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# Tuning the absorption band in the THz range of YBCO films patterned by means of HEHI lithography

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ABSTRACT

High energy heavy ion lithography was used for modulating through implanted nanostructures the local structural and electrical properties of high temperature superconducting $YBa_2Cu_3O_7$ films. The controlled reduction of the critical temperature of irradiated films results in a localization into heavy ion patterned micro-regions of the electrical dissipation, viable in a given temperature range and driven by ion fluence, bias current and applied magnetic field. The measurement of the response of such nanostructured YBCO films to electromagnetic radiation in the infrared band (MIR–FIR region) is presented. It turns out that the ion induced structural modification of both superconducting film and substrate is actually enabling the infrared optical absorption of YBCO, so that the viability of low noise THz detection above the liquid nitrogen temperature is shown.

## 1. Introduction

Heavy ion lithography [1,2] is a powerful way for introducing nanometric scale modification over the micron scale surface of superconducting targets as HTSC films, resulting in a local change of the superconducting properties. Such modified regions are viable to produce functional superconducting circuitry on the micron scale. The micro-collimated irradiation with high energy heavy ions (HEHI) has the peculiarity of a 3D crystal lattice modification extended to the underlying heterostructure (film, buffer layers, and substrate) due to the deep implantation length of the ions as well as to the presence of ancillary defects. In the HTSC film, the HEHI create nanometric columnar defects [3], and in the substrate-heterostructure the ions implant with a depth dependent on the ion energy, while the ion fluence is the control parameter for tuning the degree of crystal lattice amorphization in the HTSC film. Micro-collimated HEHI irradiation of $YBa_2Cu_3O_{7-x}$ (YBCO) films, at relatively high fluences (larger than $10^{11}$ ion $cm^{-2}$), results in a local depression of the critical temperature, $T_c$, and of the critical current density, $J_c$. Then, well-defined micro-regions of YBCO films can be tailored "ad hoc" without destroying the superconductivity. The central issue is that this approach leads to a functional decoupling of suitably modulated micro-regions with respect to the as-grown one, extended across a temperature range controlled by ion fluence and bias current. Thus in a tunable temperature range, once fixed the bias current of patterned samples, it is possible to localize the electrical dissipation due to external electromagnetic signals [4–6]. The viability to exploit in a dynamic regime this functional electromagnetic decoupling was demonstrated under external photon excitation (in the VIS spectrum) [7].

For what concerns the far-infrared spectrum, several approaches have been pursued in order to develop YBCO photodetectors [8]. Our approach is expected to overcome the intrinsic limitations of YBCO (cut-off frequency at the as-grown gap value of 20 meV and poor absorption in the far-infrared regions [9,10]), because the HEHI lithography process should reduce (and makes broader their distributions) both the energy gap and the frequency of low-energy vibrational modes of YBCO. This expectation was indeed suggested by the measured local $T_c$ depression of the irradiated regions and by the measured increased absorption of the VIS radiation [7].

In this paper, we demonstrate that the structural modifications, induced by HEHI patterning of both the superconducting film and the substrate, decisively enhance the absorption of the electromagnetic wave with millimeter wavelength. Moreover, THz detection enabled by our approach can be performed in a steady-state electrical measurement-protocol and above the liquid nitrogen temperature.

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## 2. Experimental details

HEHI lithography facilities were developed at the INFN laboratories on Linear Tandem Accelerator and on Superconducting Cyclotron Accelerator beam lines [2]. Stainless steel masks with laser-cut micro-apertures (either pinhole or slit shape) are used to collimate the beam and a moving sample-holder with nanometric resolution allows one scanning the sample surface under the beam. As summarized in the introduction, the HEHI irradiation induces structural modifications both in the substrate and in the HTSC film. The strain due to ion implantation in the substrate causes a local increase of the YBCO film thickness, experimentally determined by Atomic Force Microscopy [4,5]. Columnar defects are induced in the HTSC film and generate in-plane stress and amorphization of the material on the nanometric scale [3]. The local depression of $J_c$ and $T_c$ due to these structural modifications is achieved above a fluence, $\phi$ larger than $10^{11}$ ion cm$^{-2}$.

The YBCO films were deposited by thermal co-evaporation on 450 μm yttria stabilized zirconia substrate with 40 nm $CeO_2$ buffer layer [11]. The YBCO thickness is 300 nm experimentally corresponding to a maximum of $J_c$ of $3 \times 10^1$ A m$^{-2}$ at $T = 4.2$ K and of about $3 \times 10^{10}$ A m$^{-2}$ at $T = 80$ K [12]. The $T_c$ of the as-grown samples is about 89 K, at the transition onset, and the transition width, $\Delta T_c$, is less than half a Kelvin degree [6].

In all the experiments we performed [4–6], the same YBCO film thickness, buffer layer and substrate were used in order to obtain a one to one correlation between the induced structural modification and the HEHI fluence (at the same energy). In this experiment, we used 114 MeV Au ions and the HEHI irradiated area was extended over half of the detector surface (the prototype devices in this experiment were irradiated with $\phi = 4.84 \times 10^{11}$ cm$^{-2}$, see below for the description of the prototype device).

