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Measurement of mesoscopic high-T_c superconductors using Si mechanical micro-oscillators

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Abstract

In a superconducting mesoscopic sample, with dimensions comparable to the London penetration depth, some properties are qualitatively different to those found in the bulk material. These properties include magnetization, vortex dynamics and ordering of the vortex lattice. In order to detect the small signals produced by this kind of samples, new instruments designed for the microscale are needed. In this work we use micromechanical oscillators to study the magnetic properties of a $Bi_2Sr_2CaCu_2O_{8+\delta}$ disk with a diameter of 13.5 μm and a thickness of 2.5 μm. The discussion of our results is based on the existence and contribution of inter and intra layer currents.

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Keywords: MEMs; Mesoscopic; High T_c

1. Introduction

The study of the vortex physics in mesoscopic samples [1,2] is difficult due to the need of instruments sensible enough to detect their signals. Sensitive instruments such as SQUIDs are not the best option because they are not designed to measure microscopic samples. The use of mechanical oscillators as magnetometers is not a new idea, they have been used successfully for this application for some time [3]. Our approach for studying mesoscopic high T_c samples is to use silicon micro-oscillators (following the work of Ref. [4]) which have a torsional mode with a resonant frequency $\nu_r \approx 45\,\text{kHz}$ and a quality factor $Q > 10^4$ at low temperatures. This instrument integrates high sensitivity and reduced size with a small signal loss, which is an important factor in the measurement of micron sized samples.

In this work we present the response of a micro-oscillator with a $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) disk mounted on top of it, in the presence of an external magnetic field H. The system (oscillator and sample) is shown in Fig. 1.

2. Experimental details

The mechanical micro-oscillator was manufactured at MEMSCAP [5] following the MUMPS specifications. It consists of a central plate connected to two serpentine springs which are anchored to the substrate. Below the plate two separate electrodes carry the electrical signals. The plate is electrically grounded and harmonically driven by one of the electrodes. The other electrode is used to detect the amplitude and phase of the mechanical oscillations capacitively. The plate and the detection electrode form a capacitor of $\approx 10\,\text{fF}$. The motion of the plate produces a variation in the capacitance $\delta C < 1\,\text{fF}$. A bias voltage $V_b = 1.6\,\text{V}$ is held constant in the capacitor and the current, proportional to δC is measured by means of a transimpedance amplifier and a lockin amplifier. This method diminishes the effect of the parasitic capacitances because V_b is constant. A sketch of the circuit is shown in Fig. 2. From the Lorentzian fit of the amplitude vs. frequency curve, ν_r and Q are derived.

The resonant frequency depends on the springs constant k and on the system's moment of inertia I:

$$\nu_r = \frac{1}{2\pi}\sqrt{\frac{k}{I}}. \quad (1)$$

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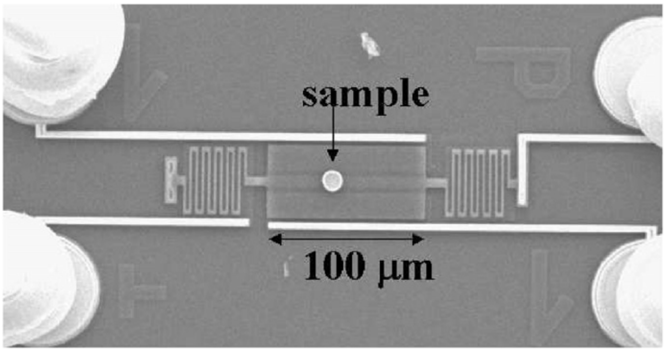

Fig. 1. Scanning electron micrograph of a high-Q mechanical oscillator with a BSCCO disk with a diameter of 13.5 μm and a thickness of 2.5 μm. The sample was glued by means of micro-pipettes and micro-manipulators.

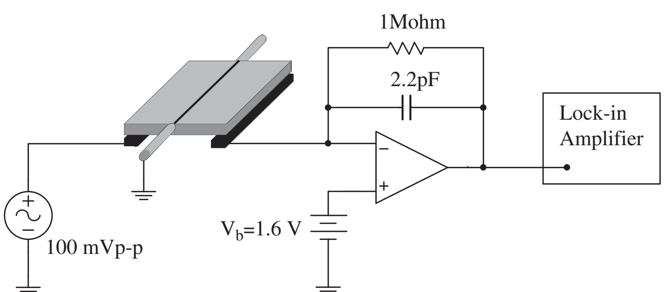

Fig. 2. System under study. The plate is driven by a sinusoidal voltage. The displacement is capacitively detected with a current–voltage converter and a lock-in amplifier.

