CMOS Cantilever Microstructures As Thin Film Deposition Monitors

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Abstract

Increasing the mass of an oscillating microcantilever causes a decrease in its vibrational resonant frequency. We have deposited MgF_2 on our CMOS designed cantilever-in-cantilever microdevices and observed the resonant frequency decrease linearly with layer thickness. With initial results showing a sensitivity on the order of Ångstroms, such devices demonstrate potential for novel application as thin film monitors.

1 Introduction

Accurately monitoring changes in thickness of material during a thin film deposition is critical for the manufacture of semiconductors and optical components. Typically, thin film monitoring is accomplished by placing a quartz crystal next to the target [1]. The change in resonant frequency of the crystal over time is monitored and then correlated to the thickness of material accumulated on the crystal, and hence on the sample. However, each crystal must be replaced after only a relatively limited amount of material has been deposited. Our cantilever-in-cantilever (CIC) devices, which resonate in the 5 – 20 kHz range, show a linear decrease of resonant frequency with deposited layer thickness, and preliminary results indicate that they can be subjected to multiple depositions. Applications of resonating microdevices include pressure [2], humidity [3], and etch progress sensing [4]. Our proof-of-concept experiment demonstrates that our CICs have novel application as simple, inexpensive, and highly sensitive thin film deposition monitors.

2 Device Description

A magnetically actuated single CIC structure is sketched in Fig. 1. The approximate dimensions of the entire structure are 320μm x 280μm. The magnetic field **B** is oriented as shown.

Fabricated with the MITEL 1.5 μm CMOS process, CIC microstructures are nested cantilevers with a metal path running along the arms and across the end of the platform. The path conducts an alternating current that interacts with an externally applied magnetic field to produce deflection via a Lorentz force out of the plane of the device. The aluminum metal layers are typically 10 μm wide and 0.8 μm thick, and are separated by 0.8 μm of inter-metal oxide. The overall device thickness is approximately 5 μm. The magnitude of the bending is measured by the polysilicon piezoresistors at the base of the structure's arms [5].

Piezoresistors are resistors whose magnitude of resistance varies in proportion to the strain applied to them. Applying a constant current through and measuring the voltage across the piezoresistors directly measures this change in resistance. Hence, the voltage measured is related to the amount of bending of the structure.

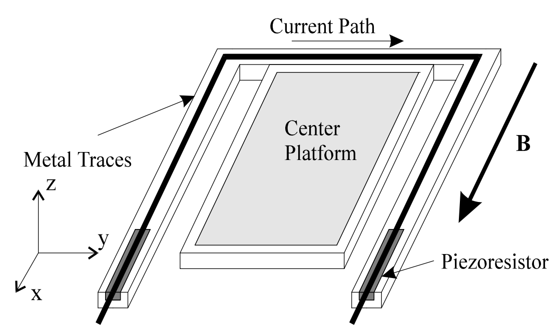

Figure 1. Single cantilever-in-cantilever microdevice.

3 Experiment

The experiment was set up as shown in Fig. 2.

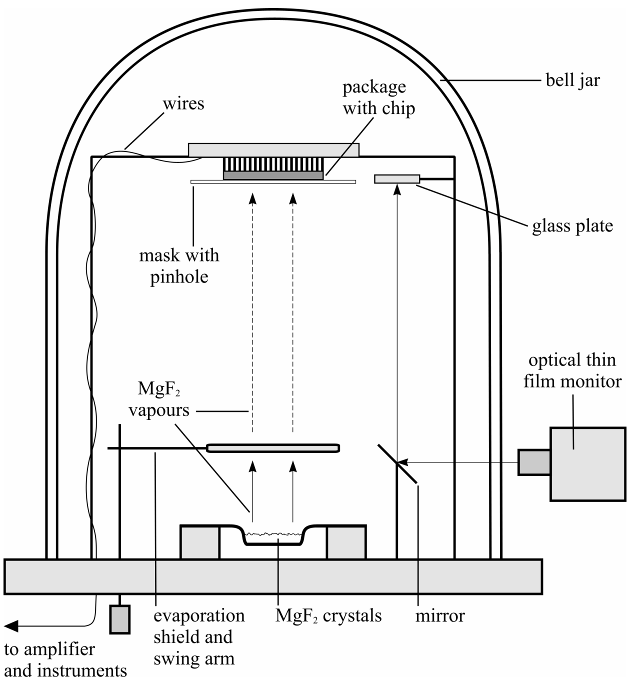

Figure 2. Experimental setup. The optical thin film monitor is used as a calibrator. The evaporation shield is used to control the deposition.

