are usually operated in this temperature range and with I_B between 1 and 10mA. The dashed line with arrows below a certain temperature T_s indicates the region where fast optical response is clearly observed. Here, "fast response" means that the voltage trace on an oscilloscope display can resolve the Nd:YLF laser pulses.

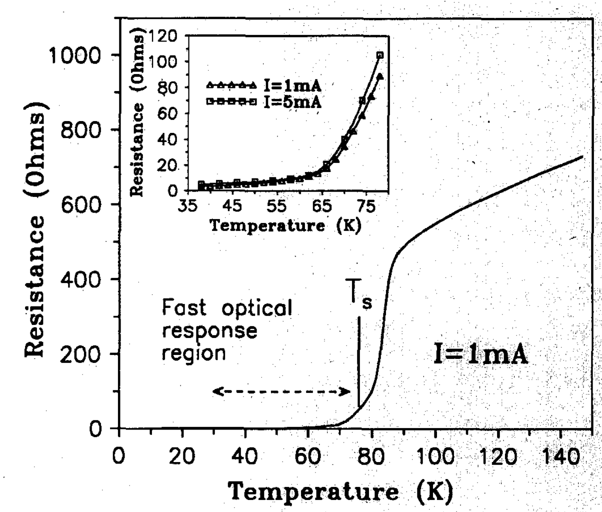

Fig.3 R-T curve of an NG detector at 1mA. The inset shows the same curve with an expanded vertical scale.

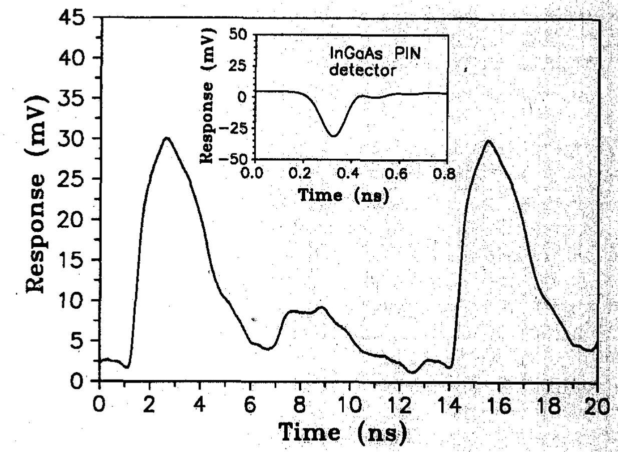

Fig.4 Temporal optical response of an NG detector on MgO to the Nd:YLF laser measured at 66K, 5mA and 0.5nJ per pulse. The inset shows the trace of the laser pulse detected by an InGaAs photodiode.

A response curve at 66K and 5mA is presented in Fig.4. A 10%-90% rise time (τ_r) of about 0.7ns and a 90%-10% fall time (τ_f) of about 2-3ns can be found. The inset of Fig.4 shows the Gaussian-shaped laser pulse detected by an InGaAs PIN diode (Antel AR-D25), which is an ultrafast photodetector (τ_r<35ps, spectral response from 0.85 to 1.7μm [12]). The τ_r of 0.7ns and a full-width at half maximum (FWHM) of 2.5ns of our NG YBCO detector correspond to a 3-dB cut-off frequency of 0.3GHz. Note that the small peak between two consequent optical pulses is due to a transmission-line reflection in the circuit. This reflection can be eliminated by a well-designed device with improved electrical leads.

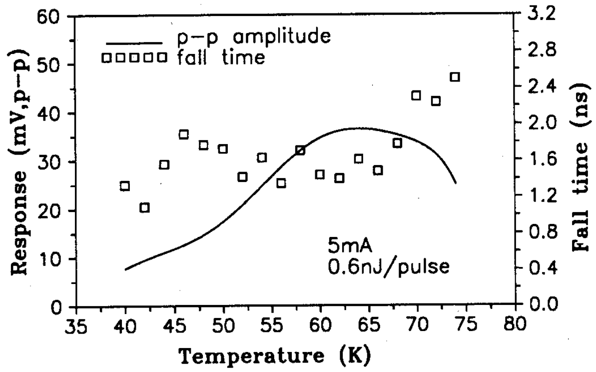

Fig.5 Response parameters τ_f and the p-p amplitude as a function of temperature for an NG detector.

