Nanostructured Superconductive Sensors Based on Quantum Interference Effect for High Sensitive Nanoscale Applications

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Abstract. Recently it has been proven that the magnetic response of magnetic nano-objects such as nanoparticles, nanobeads, and small cluster of molecules can be effectively measured by using a Superconducting Quantum Interference Device (SQUID) with a small sensitive area. Here, we present a high sensitivity nanoSQUID based on deep submicrometer Josephson tunnel junctions fabricated by a Focused Ion Beam (FIB) sculpting method. The nanosensor consists of a niobium superconducting loop ($0.4 \times 1.0\ \mu m^2$) interrupted by two sandwich nanojunctions (Nb/Al-AlOx/Nb) having an area of about (300×300) nm^2. An experimental investigation of the main characteristics of such nanodevice as a function of the temperature is presented.

Keywords: Quantum sensor · nanoSQUID · Spin sensitivity

1 Introduction

In the last years, great efforts have been devoted to the development of Superconducting Quantum Interference devices (SQUIDs) having a flux capture area lower that 1 μm^2 [1–9]. In fact, it can be shown that the magnetic moment sensitivity increases by decreasing the SQUID loop area. Employing the nanofabrication techniques is possible to fabricate nanoSQUIDs having sensitive enough to explore new stimulating nanoscience topics such as the study of magnetic nanoparticles, single electron and molecular magnets. Typically a nanoSQUID consists of a submicron superconducting loop with two nano-constrictions acting as a Josephson elements (Dayem nanobridges) [1–4]. However, due to a non-sinusoidal current-phase relationship, a SQUID based on

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Dayem bridges exhibits a quite different behavior compared to a standard one based on Josephson tunnel junctions [10]. For this motivation, in the last years the researchers are developing nanoSQUID based on tunnel Josephson nano-junctions [1, 8, 9]. In this paper, we report niobium nanoSQUIDs based on sandwich nano-junctions and their characterization as a function of the temperature down to 300 mK.

2 Nanodevice Fabrication

The nanosensors reported here are realized joining two Josephson junctions with a Nb/Al-AlOx/Nb SNIS (Superconductor-Normal metal-Insulator-Superconductor) structure, through a nano-superconducting loop. These devices have been fabricated by means of a Focused Ion Beam (FIB) sculpting method, used as lithographic technique to define the various elements of the SQUID.

The entire technological process includes a few fabrication steps. At first, the Nb/Al-AlOx/Nb multilayered structure is patterned by optical lithography, deposited by a radio frequency sputtering system, in a high vacuum chamber, and subsequently defined by a lift-off procedure. The thickness of the two Niobium electrodes is 250 nm, while the Al layer is 6 nm thin, with an oxidation exposure of about 3700 Pa s. Afterwards, driving ion beam on the sputtered structure and opportunely orienteering the sample surface with respect to the beam trajectory, a multilayered lamella (around 400 nm) is realized through a consecutive removal of the material in excess, with the working surface perpendicular to the beam line. A rectangular hole ($1 \times 0.4\ \mu m^2$) was realized in the center of the strip, resulting in two parallel lamellae and defining both the Josephson junction's width and the loop of the nanoSQUID device. Afterwards the sample is oriented parallel to the beam trajectory and two side cuts through the two lamellae were performed defining the length of the junctions. Figure 1 depicts a sketch showing the main fabrication steps and a Scanning Electron Micrograph (SEM) image of a nanoSQUID. The aspect-ratio (ratio between the height and the width) referred to the single lamella is about 2, resulting in a three dimensional structure.

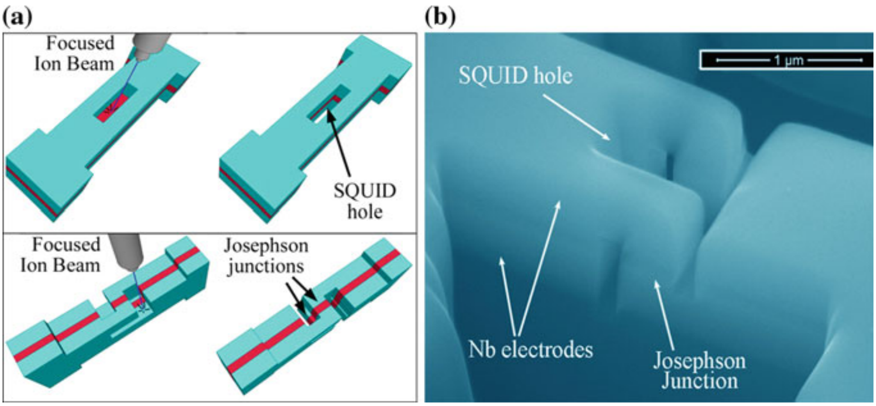

Fig. 1 **a** Sketch of the main fabrication steps of a nanoSQUID. The fabrication is based on a combination of the optical lithography and Focused Ion Beam (*FIB*) sculpting technique. **b** Scanning electron micrograph of a three-dimensional nanoSQUID

