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# Torque magnetometry in $YBa_2Cu_3O_{7-\delta}$ single crystals using high sensitive micromechanical torsional oscillator

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## Abstract.

We have developed a high-sensitive micro-torsional oscillators and fabricated with a standard silicon process, as a platform to study the low temperatures magnetic properties of micron sized samples. When the oscillator-sample system interacts with a magnetic field, the displacement of the oscillator from its equilibrium position can be detected as a small change in the capacitance ( $\approx 0.001$  pF).

We use this device to study the magnetic response of a thick twinned  $YBa_2Cu_3O_{7-\delta}$  disk when the magnetic field is tilted away from the c axis in the temperature range  $80\text{ K} < T < 100\text{ K}$  ( $T_c \approx 92\text{ K}$ ).

## 1. Introduction

Microelectromechanical torsional oscillators have previously been shown to be particularly useful for high sensitive measurements of small signals in a variety of nonmagnetic and magnetic experiments. These measurements include the de Haas–van Alphen oscillations [1], mesoscopic superconductors [2, 3] and Casimir effect [4, 5].

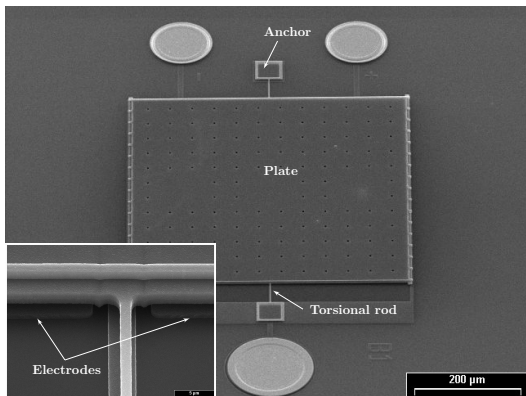
When the magnetic sample is affixed to a micromechanical oscillator and an external magnetic field is applied, the magnetic torque produces a measurable tilt of the oscillator. The magnetic properties of the attached sample can be extracted from of this change in the resonator[6].

In this work we present the response of a micro-oscillator with a  $YBa_2Cu_3O_{7-\delta}$  (YBCO) disk mounted on top of it, in the presence of an external magnetic field  $H$  for varying temperatures and angles.

## 2. Torsional oscillator

The polysilicon mechanical micro-oscillators, based on an original design by Chan *et al.* [4], was fabricated in the MEMSCAP [7] foundry using its Polysilicon Multi-User MEMS Processes (Poly MUMPS). The device consists in a  $500 \times 500\text{ }\mu\text{m}^2$  suspended central plate that is anchored to the substrate by means two torsional rods. Two independent electrodes under the plate at each side allow the measurement of the capacitance between electrodes and the plate. The nominal separation on rest between the plate and electrodes is  $2\text{ }\mu\text{m}^2$ . Photomicrograph images of the completed device are displayed in the Figure 1.





**Figure 1.** SEM image of the mechanical torsional oscillator. The inset shows a detail of the two electrodes located directly under the paddle. The gap between the electrodes and the paddle is fixed by the multilayer process and is  $2\mu\text{m}$ .

This structure has a variety of the possible modes of vibration. The torsional mode is the lowest in energy and will be the only one described in this paper as the device was designed for applications requiring torsional oscillations. In this normal torsion mode, i.e., not taken into account deformation of the arms, the restitution elastic constant for a torsion beam with an almost square profile  $w \simeq t$  can be calculated analytically [8]:

$$k = \frac{E}{2(1+m)l} \left[ \frac{w^3t + wt^3}{6} \right] \quad (1)$$

where  $l$ ,  $w$  and  $t$  are respective length, width and thickness of the torsion arms. For polysilicon the Young's modulus is  $E = 158\text{ GPa}$  and the Poisson's ratio  $m = 0.28$ . The total torsional elastic constants for different designs are show in Table 1.

The normal torsion resonance frequency is given by

$$\nu_0 = \frac{1}{2\pi} \sqrt{\frac{k}{I}} \quad (2)$$

where  $I$  is the moment of inertia of the full structure along the rotational axis,  $\approx 4.23 \cdot 10^{-17}\text{ kg} \cdot \text{m}^2$ . Using this value in (2) we obtain  $\nu_0 \approx 2\text{ kHz}$ . To validate this analytical solution we compare with the results from the modal analysis obtained by finite element method simulations (FEM 3D) of the proposed device.