Fig.5 shows τ_f and the peak-to-peak (p-p) response amplitude as a function of temperature at I_B=5mA. It can be seen that the τ_f decreases slightly from 75 to 60K, while the p-p response amplitude changes significantly with temperature. Decreasing the temperature from 80 to 40K, the response amplitude first increases up to a maximum value, remains there constant for a relatively broad temperature range, and then decreases monotonously. If the temperature is further reduced, the response amplitude becomes too small to be detected due to our detection limit of 2mV/div and noise of the system.

B. Optical response of FG detectors to cw lasers

A peculiarity of the aerosol-deposited FG films is that, at temperatures well below T_c and in a high current range, a Current Induced Voltage Step (CIVS) in the I-V curve has been found [13]. Related to this voltage jump, a resistive step in the R-T curve and a sharp optical response peak are observed. Fig.6 shows the R-T curve and optical response of an FG detector for two different values of I_B: 1mA and 7.5mA. At 1mA the R-T curve shows a normal resistive transition. However, at 7.5mA, there is a significant shift to the low temperature direction. Finally, an abrupt resistive transition takes place. The optical responses at 1mA and 7.5mA to a cw HeNe laser of 1mW are shown in Fig.6(b).

In order to check that the sharp response peak in Fig.6(b) is not a processing-induced artifact, we have examined all of our aerosol-deposited FG films. The response behaviour is qualitatively the same. Furthermore, we have also examined NG films. No sharp response peak could be found. Fig.7 shows the quasi-cw optical response to the GaAs laser as a function of I_B at different temperatures. We chose temperatures from the midpoint of the transition to one low enough to observe the sharp response peak. Again it is shown that in the low I_B range there is no sharp peak, while in the high I_B region, a sharp peak is present. Due to the presence of the sharp optical response peak, a high responsivity up to 10V/W can be obtained in the vicinity of the peak [11].

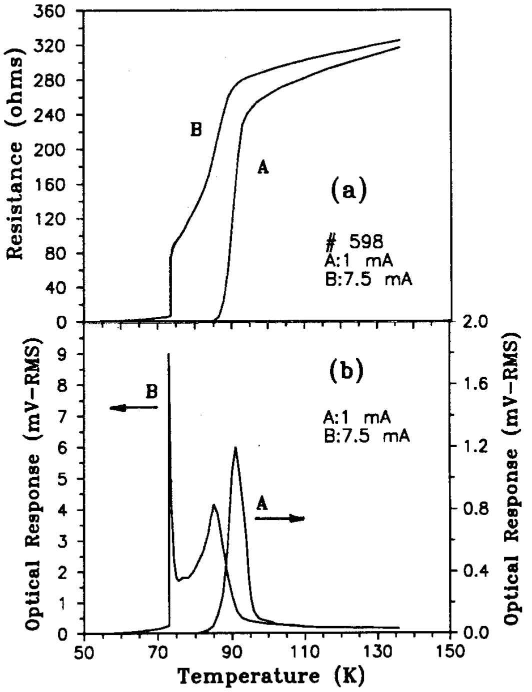

Fig.6 The resistance in (a) and cw optical response in (b) of an FG detector as a function of temperature.

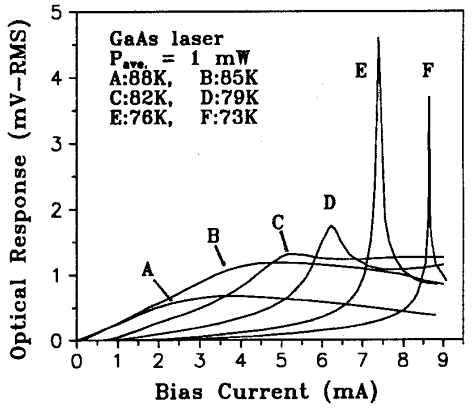

Fig.7 Optical response of an FG detector as a function of I_B at different temperatures.

