Nanostructuring YBCO Thin Films by Heavy-Ion Beam for Far-Infrared Radiation Detection

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INTRODUCTION

In the framework of the INFN-Mo.Na.De. (Modulated Nanostructured Devices) experiment, we produced Far-Infrared (FIR) detectors from superconducting YBCO (YBa₂Cu₃Oₓ₋ₓ) films, functionalized by means of a heavy-ion treatment. The detectors are basically composed by two series meanders, one of which nanostructured by heavy-ion irradiation and acting as the sensor, the other one used as a thermoelectric voltage reference. Two selected film/substrate layouts were analysed, namely, YBCO grown on CeO₂ buffered YSZ (Yttria Stabilized Zirconia) and YBCO grown on MgO. For quasi-static measurements, it turns out that both films/substrates show almost the same response. A model based on non-equilibrium theory yields the estimation of NEP (noise equivalent power) and of relaxation times. From these calculations, the YBCO grown on MgO substrate should exhibit the faster relaxation time (few μs) and we experimentally verified that devices on MgO substrate can resolve time-varying FIR pulses with repetition rates as fast as 800 Hz. The presented performances are compatible with the necessary requisites for FIR characterization of high-energy electron beams (e.g., Free Electron Lasers) and hot plasmas (e.g., Collective Thomson Scattering).

EXPERIMENTAL

YBCO films are grown by thermal co-evaporation on single crystal substrates (YSZ and MgO). In the case of YSZ, the lattice matching with YBCO is obtained through a buffer layer of CeO₂ (40 nm) [1]. Thickness of films is in the range of 250–300 nm. Standard optical lithography and wet-etching are used to pattern the device layout.

FIR detector layout is shown in figure 1. It consists of a three-terminal double meander structure (line width: 35 μm, single meander total length: 36 mm), in order to have one common voltage contact and to be biased with the same electrical current. Only one of the meanders is nanostructured by heavy-ion irradiation [2].

For the devices here presented, 114 MeV Au-ions with a fluence of 4.84•10¹¹ cm⁻² were used. In figure 2 the resistance vs. temperature curves for both YBCO films grown on YSZ and on MgO, respectively, are shown. It is remarkable that at the same energy and fluence, the same ΔTᵣ between the nanostructured material and the as-grown one is obtained. Moreover the slope at the superconducting transition is practically unchanged after irradiation. This allows biasing the device in such a way to lead its active element (the heavy-ion treated meander) into a quasi-dissipative state, while leaving the reference meander in a fully dissipation-free state.

The FIR radiation is provided by a commercial high-pressure mercury arc-lamp, suitably filtered (with high-resistivity silicon plus Zitex plastics) to cut off any unwanted electromagnetic spectra but FIR one (high transmission for frequencies below 4 THz) [3].

In quasi-static conditions, the estimated incident power belonging to the FIR spectrum is at maximum 300 nW and the shutter closing time is about 1 sec. In figure 3 an example of quasi-static response to FIR radiation is shown.
for YBCO on both YSZ and MgO. It is clearly demonstrated that only the nanostructured meander is brought into a dissipative state and that the same response to quasi-static excitations is shown by YBCO on both substrates (in the presented measurements, the responsivity sets to about 3.3 V/W). The signal coming from the as-grown YBCO meander is of thermo-electric origin and serves as thermoelectric voltage reference.

Fig. 3. Photoresponse to FIR radiation (Hg arc lamp filtered by Zitex plus high-res Si) for two devices: YBCO/CoO2/YSZ (T=81.4 K, I=1mA) (upper) and YBCO/MgO (T=81.4 K, I=1mA) (lower). Only the irradiated meander displays a dissipative signal. Responsivity is about 3.3 V/W.

NEP and relaxation time are estimated on the basis of the non-equilibrium theory for bolometric detectors [4]. In our devices the main contribution to the NEP comes from the thermal noise [3]. In particular, the thermal NEP is 1.3·10^{-11} W·Hz^{-1/2} for YBCO on YSZ [3] and 1.95·10^{-10} W·Hz^{-1/2} for YBCO on MgO [2]. Estimated values of the relaxation times set to 1 ms for YBCO on YSZ and 4.4 µs for YBCO on MgO. Thus, for the same geometrical parameters, the MgO substrate is the best choice for dynamical measurements, essentially due to its higher thermal conductance and consequent more rapid heat transfer with respect to YSZ.

For dynamic measurements, an electromechanical chopper is used instead of the shutter, with maximum chopping frequency of 800 Hz. In figure 4, the measurement of the dynamic response of MgO based device to time-varying FIR radiation is shown. It is worthy to note that since the Hg arc lamp is not a point-like source, the corresponding shape of the FIR radiation signal is a triangular waveform, whose period is only determined by the electro-mechanical chopper velocity. From figure 4, we observe a linear response, and a relaxation time lower than 1 ms (actual rising and falling signal fronts are linearly resolved within half a period, i.e., 625 µs) [2]. It turns out that our approach enables the detection of time-varying infrared signals, with high sensitivity on a bandwidth of at least 1 kHz, e.g., as requested for characterizing the electromagnetic emission from high-energy electron beams or hot plasmas [5].

Fig. 4. Analog oscilloscope measurement of YBCO/MgO with chopped arc lamp (filtered by high-res Si). The triangular waveform comes from the almost uniform illumination of the chopper blade. Chopper frequency was 800 Hz, device bias current was 1.9 mA and T=81.5 K.