A continuous-wave FIR radiation was produced by an high pressure Hg arc lamp (OSRAM HBO 100W) [13]. The scheme of the setup is presented in Fig. 1. The millimeter wavelength range in the FIR spectrum (frequency below 3 THz, wavelength 100 μm) was selected by proper filtering. In particular, we substituted the optical window of the cryostat (Oxford Microstat) with high-resistivity *n*-type Si, that enables the transmission of the MIR–FIR component only toward the sample. The remaining spectrum can be filtered either by Teflon foil (2 mm thick) or by the more efficient Zitex G110, in order to cut optical frequencies above 4 THz (wavelength 75 μm). The transmission spectra of Teflon and Zitex, along the transmission spectrum of Silicon, are reported in Fig. 2.

The real-time sampling of the voltage was performed by dual-channel Keithley Nanovoltmeter 2182 (sampling time 100 ms).

We developed a prototype sensor layout, by UV photolithography, as depicted in Fig. 3a. The detecting unit consists of a couple of meanders connected in series, see Fig. 3b, and one of them was uniformly irradiated. Typical measurements are presented for one of produced prototypes.

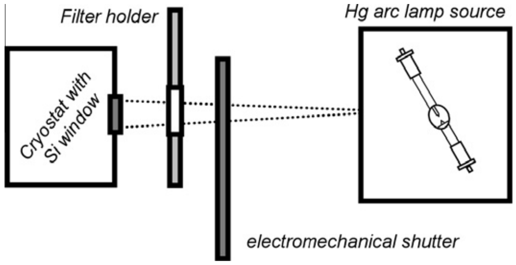

**Fig. 1.** Scheme of the experimental set-up, composed by the infrared source (Hg arc lamp), an electromechanical shutter, the filter holder and the cryostat.

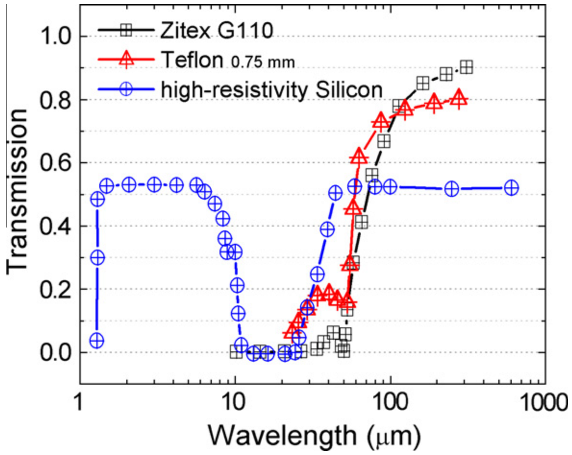

**Fig. 2.** (a) Transmission spectra of high-resistivity Silicon, Teflon and Zitex G110 materials in the MIR–FIR band (data taken form [13]).

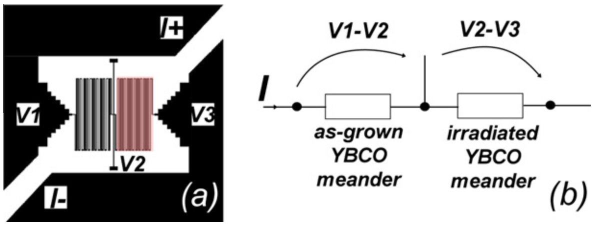

**Fig. 3.** (a) Device layout: (1) bias current leads, (2) voltage pick-up pads, and (3) sensitive area ($1.62 \times 3.3$ mm$^2$) and (b) simplified electrical scheme of the prototype device.

## 3. Results and discussion

### 3.1. Resistance versus temperature characterization

The superconducting transitions of the two series meanders are separately presented in Fig. 4. Except for cooling, the bias current was kept strictly constant during the experiment and it was set at 1 mA (corresponding in the serpentine to an electrical current density of $8.3 \times 10^7$ A m$^{-2}$). This value was chosen to reduce spurious heating of the device in each part and to guarantee a good

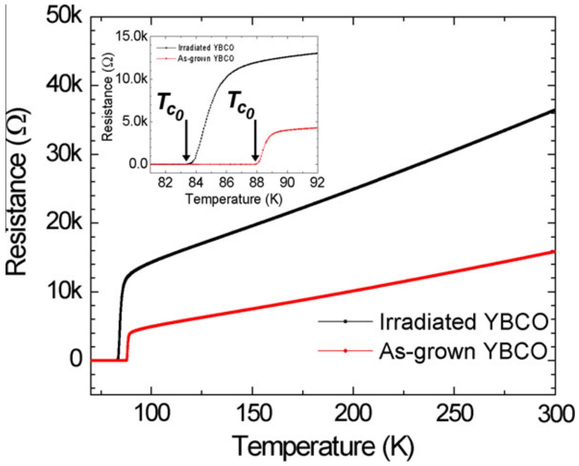

**Fig. 4.** Resistance versus temperature plot, simultaneously measured on both the meanders during slow cooling. The bias current was kept constant at 100 μA. As visible from the inset, the transition width of the irradiated zone is remarkably enlarged with respect to the as-grown YBCO (about 4.5 K versus 0.5 K).