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$YBa_2Cu_3O_{7-\delta}$ nanorings to probe fluxoid quantization in High Critical Temperature Superconductors

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ABSTRACT

We have realized $YBa_2Cu_3O_{7-\delta}$ (YBCO) nanorings and measured the magnetoresistance $R(B)$ close to the superconducting transition. The large oscillations that we have measured can be interpreted in terms of vortex dynamics triggering the nanowires to the resistive state. The Fast Fourier Transform spectrum of the magnetoresistance oscillations shows a single sharp peak for nanorings with narrower loop arm width: this peak can be univocally associated to a $h/2e$ periodicity as predicted for optimally doped YBCO. Moreover it is a clear evidence of a uniform vorticity of the order parameter inside the rings, confirming a high degree of homogeneity of our nanostructures. This result gives a boost to further investigations of YBCO nanorings at different dopings within the superconducting dome, where in the underdoped regime a $R(B)$ periodicity different from the conventional $h/2e$ has been predicted.

1. Introduction

Multiply-connected structures like cylinders and rings are the basic structures for studying a variety of quantum mechanical effects, including the fluxoid quantization [1–4]. These structures have attracted a lot of interest in the last few years, after theoretical studies have predicted the appearance of an additional h/e component in the magnetoresistance of nanorings made by High Critical Temperature Superconductors (HTSs), associated with the d-wave symmetry of the order parameter [5–9]. At the same time, theories based on a charge stripe order, to explain the microscopic mechanism for HTS, have predicted the appearance of a $h/4e$ periodicity (corresponding to half a quantum of flux), replacing/coexisting with the usual periodicity of $h/2e$ [10]. The analysis of the magnetoresistance $R(B)$ oscillations, which can be observed in nanorings at temperatures close to the superconducting critical temperature T_C (Little–Parks effect), allows the identification of the charge of the carrier responsible for the superconducting phenomenon. In the case of HTS, these measurements can shed light on the HTS pairing mechanisms. Magnetoresistance measurements made on HTS nanorings [11,12], and in particular on $YBa_2Cu_3O_{7-\delta}$ (YBCO) submicron rings [13], have shown, up to now, that in the optimally doped regime only the periodicity $h/2e$ is present.

However, the various theories for the microscopic mechanism of HTS give the sharpest predictions in the underdoped regime. The study of fluxoid quantization in HTS nanorings as a function of doping remains an important tool to discriminate among the various theoretical approaches, where a crossover from $h/2e$ to h/e or $h/4e$ flux periodicities is predicted [14]. An important step in this field is the realization of nanorings with homogeneous superconducting properties close to the as grown films. In this way any new periodicity possibly detected in the magnetoresistance oscillations can be univocally associated to a different elemental charge carrier (compared to the conventional $2e$ Cooper pair) or to new effects related to the d-wave symmetry of the order parameter.

In this contribution we report on recent developments in the fabrication and measurement of YBCO nanorings, where the superconducting properties are uniform across the arms of the nanorings down to dimensions of the order of 50 nm.

The nanorings are made of nearly optimally doped YBCO, with cross sections down to $50 \times 30\,\mathrm{nm}^2$, using an improved nanopatterning procedure described in Refs. [15–17]. As a consequence of the soft ion milling procedure and of the presence of a Au capping layer on top of the nanowires, we have achieved YBCO nanostructures, demonstrating "pristine" superconducting properties, characterized by a critical current density close to the theoretical Ginzburg–Landau depairing limit [18].

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2. Nanoring fabrication and design

The devices have been realized by patterning 30 nm thick YBCO films, provided by Theva GmbH, grown on MgO (001) substrates and with a T_C of 85 K. Details on the nanopatterning procedure can be found elsewhere [15,18]. Fig. 1(a) shows the typical ring geometries we have realized: the rings have the internal radius r_{int} in the range 120–200 nm, and the arm width w is in the range 50–80 nm. The four wide electrodes, used as current and voltage probes during the measurements, are situated very close to the nanostructures. For our geometries we have made numerical calculations of the current density across the nanorings to evaluate the effective area A_{eff}, following Refs. [19,20], which is fundamental to determine the flux across the ring and therefore the periodicity of the magnetoresistance oscillations. The values we have obtained are in very good agreement with those of the geometrical area of the ring $A_g = \pi r_{avr}^2$, with $r_{avr} = r_{int} + (w/2)$ being the average radius.

For comparison, we have also fabricated a few wider rings, with arm width w in the range 150–200 nm (see Fig. 1(b)).

3. Magnetoresistance measurements

Resistance vs Temperature $R(T)$ and magnetoresistance $R(B)$ measurements of different nanorings have been carried out in a Physical Property Measurement System (PPMS) of Quantum Design with a temperature stability of about ±1 mK, using a 4-point measurement scheme. In the following, we will focus on the nanoring shown in Fig. 1(a), which exhibits the typical characteristics of most of the devices we have measured.

Fig. 2(a) shows the $R(T)$ curve. Since the electrodes are closely attached to the nanostructure, only the transition related to the nanoring is observed. The broadening of the resistive transition can be fitted in terms of a vortex slip model [21], considering the actual dimensions measured by AFM: we have extracted feasible values for λ_0 and ξ_0 ($\lambda_0 \approx 340$ nm and $\xi_0 \approx 2.5$ nm), only slightly higher than those we have obtained from nanowires with similar widths [18], which is possibly related to the thinner YBCO layer [22]. This result highlights the high quality of our nanostructures even with cross sections as small as 50×30 nm^2.

