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$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ disk with a diameter of 13.5 microns and a thickness of 2.5 microns. The discussion of our results is based on the existence and contribution of inter and intra layer currents.

Key words: MEMs, mesoscopic, high $T_c$

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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 [4]) which have a torsional mode with a resonant frequency $\nu_r \approx 45$ 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$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (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.

![Fig. 1. Scanning electron micrograph of a high-Q mechanical oscillator with a BSCCO disk with a diameter of 13.5 microns and a thickness of 2.5 microns. The sample was glued by means of micro-pipettes and micro-manipulators.](image)

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 \( \delta C \), is measured by means of a transimpedance amplifier and a lock-in 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, \( \nu_r \) and \( Q \) are derived.

The resonant frequency depends on the springs constant \( k \) and on the system’s moment of inertia \( I \):

\[
\nu_r = \frac{1}{2\pi} \sqrt{\frac{k}{I}}.
\]

(1)

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 \( \Delta \nu_r = 868 \text{ Hz} \) in agreement with calculations (Fig. 3).

On the other hand, \( \nu_r \) 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

\[
\tau = (\vec{M} \times \vec{H})V = MHV \sin \theta,
\]

(2)

where \( M \) is the magnetization, \( V \) is the sample’s volume and \( \theta \) is the angle between \( \vec{M} \) and \( \vec{H} \). For small \( \theta \)

\[
\tau = MHV \theta = k_s \theta.
\]

(3)

The effective \( k_s \) 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 Fig. 4.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 in the angle of equilibrium $\theta_0$. However, the change in $k_e$ produced by this current is negligible if $\theta_0$ is small as in this case. The current induced by the alternating tilt of the oscillator produces a restoring torque proportional to $\sin \theta$. Finally, when $H$ is parallel to the oscillator the torque is restoring (not restoring) if $m$ and $H$ are parallel (anti-parallel). If $m$ and $H$ are perpendicular the current induced by the alternating tilt of the oscillator always produces a restoring torque.

The sample (BSCCO) has a layered structure. On mounting the disk, the Cu-O layers ($ab$ planes) are parallel to the oscillator. Following the previous description, currents in the layers can be associated with a coil perpendicular to the oscillator and currents between layers with a coil parallel to it.

3. Results

We did ZFC (zero field cooling) and FC (field cooling) measurements. The difference $\Delta \nu_r$ between $\nu_r$ measured with and without an applied $H$ reflects the magnetic response of the sample, eliminating any intrinsic effect in the oscillator produced by changes in temperature. When an external magnetic field is applied perpendicular to the $ab$ planes of the sample, Meissner currents appear. These currents screen $H$ causing a non-restitutive torque to the $ab$ planes of the sample, Meissner currents appear. These currents screen $H$ (as we already said in the previous section). The maximum deflection of the oscillator depends on the width of the plate and the minimum distance between the plate and the electrode before snap-down takes place. This phenomenon consist in the collapse of the plate with the bottom electrode and it happens when the deflection reaches a third of the equilibrium distance between them [6]. In our case the maximum possible $\theta$ is $\approx 1.5$ degrees giving a maximum change in $m$ of 0.035%. On the other hand, when $H$ is parallel to the layers $m$ is induced by the tilt of the oscillator (perpendicularly

4. Discussion and Conclusion

In the first case, when $H$ is perpendicular to the layers of the sample, $m$ is proportional to $1 - \cos \theta$ (as we
to the planes $ab$ of the sample) and is proportional to $\sin \theta$.

It is well-known [7] that in BSCCO 2D samples, the phase transition to the vortex state depends on the component of $H$ perpendicular to the $ab$ planes of the sample ($H_{\perp}$) and not on the component parallel to them. Considering an error of 0.4 Hz in the measurement of $\nu_r$ and from the curves of Fig. 5 we obtain $T_c(H_{\perp} = 2450e) = 78.7 \pm 0.7$ K. Due to the importance of pinning, in the ZFC measurement $\nu_r$ is smaller than in the FC measurement at low temperatures. When the temperature increases these two curves become closer, and for $T > 46.4 \pm 0.7$ K the behavior of the system is reversible. On the other hand, when $H$ is applied parallel to the sample (Fig. 6) the measurements are almost reversible in all the range of temperatures. In order to generate PVs, it is necessary to reach the critical angle for which the perpendicular component of $H$ equals $H_{c1}$. The maximum component of $H$ perpendicular to the $ab$ planes (appearing when the oscillator tilts) is of 6.5 Oe and, based on the observed reversibility, we can say that $H_{c1}$ is not reached.

These Si mechanical micro-oscillators are very sensitive magnetometers, suitable to study mesoscopic high $T_c$ samples. The change in the resonant frequency ($\Delta \nu_r$) can be positive or negative, depending on factors such as sample size, geometry and anisotropy. These factors determine how the currents and magnetic moments are generated in the sample.

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