C. Optical response of FG detectors to the pulsed GaAs laser

Figs.8(b) to (f) show the temporal optical responses of an FG detector to the 65ns-pulse-width GaAs laser at 5mA and different temperatures from 85 to 65K, when the detection circuit is terminated with 50Ω. Fig.8(a) is a reverse output trace of the InGaAs photodiode. In the set of traces in Fig.8, it can be found that the τ_r is almost the same. From high to low temperatures, the p-p response amplitude increases at the beginning and then decreases. The temperature dependence of the optical response in Fig.8 is qualitatively in agreement with the results obtained with an NG detector in Fig.5.

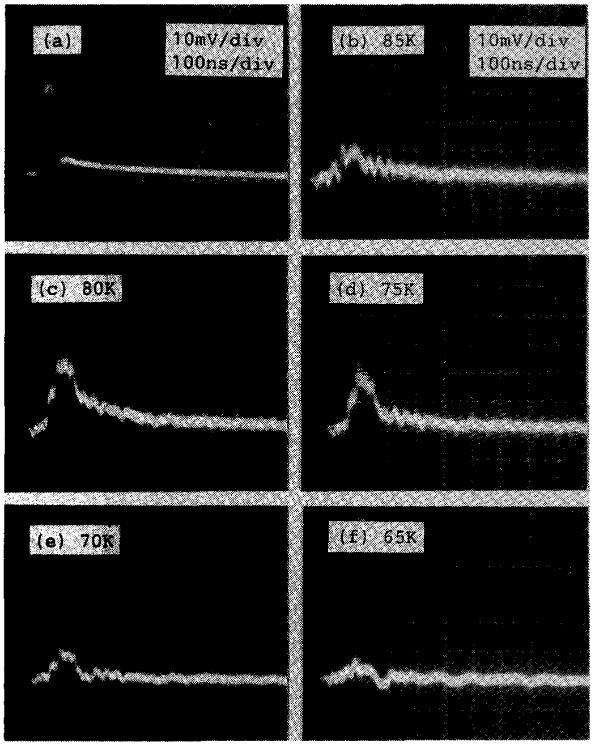

Fig.8 Oscilloscope traces of the GaAs laser, detected (a) by an InGaAs photodiode and (b)-(f) by an FG YBCO detector on $SrTiO_3$.

In an approximation the FWHM response time, τ_{det}, of the FG detector can be obtained by:

$$\tau_{total}^2 \approx \tau_{laser}^2 + \tau_{det}^2. \tag{1}$$

where τ_{total} is the response time, as shown in Fig.8(d) (≈ 80ns), and τ_{laser} is the laser's pulse width in Fig.8(a) (≈65ns). This results in $\tau_{det} \approx 46$ns.

D. Detector noise and sensitivity

The figures of merit of a photodetector for pulsed performance are not commonly defined in the literature. In the following, attempts have been made to estimate noise and a noise equivalent power (NEP) for an FG detector. The response curve to the pulsed GaAs laser at 75K and 5mA, displayed on a dynamic signal analyzer, is shown in Fig.9. One clearly sees: (1) the optical response signals (peaks) in the Fourier transform spectrum, and (2) a voltage noise spectral density, $S_v^{1/2}(f)$. The $S_v^{1/2}$ at 50kHz is 42nV/Hz$^{1/2}$.

Although the NEP can be simply defined as $S_v^{1/2}(f)$ divided by a peak responsivity, in some cases, the results obtained by this way are not satisfactory. One of the reasons for that is the difficulty in the estimation of the absorbed peak power. In the following, we describe a comparative method for measuring the NEP for pulse performance. According to the definition, NEP is the incident power needed to obtain an S/N ratio of 1. If we use the same criterion (S/N=1), it is easy to measure the power required to generate such a signal output. This measurement can be carried out on YBCO detectors as well as on commercially available detectors under the same experimental conditions. If the NEP of the latter is known, then that of the former can be obtained. In our case, the InGaAs detector is taken as a reference, which has a NEP of about 5×10^{-11}W/Hz$^{1/2}$ at 1.55 μm and about 1×10^{-10} W/Hz$^{1/2}$ at 0.9μm [12].