**Table 1.** Elastic constants to different designs ( $w = t \approx 2\mu\text{m}$ )

| Design | rods | Length( $\mu\text{m}$ ) | $k(\text{N} \cdot \text{m} \cdot \text{rad}^{-1})$ |
|--------|------|-------------------------|----------------------------------------------------|
| A      | 2    | $l \approx 15$          | $4.38 \cdot 10^{-8}$                               |
| B      | 2    | $l \approx 25$          | $2.63 \cdot 10^{-8}$                               |
| C      | 4    | $l \approx 200$         | $5.41 \cdot 10^{-9}$                               |

### 3. Capacitive Detection

When a sample is mounted and affixed to the center of polysilicon plate both rotate together. In practice, this rotation can be detected measuring the capacitance between the mobile plate and each fixed electrode (Fig 2). The plates of this capacitor are no longer parallel, however we

can approximate it by a combination of  $N$  differential parallel plate capacitors with length  $L$  and infinitesimal width  $dr$  [9]:

$$dC = \frac{\epsilon_0 L \cos(\phi) dr}{g(r)} \quad (3)$$

where  $g(r) = h_0 + r \tan(\phi)$ . Taking the limit  $N \rightarrow \infty$ , the total capacitance is then given by

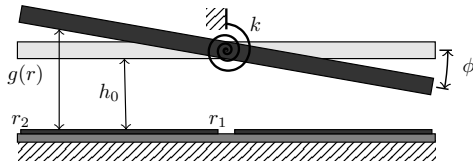
$$C = \frac{\epsilon_0 L}{\sin(\phi)} \ln\left(\frac{h_0 + r_2 \tan(\phi)}{h_0 + r_1 \tan(\phi)}\right) \quad (4)$$

This equation can be solved numerically to obtain  $\phi$  from capacitance data.

The torsional rods provide a restoring torque  $k\phi$  to counter an external torque on the top plate. In the case of anisotropic magnetic samples the existence an external magnetic field  $\mathbf{H}$  non parallel to the sample magnetization produces a torque:

$$\tau = \mathbf{M} \times \mathbf{H} = MVH \sin(\alpha) = k\phi \quad (5)$$

where  $M$  is the magnetization,  $V$  is the sample's volume and  $\alpha = \theta_H - \phi$  is the angle between  $\mathbf{M}$  and  $\mathbf{H}$ . In equilibrium, the magnetic torque and the restoring torque  $k\phi$  are equal (stable condition).



**Figure 2.** Schematic view of the mechanical torsional micro-oscillator. The width of the electrode is  $r_2 - r_1$  with  $r_1 = 4 \mu\text{m}$  and  $r_2 = 249 \mu\text{m}$ .

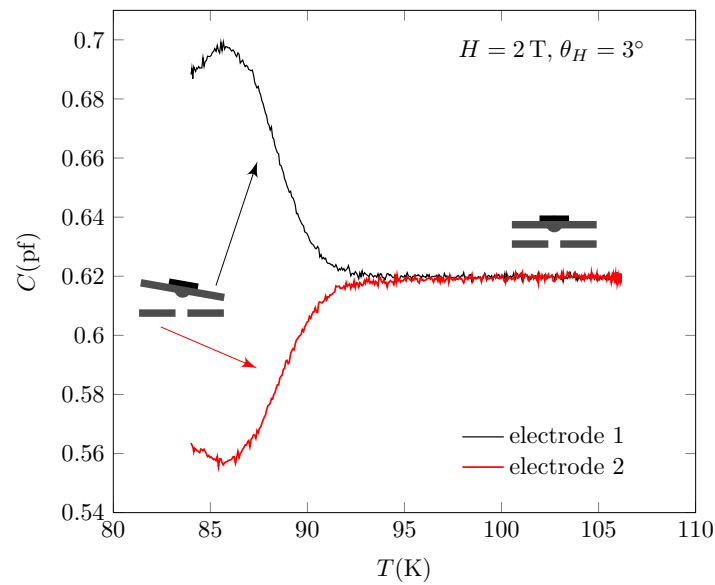
#### 4. Measuring YBCO samples with the micro-oscillators

The microoscillator–sample system is mounted onto a rotatable sample holder with an angular resolution of  $\theta \approx 0.05^\circ$  inside a cryostat with a superconducting 18 T magnet. In this experiment have been used YBCO twinned single crystals, grown using the flux growth technique (the details of the heat treatments are described in Ref.[10]). Disks of diameter  $100 \mu\text{m}$  and thickness  $8 \mu\text{m}$  were prepared using Ga ion-milling (FIB) in CNN Argonne National Laboratory.