After the sample is glued to the oscillator, the system's moment of inertia is modified. In our case, the sample is a single crystal BSCCO disk fabricated by lithographic techniques and ion milling. The frequency variation was $\Delta\nu_r = 868$ Hz in agreement with calculations (Fig. 3).

On the other hand, ν_r is also modified by variations in the effective k of the system. If the sample is magnetic, an external magnetic field H produces an additional torque

$$\vec{\tau} = (\vec{M} \times \vec{H})V = MHV \sin\theta, \tag{2}$$

where M is the magnetization, V is the sample's volume and θ is the angle between $\vec{M}$ and $\vec{H}$. For small θ

$$\tau = MHV\theta = k_s\theta. \tag{3}$$

The effective k_e is obtained by adding k_s to the spring constant k. As a consequence, the resonant frequency increases (decreases) if this torque is restoring (not restoring). The size, geometry and anisotropy of the sample play an important role in the magnitude and direction of its magnetization M. For example, in a spherically symmetrical sample which is in the Meissner state, M remains antiparallel to H during the whole period of oscillation and the magnetic torque is zero ($k_s = 0$).

A more complete analysis of the system response can be made by supposing a constant current flowing in a coil placed on the oscillator in the presence of H. The coil carries the original current plus any current induced by the tilt of the oscillator and generated by Lenz's Law. In this way, a change in the angle between the coil and the magnetic field produces a change in the induced current and therefore in the total current flowing in the coil. In Fig. 4(a) and (b) we sketch the case where H and the coil are perpendicular to the plate. The original current in the coil generates a magnetic moment m that interacts with H exerting an additional torque, which is restoring (not restoring) when m and H are parallel (anti-parallel). The induced current in the coil produced by the tilt of the oscillator is proportional to $1 - \cos\theta$. On the other hand, when the coil is parallel to the plate and perpendicular to H as in Fig. 4(c) the original *static* current produces a change

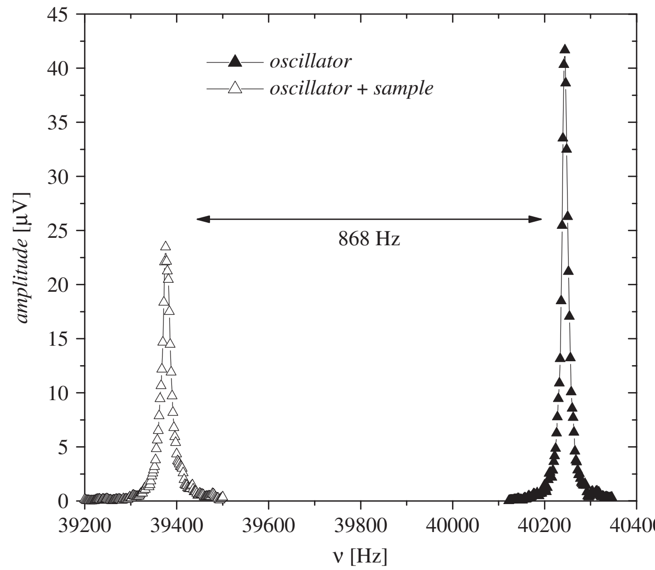

Fig. 3. Response of the oscillator with and without sample. When the sample is mounted on top of the oscillator the system moment of inertia increases and the resonant frequency decreases 868 Hz.

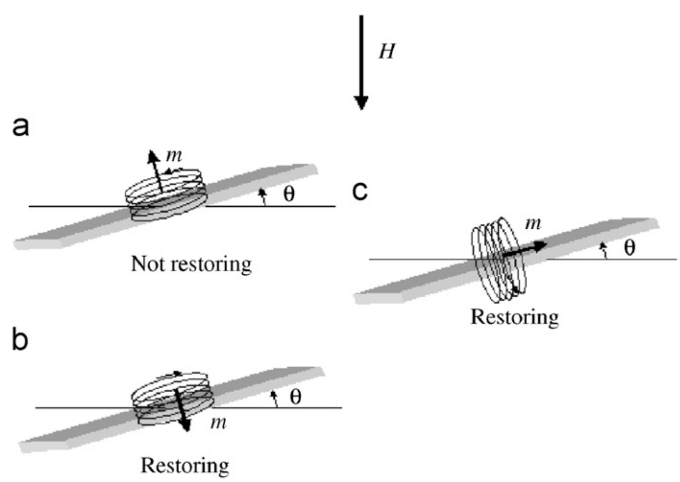

Fig. 4. Different behavior of the system when is applied an external magnetic field. Currents in the layers of the sample are depicted as a coil perpendicular to the plate and currents between layers as a coil parallel to it.