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Nanostructuring YBCO thin films by heavy-ion beam for local magnetic field and infrared photon detection

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ABSTRACT

We report about the functional exploiting of the High-Energy Heavy-Ion (HEHI) lithography aimed at modulating in confined regions both structural and electrical properties of high temperature superconducting $YBa_2Cu_3O_{7-x}$ (YBCO) films. We discuss the physical behaviors related to the HEHI modification of such films by means of 3D columnar defects, exhibiting nanometric cross section. A major part of this paper is devoted to the viability of well-defined (B,T,J) phase-diagram zones, where electrical decoupling between as-grown and modified parts occurs and so guarantees external-signal localization.

In order to stress out complementary behaviors into different phase-diagram regions of locally modified YBCO films, we present low-temperature magnetic imaging, accounting for the case where a spatially continuous Meissner state holds on throughout the whole sample. In this case, the continuity of the Meissner state hampers localization of dissipative signals in the nanostructured region. On the contrary, inside the (B,T,J) phase-diagram zones belonging to the temperature range where the Meissner state is spatially broken, the temperature range of dissipation confinement under external stimuli can be functionally exploited. Then the main target of a road map pointing towards position-sensitive infrared superconducting sensors is enlightened by means of crucial experimental results. With this respect, a device layout, consisting into HEHI modified YBCO film grown either on YSZ or MgO substrates, is chosen to test the functional behavior of infrared detectors working above liquid nitrogen temperature and, in the case of MgO substrate, displaying sub-millisecond response-time.

1. Introduction

The local modification of oxide materials by High-Energy Heavy-Ion (HEHI) beams allows one to locally "decorate" in 3D the ion-affected zones by means of columnar defects [1]. They exhibit nanosize cross sections [2]; their relative distance is modulated by ion fluence and their implantation depth is defined by ion energy [3,4]. Moreover, the ion-beam modified region can be carved with arbitrary geometry.

The study of superconducting material modification by ion beams involves the very core of superconductivity and belongs to the complexity world [5]. This world, thought fascinating, is still far away from a complete formal understanding. In this framework and in view of available applications of the unique superconductor properties, we discuss two complementary behaviors, which are labeled by characteristic states and are experimentally observed because of confined, heavy-ion induced modifications with specific patterns.

Thus, the first issue addressed in the paper is aimed at outlining the complex behavior of HEHI-modified High Temperature Superconductor (HTSC) films: in this case the effects of ion-beam modification, which is localized in a region of the film, must be investigated in the *irreversible part* of (B,J,T) phase diagram in order to keep a continuous Meissner state inside the superconductor. For practical purposes, one can work at "low enough" temperature and analyze the behaviors that are related to different external applied fields or to transport current; both of them cause nucleation of superconducting vortices and feed the complexity of the system. In this case, the overall response is sustained by the spatial coherence of the continuous Meissner state. This behavior can be directly observed by means of magnetic imaging (see below) and modeled by continuous electrodynamics [6].

The second issue contains the focus of the present paper and it is dealing with the opposite effect, namely the breaking of the spatial coherence of the Meissner state otherwise running throughout the whole sample (also across HEHI modified regions). The resulting effect is the decoupling of the superconducting states

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belonging to the as-grown and to the modified regions, respectively, and it can be made functional in order to localize the dissipation (as induced by an external stimulus), only when the superconductor is probed inside a selected region of the (B,T,J) phase diagram [4]. In order to master this region for application purposes, the leading parameter is the "gap" in the (B,T,J) phase-diagram between as-grown and HEHI modified superconductor. In particular, the HEHI irradiation enables to control the local critical temperature of the HTSC film, without changing the resistance slope, as done, on the contrary, by other experimental means for HTSC modification (e.g., LASER irradiation or chemical doping). In this case the "temperature gap" ΔT_c becomes functional for the application, with a specific road-map pointing towards magnetic field and photon detectors (the latter is devoted to medium and far infrared radiation sensing).

The paper is organized as follows: in Section 2, we report about experimental techniques concerning HTSC $YBa_2Cu_3O_{7-x}$ (YBCO) film growth, HEHI lithography of YBCO films, magneto-optical imaging and electrical transport measurements (including photo-response); in the Section 3, at first, we deal with magnetic imaging of the HEHI patterned films, at low temperature, then with measurements of magneto-resistance and of photo-response in the infrared spectral region of functionalized HTSC films. Finally, we resume the outcome and perspectives of this work in Section 4.

2. Methods

2.1. Superconducting film deposition

Three hundred nanometer thick YBCO films (*c*-axis oriented, critical temperature about 89 K, transition amplitude about 0.5 K), are grown by thermal co-evaporation [7] either on Yttria Stabilized Zirconia (YSZ), with a 40 nm thick CeO_2 buffer layer, or on MgO single crystal. Standard photolithography and chemical wet-etching are used to define the superconducting film geometry.