We have measured the magnetoresistance of the ring at different temperatures within the resistive transition (see colored opened squares in Fig. 2(a)). Large oscillations appear as a function of the flux enclosed by the ring (see Fig. 2(b)). Considering the geometrical area of the ring $A = \pi r_{avr}^2$, with $r_{avr} = 175$ nm, and the magnetic field periodicity $B_0 = 22$ mT, we have that the flux periodicity $\Phi = B_0 \pi r_{avr}^2$ is equal to Φ_0, in agreement with a conventional $h/2e$ quantization.

Oscillations of the resistance as a function of the externally applied magnetic field are observed in the range 78–82 K. The temperature dependence of the amplitude of these oscillations, ΔR, is shown in Fig. 3(a) (colored circles).

The most straightforward interpretation for these oscillations is the Little–Parks effect [3,23]. According to this model, the expected temperature oscillations should have an amplitude $\Delta T_C = 0.14 T_C (\xi_0/r_{avr})^2 \approx 1.5$ mK, with $T_C \approx 82$ K, defined at the onset of the superconducting transition, and $\xi_0 \approx 2$ nm. Since in the actual experiments one measures the resistance oscillations as a function of H rather than ΔT_C, it is possible to calculate the upper limit of the resistance amplitude predicted by the Little–Parks effect via the expression $\Delta R = \Delta T_C (\mathrm{d}R/\mathrm{d}T)$. The gray dashed line in Fig. 3(a) shows the expected Little–Parks ΔR. The discrepancy between the measured resistance amplitudes ΔR and those predicted by the Little–Parks effect is more than a factor 10.

These large magnetoresistance oscillations, which cannot be ascribed to classic Little–Parks oscillations, have been already observed in HTS nanoloops [11,24] and explained in terms of the vortex dynamics, triggering the resistive state in 3-dimensional nanowires. The analysis of the $R(T)$ curve of our nanoring confirms this scenario, since we have successfully fitted the resistive transition within the vortex-dynamics model. The energy barrier for vortex entry [25] is oscillatory, as a consequence of the interaction of the thermally excited moving vortices with the screening current circulating in the two arms of the ring, which is a periodic function of the externally applied magnetic field. The equation describing the temperature dependent amplitude of the magnetoresistance oscillations is [11]:

$$\Delta R \approx R_0 \left(\frac{\epsilon_0^r}{2k_B T} \right)^2 \frac{K_1(\gamma)}{(K_0(\gamma))^3}, \tag{1}$$

where $\epsilon_0^r = \Phi_0^2 w / (4\pi\sqrt{\pi} r_{avr} \mu_0 \lambda_P(T))$ is the characteristic energy of a vortex in a nanoring, $\lambda_P(T) = \lambda_L^2(T)/t$ the Pearl length, t the thickness of the ring arms, R_0 the resistance at the onset of the superconducting transition, K_0 and K_1 the zero-order and first-order modified Bessel functions of the first kind respectively and $\gamma = (E_v + E_0/4)/(2k_B T)$, with $E_v = (\Phi_0^2/(4\pi\mu_0\lambda_P(T))) \ln(2w/(\pi\xi(T)))$ the energy barrier for vortex entry, in the limit of zero bias. We have fitted the measured $\Delta R(T)$ with Eq. (1), by using λ_0 and ξ_0 as fitting

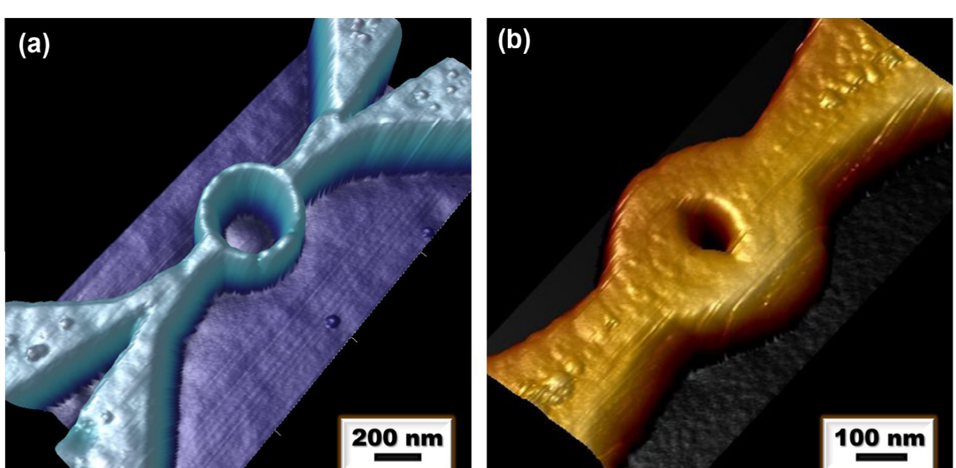

Fig. 1. (a) AFM picture of a typical 30 nm thick nanoring, with internal radius of 150 nm and a linewidth of 50 nm. (b) AFM picture of a wider nanoring (w = 160 nm), used for comparison.