3 Characterization and Performances

The nanoSQUID characterization consisted in measurements of current-voltage characteristics, critical current versus external magnetic field and switching current distributions, for different temperature ranging from 9 K to 300 mK. The above measurements give us the behaviors of the critical current, of the modulation depth and of the magnetic flux noise as function of the temperature. In Fig. 2a, the current-voltage characteristics of the nanodevice for two temperatures are reported. The curves do not exhibit hysteresis for temperature higher than 4 K. It is due to both small critical current values as well thermal rounding. As expected, by decreasing the temperature, the β_c (hysteresis parameter) value increases and the hysteresis occurs. It becomes more evident by decreasing the temperature. However, the occurrence of the hysteresis does not prevent to employ the nanodevice as a high sensitive magnetic sensor [11]. The critical current as a function of the external magnetic flux (I_c-Φ) for different temperatures is shown in Fig. 2b. The curves show smooth maxima and cusped-like minima, nominally signature of a sinusoidal current-phase relationship, typical of standard SQUIDs [12]. From the figure is possible to obtain the current responsivity ($I_\Phi = \partial I_c/\partial \Phi_{ext}$) by taking the derivative of the I_c-Φ curves (Fig. 2b) at the point where the slope is steepest. The magnetic flux noise of the sensor is given by $\Phi_N = I_{c,N}/(\partial I_c/\partial \Phi_{ext})$ where $I_{c,N}$ is the measurement error of the critical current which can be obtained by measuring the switching current distributions (Fig. 3a). The $I_{c,N}$ can be assumed as the minimum current variation corresponding to two distinguished distributions. Performing small thermal shifts, we have measured an $I_{c,N}$ = 100 nA, which results independent on the temperature in the whole range of temperature investigated. In the Fig. 3b, the values of Φ_N as a function of the temperature is reported. The noise decreases by diminishing the temperature assuming a minimum value of about $1.4 \times 10^{-4}\ \Phi_0$ for T = 300 mK.

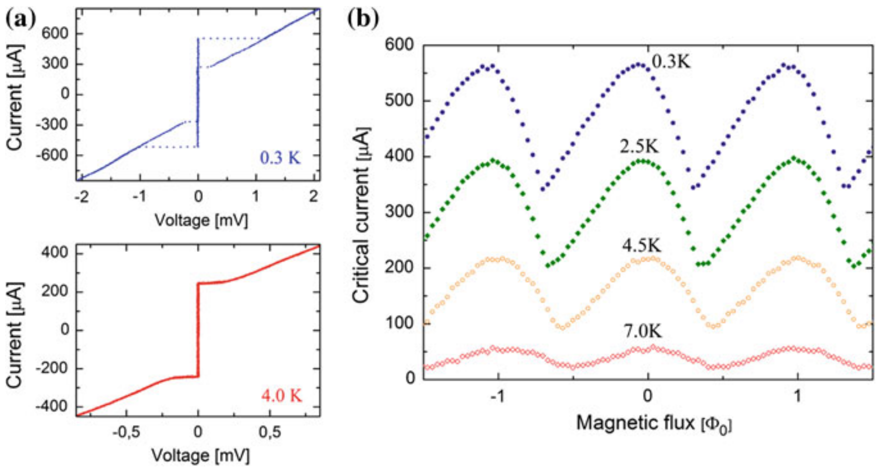

Fig. 2 **a** Current versus voltage characteristics of a nanoSQUID measured at two different temperatures. **b** Critical current versus magnetic flux curves measured at temperature ranging from 7.0 K to 300 mK

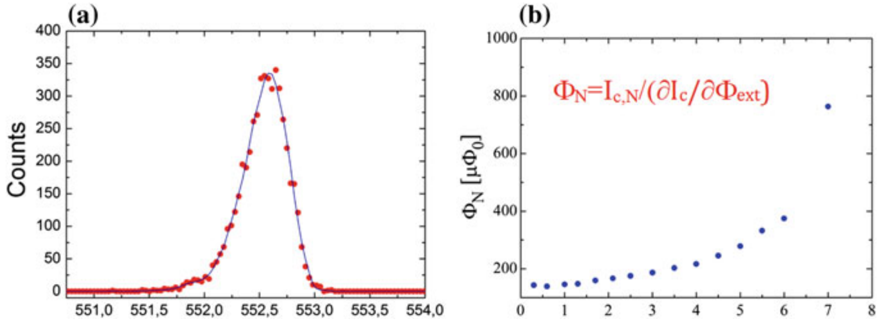

Fig. 3 **a** Critical current switching distribution of a nanoSQUID measured at 300 mK by using the time of flight technique [11]. **b** Magnetic flux noise of the nanosensor obtained by the ratio of the critical current resolution and the current responsivity

4 Conclusions

A fabrication and characterization of a quantum magnetic nanosensor has been reported. Measurements of current-voltage, critical current-magnetic flux characteristics and switching current distributions from the zero voltage state for different temperatures have been performed. The high critical current modulation depths and the low intrinsic dissipation exhibited by these devices ensure a suitable sensitivity for nanoscale applications in the whole temperature range investigated.

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