YBCO nanowires for ultrasensitive magnetic flux and photon detectors

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***Abstract* — We present our last results on superconducting YBCO nanostructures: the nanowires, fabricated using the improved nanopatterning procedure we have presented in our previous publications, and preserving the superconducting properties close to the as grown films, have been employed in different devices, realized both for fundamental studies and applications. The nanoSQUIDs, realized in the Dayem bridge configuration, and characterized by a record value of the white flux noise, appear extremely promising for applications ranging from studies of nanomagnetism to low field magnetic resonance imaging. The nanorings instead, used for Little Park experiments and characterized by a uniform vorticity of the order parameter, are expected to shed light on different issues on HTS pairing mechanism, especially in the underdoped region. Finally, YBCO/LSMO nanowires, showing high degree of homogeneity, have been fabricated. The presence of the ferromagnetic LSMO layer makes these nanowires ideal candidates both for the investigation of cuprate/manganite-oxide interfaces and for photo-response measurements.**

I. Introduction

IN the recent years there has been great attention towards the study of the superconducting phenomenon at the nanoscale. The motivation is driven by two contrasted interests: to understand the enhancement of the superconducting properties in low dimensional structures like nanowires [1] and nanodots [2] and at the same time to establish the critical size limit beyond which the superconducting phenomenon cannot be sustained [3]. Moreover, nanoscale superconductors pave the way for new exciting developments towards quantum-limited sensors for single photons [4] and spins [5].

The realization of wires with highly homogeneous superconducting properties is essential to enable fundamental studies and reproducible devices. While the reliable fabrication of nanostructures is nowadays feasible for conventional superconductors, it still represents an extremely challenging task for cuprate High critical Temperature Superconductors (HTSs), because of their chemical instability, mostly related to oxygen out-diffusion, and their extreme sensitivity to defects and disorder due to very short coherence length.

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Despite these technological difficulties, we have recently shown [6-8] an optimized nanopatterning for $YBa_2Cu_3O_{7-x}$ (YBCO) nanowires with cross sections as small as 40×50 nm^2 based on a soft etching procedure preserving an Au capping layer on top of the nanostructures. The high values of the critical current, close to the theoretical depairing limit ($1\text{-}3{\cdot}10^8$ A/cm^2), achieved in our nanostructures demonstrate that the superconducting properties close to the as grown films are preserved. As a consequence, these nanostructures represent model systems to investigate the intrinsic properties of HTSs, for instance studying the fluxoid quantization in superconducting loops, as in nanoSQUIDs and nanorings.

II. Characterization Of Devices And Results

A. Dayem bridges YBCO nanoSQUIDs

We have realized YBCO nanoSQUIDs, implementing the nanowires in the Dayem bridge configuration (Fig. 1(a)) [9]. These devices work in the full temperature range up to T_C (83 K), exhibiting critical current modulations as a function of an external magnetic field, never seen before for similar HTS devices (Fig. 1(b)). The depth and the periodicity of these modulations have been both well reproduced, considering a simple model in which the circulating currents around the loop and kinetic inductance of the nanowires are dominant. Moreover, they show record values for the white flux noise, below $1\mu\Phi_0/Hz^{1/2}$ above 10 kHz, making them very attractive for many applications, as for the investigation of magnetic nanoparticles between their transition from the ferromagnetic to the paramagnetic state.

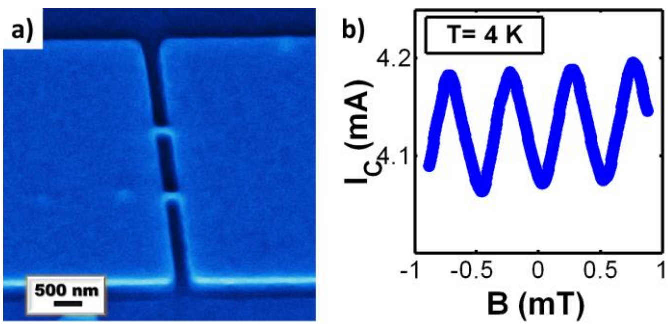

Fig. 1. a) Scanning electron microscopy picture of a Dayem bridge nanoSQUIDs, consisting of two nanowires in parallel connecting two wider electrodes. b) Critical current modulation of a nanoSQUID measured at 4 K as a function of an externally applied magnetic field.

B. YBCO nanorings

We have also realized YBCO nanorings (Fig. 2(a)). Magneto Resistance R(B) measurements close to T_C show typical Little Park oscillations with a period h/2e, indicating a conventional 2e value for the elemental superfluid charge. However, differently to what previously reported in literature [10], as a consequence of the high degree of homogeneity of our nanostructures, we have a clear evidence of a uniform vorticity of the order parameter inside the rings (Fig. 2(b)). The same experiment is in progress on underdoped YBCO nanorings, for which unconventional R(B) oscillations are predicted [11]. The detection of a periodicity which is different from h/2e could have important implications to discriminate between different theoretical models for the microscopic mechanism leading to high critical temperature superconductivity.