2.2. HEHI lithography

HEHI lithography was first exploited by Kwok [8]. We perform this technique at the Istituto Nazionale Fisica Nucleare (INFN) accelerator facilities, by means of ^{197}Au ions (energy range 114–250 MeV, this work). The Au ions release, for at least one third of their path in YBCO, enough energy (of the order of tens MeV ions^{-1} μm^{-1}), to produce well correlated columnar defects along the ion direction. By means of scanning electron microscopy study of YBCO single crystals [9], we verified that columnar defects in YBCO are present down to 6 μm, see Fig. 1, and HEHI implant around 16 μm (250 MeV ^{197}Au).

For what concerns YBCO films, the HEHI implant into the substrate, around a depth of 10–20 μm (114–250 MeV, respectively), as preliminary estimated by SRIM.EXE© [10] simulations. Transmission Electron Microscopy (TEM) measurements show that Au ions impinging YBCO films create insulating columnar nanostructures [1,2] with diameter of about 7 nm surrounded by a larger strained zone (within 20 nm), where some oxygen reordering is expected [2,11].

In order to produce micro-scale nanostructured regions inside the YBCO films, the HEHI beam is micro-collimated by means of laser-cut stainless steel masks or by micron size pinholes and focused on a planar sample holder moving with nanometric resolution [12]. A Monte–Carlo simulation, presented in Fig. 2, shows how the ion density reaching the target throughout the pinhole (thickness 150 μm) is quite constant. Currently, the smallest width available by our HEHI lithography process is 5 μm (as shown below).

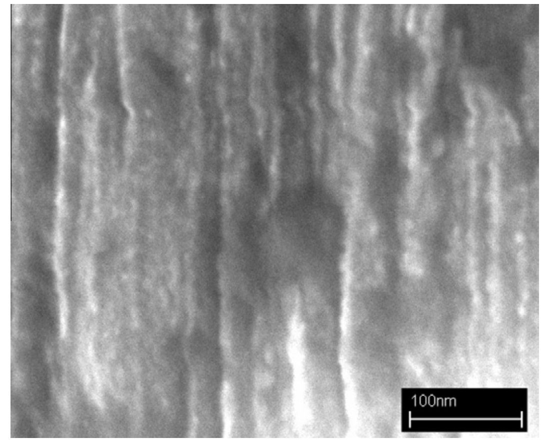

Fig. 1. Single columnar defect visualization by means of scanning electron microscopy on irradiated YBCO single crystal. Irradiation was performed with ^{197}Au at 250 MeV with a fluence of 1.9×10^{11} cm^{-2}, the ion beam was perpendicular to the crystal *ab*-plane. Note the "sausage" structure of columnar defects that is formed along YBCO *c*-axis.

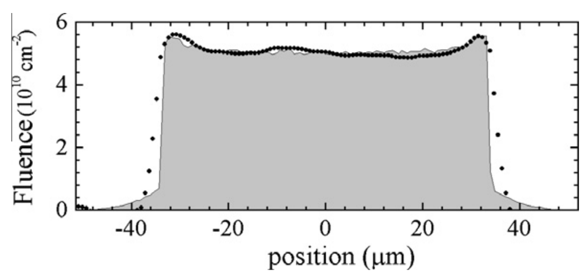

Fig. 2. Monte–Carlo simulation (line) and measured polyester sheet darkening level (points) of HEHI irradiation (250 MeV), through a metallic mask with a microscopic slit (about 80 μm wide). The two peaks are due to the HEHI scattered by the slit edges of the metal mask.

2.3. Magneto-optical imaging

The visualization of the magnetic pattern is obtained by means of the magneto-optical technique with an indicator film [13]. A model-independent algorithm is used to extract the actual current density distribution [14]. In this way, a complete set of electrodynamical measurements can be performed on thin and flat samples, whose surface is fully contained in the measured area.

2.4. Electrical transport and photo-response measurements

Electrical transport measurements are performed with a constant current source and multi-pad voltage pick-ups. The quasi-static dissipative signals across HEHI modified regions are picked up by means of a dual-channel nano-voltmeter. As infrared radiation source, a suitably filtered high-pressure Hg arc-lamp (with high resistivity Silicon window for transmitting the infrared spectrum) and a instrumentation amplifier ($G = 1000$, bandwidth 300 kHz, for details see [15]), are used. In order to record the dynamic response, the beam is guided throughout an electro-mechanical chopper and the signal is visualized by means of a analog oscilloscope (bandwidth 20 MHz).

3. Results

3.1. Low temperature magnetic imaging

The magnetic field distribution of a patterned sample is shown in Fig. 3. The HTSC film is patterned as a rectangular strip (width