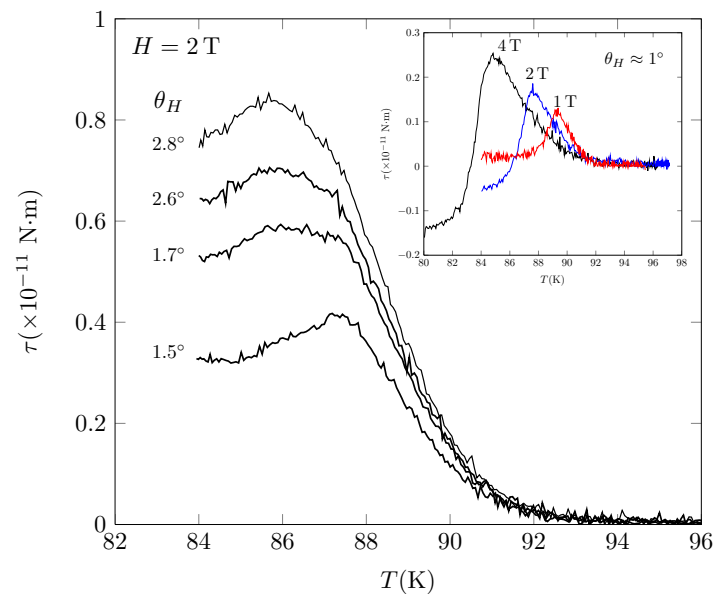
We did FC (field cooling) and FCW (field cooling warming) measurements. The changes in the capacitance were measured using a commercial high-precision capacitance bridge in a differential configuration. In the Fig.3 shows a measurement of the capacitance as a function of temperature in both electrodes with external magnetic field  $H = 2 \text{ T}$ . On measuring the capacitance in both electrodes allow us to subtract any time dependent drift usually found in low capacitance measurements.

The superconducting response of the YBCO disk was checked by measuring the torque as a function of temperature with the field  $H$  held constant. The result, shown in Fig. 4, provides a direct measure of  $T_c$  ( $= 92 \text{ K}$ ). With a torsional spring constant as small as  $5.41 \cdot 10^{-9} \text{ N} \cdot \text{m} \cdot \text{rad}^{-1}$ , the device yields a sensitivity  $\Delta\tau = 2.4 \cdot 10^{-13} \text{ N} \cdot \text{m}$  for torques acting at the plate. As  $\mathbf{H}$  is rotated away from the  $c$ -axis, the torque increases. This behavior is related to the progressive rotation of the magnetic moment, which yields a zero torque when fully aligned to  $\mathbf{H}$ .

From the inset Fig. 4 we can observe two different behavior on the temperature range and to a small angle  $\theta_H$ . First, the torque data are softly moved to lowest temperature as the magnetic field is increased, therefore  $T_c$  decreases slightly. On the other hand, as the temperature decreases (in the a FC protocol), the torque suddenly begins to decrease as from a  $T < T_c$ , indicating a change in the direction and magnitud of the magnetization.



**Figure 3.** Temperature dependence of the capacitance in both electrodes (differential configuration) for FC measurements with external magnetic field  $H = 2$  T. The magnetic field is initially (high temperatures) tilted  $3^\circ$  away from the c axis.



**Figure 4.** Temperature dependence of the torque of the twinned disk of YBCO for a succession of angles between  $H$  and  $c$ -axis. The magnetic field was held constant at 2 T. Inset: Temperature dependence of the torque for different applied magnetic fields.

## 5. Conclusion

The Si mechanical micro-oscillators proposed here with rectangular plate and thin torsion bars are suitable to measure high  $T_c$  samples with high sensitivity. Detection of torques of  $\approx 2.4 \cdot 10^{-13} \text{ N} \cdot \text{m}$ , corresponding to a magnetic moment of  $\approx 2.4 \cdot 10^{-13} \text{ A} \cdot \text{m}^2$  at 1T has been achieved.

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