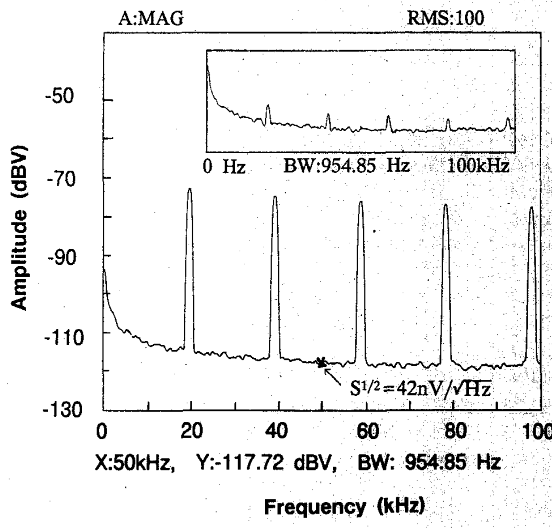

Fig.9 Optical response of an FG detector to the pulsed GaAs laser. The inset shows a criterion for determining the relative NEP.

During the measurements, a neutral density filter is used to reduce the incident power. The response signal, as shown in the inset of Fig.9, is used as a criterion (S/N≈1). It has been found that the incident optical power for an YBCO detector is about 8 times larger than that for the InGaAs detector, when the signal (S/N≈1) can be yielded. Assuming the active area of both detectors is comparable (actually, the size of the YBCO detector is smaller), the NEP of the YBCO detector can be roughly estimated to be 8×10^{-10}W/Hz$^{1/2}$ at 75K and 5mA. The same analysis has been carried out for an NG detector on $SrTiO_3$. The NEP obtained at 86K and 5mA is in the range of $(1\text{-}3)\times10^{-9}W/Hz^{1/2}$.

IV. DISCUSSION AND CONCLUSIONS

The mechanism of the fast optical response of HTS films at a temperature below T_c is still a controversial issue whether it is a purely bolometric [5] or at least partially nonbolometric [2,3,4] (e.g., breaking of the Cooper pairs and generation of quasiparticles) effect. We found that some of our results could not be properly explained by a simple heating effect. For example, we have estimated a lattice temperature rise (δT_{pulse}) in the optical response to the Nd:YLF laser. Assuming a pure bolometric response signal: $\delta V = I_B \times (dR/dT) \times \delta T$, when δV, I_B and dR/dT are known, the temperature rise δT (for a 1mW optical power) near T_c can be obtained. The δT of an NG device on MgO is about 5mK/mW. A 1nJ energy pulse in a 2.5ns time duration (see Fig.4) results in an average power of 400mW. Therefore, the δT_{pulse} (per pulse energy) in the same time duration can be calculated to be about 2K/nJ. This value is in agreement with the results of a simple thermal model prediction giving a value of 1.5K/nJ [3]. This implies that the operating temperature of 66K in Fig.4 is much lower than the temperature T_c-δT_{pulse}. In other words, the photoinduced lattice temperature rise does not seem to be high enough to raise the device temperature above T_c.

On the other hand, in our experiments, some evidence can be provided to support a bolometric effect. Fig.4 shows that the FWHM response time τ of an YBCO detector on MgO is about 2.5ns, when the film thickness is comparable to the optical penetration depth ($\approx$70nm). The τ of a bolometer is equal to C/G, where C is the thermal capacity (data of YBCO films, see [5]) and G is the thermal conductance. Because the thermal conductivities of $SrTiO_3$ and MgO are 0.2W/cmK [14] and 3.4W/cmK [15], respectively, it is easy to estimate that the τ on $SrTiO_3$ is about 42ns with the same geometry. This value is very close to the observed results from Eq.1.

Based on the above discussion, the optical response for both kinds of detectors could be mainly dominated by the heating effect of the radiation. The sharp optical response peak of an FG detector is associated with the CIVS, but the response mode does not change. The deviation between the observed results and a simple thermal analysis, as discussed above, is probably due to the complexity of the thermal processes, for example, thermal boundary resistance [16].

In conclusion, we have demonstrated YBCO detectors with NG and FG morphologies. The response time on the order of ns and the NEPs of 10^{-9}-10^{-10}W/Hz$^{1/2}$ are observed, when irradiated with a pulsed GaAs laser at 0.9μm.

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