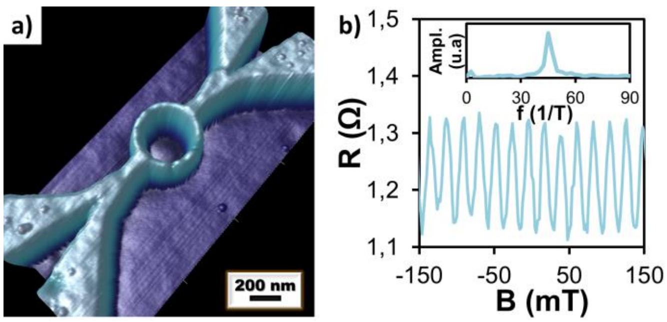

Fig. 2. a) Atomic force microscopy picture of a YBCO nanoring, with 90 nm wide arms and an inner diameter of 260 nm. b) Resistance oscillations as a function of the external magnetic field, measured at 80 K on the same device of panel a, provide evidence of the Little-Park effect. The Fourier transform of such a data is shown in the inset: assuming Φ_0=h/2e, the sharp peak at 46 T^{-1} corresponds to a superconducting loop with 350 nm average diameter, which coincides with the AFM extracted average loop diameter.

C. YBCO/LSMO nanowires for photodetection experiments

Finally, the wide range of lengths we have been able to achieve (from 200 nm to several microns) also allows implementing nanowires for applications of single photon detection. YBCO nanowires are potentially very interesting because of their fast thermalization dynamics. For this purpose, YBCO nanowires capped with a ferromagnetic $La_{0.7}Sr_{0.3}MnO3$ (LSMO) capping layer have been fabricated. The use of the ferromagnetic layer is driven by the need to protect the wires with a different capping material, since gold, used both for nanoSQUIDs and nanorings, cannot be used in optical applications, because of its high conductivity. At the same time the physics of ferromagnetic/superconducting interfaces has recently received a lot of attention [12]; indeed, in the context of photodetectors, in nonequilibrium pump-probe experiments [13] the use of LSMO has demonstrated an important functionality by reducing the electronic relaxation times when compared to bare YBCO films. The photoresponse of YBCO/LSMO nanowires has been measured. Although the interpretation of the physical mechanism lying behind these measured signals is still on going, first results have shown that there is an enhancement of the signal intensity compared to bare YBCO nanowire detectors [14].

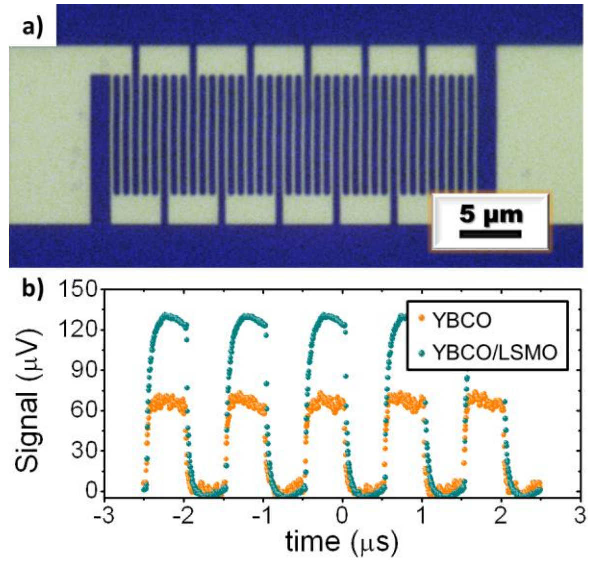

Fig. 3. a) Optical picture of 10 µm long YBCO/LSMO nanowires, embedded in a configuration covering a large area, suitable for photodetection experiments. b) Voltage responses to optical laser pulses (λ=1550 nm) measured at 5 K on two devices with the same geometry, but employing respectively bare YBCO and YBCO/LSMO nanowires.

III. Conclusion

In conclusion, by using a soft nanopatterning procedure, we have achieved YBCO nanowires with sections down to 40×50 nm^2, preserving ‘pristine’ superconducting properties of as grown films. The wide range of lengths we have been able to achieve gave us the possibility to span a broad range of applications, ranging from nanoSQUIDs and nanorings for the shortest wires to nanowires attractive in superconducting optoelectronics for the longest ones.

Our results open new perspective for the use of YBCO nanostructures both for fundamental physics and applications.

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