Throughout all trials, MgF_2 was the material used for deposition. MgF_2 is a commonly deposited substance, is inexpensive, easy to deposit, and has a relatively low evaporation point (~1200°C). During the first few trials we were restricted to depositing a nonconducting material such as MgF_2, since the entire chip (including the electrical pads) was exposed during the deposition. However, we later implemented a mask that exposes only the center platform to the deposition vapours, eliminating the non-conductivity requirement. Finally, since an optical thin film monitor was used as the calibrating device, a translucent material such as MgF_2 was required.

The mask itself is simply a piece of aluminum foil with a carefully formed pinhole whose diameter is approximately 150µm, less than the dimensions of the device platform. The hole is formed by lightly pressing the tip of a pin against a sheet of aluminum foil. The foil is then rotated around the tip of the pin several times. The pin tip "drills" through the foil, leaving a clean, symmetric circular hole. Next, the pinhole is lined up above the center of the device platform, and the foil is fastened in this position to the package on which the chip is mounted. The package is then suspended face down inside the vacuum chamber. A ceramic magnet is placed underneath the package and is positioned appropriately to produce a maximum field in the desired direction.

We define the resonant frequency of our microcantilever to be the frequency of the driving signal at which oscillation of the device reaches a maximum, i.e. the frequency at which maximum fluctuation in the signal across the piezoresistors occurs. Accurately finding such a value is easy, given ample time. However, during a deposition, the resonant frequency is constantly changing, and ideally a value should be found every few seconds. Under such time restraints, it is difficult to find the point of maximum signal amplitude. Fortunately, a 90º phase change between the AC actuating current and the piezoresistor voltage occurs when sweeping the driving frequency from one side of resonance to the other. The rate of this phase change reaches its maximum right at the resonant frequency. When the piezoresistor signal is viewed on an oscilloscope, the amplitude and the phase of the signal are both apparent, allowing one to find the resonant frequency quickly and accurately.

The piezoresistor signal has a small amplitude, on the order of millivolts. This signal is amplified using a two stage amplifier with a voltage gain of about 370, placed outside of the vacuum chamber. The resonant frequency is determined by examining this amplified signal.

4 Theory

Fig. 3 shows how sharp the frequency-response curve of the device is at high vacuum when compared to that at atmospheric pressure.

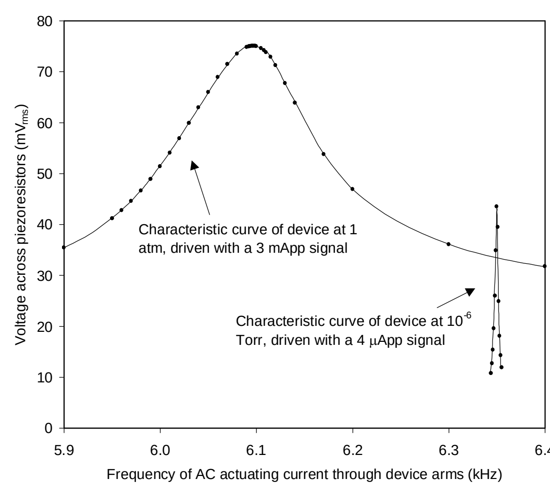

Figure 3. Low damping of CIC at 10^{-6} Torr.

This particular device has a Q factor of approximately 2400 at 10^{-6} Torr, compared to a value of 60 at 1 atm. We have found that other CIC devices at high vacuum have similarly large Q factors, with resonant frequencies that can easily be found to within 0.1 Hz. We therefore conclude that little internal damping exists in our CIC devices.

We propose the simple analogue of a mass suspended on the end of a massless spring. The natural frequency of such a system is given by

$$\omega_n = \sqrt{\frac{k}{m}} \tag{1}$$

where k is the stiffness of the spring and m is the suspended mass. Since the device experiences virtually no damping when placed under high vacuum, its resonant and natural frequencies must be nearly identical. If we assume that the mass per unit thickness of the deposited material is a constant λ, we can say that the total mass of the device as a function of d, the thickness of deposited material, is

$$m(d) = M_o + \lambda d \tag{2}$$

where M_o is the effective mass of the microcantilever. If we now also assume that the stiffness k of the device remains constant during deposition, we can write

$$\omega_o(d) = \sqrt{\frac{k}{M_o + \lambda d}}\,. \tag{3}$$

Since M_o is much greater than λd, the mass deposited, we can use the binomial theorem and consider only the first order term to obtain

$$\omega_o(d) \approx \sqrt{\frac{k}{M_o}}\left(1 - \frac{\lambda}{2M_o}d\right). \tag{4}$$

Therefore, to a first approximation, the resonant frequency of the device should vary linearly with the thickness of material deposited, and as material is deposited, the resonant frequency should decrease.

5 Results and Discussion

We have found that if material is deposited over the entire surface of the device, including the arms, the resonant frequency first increases and then decreases. Fig. 4 shows a typical plot of this nonlinear dependence of resonant frequency on film thickness.

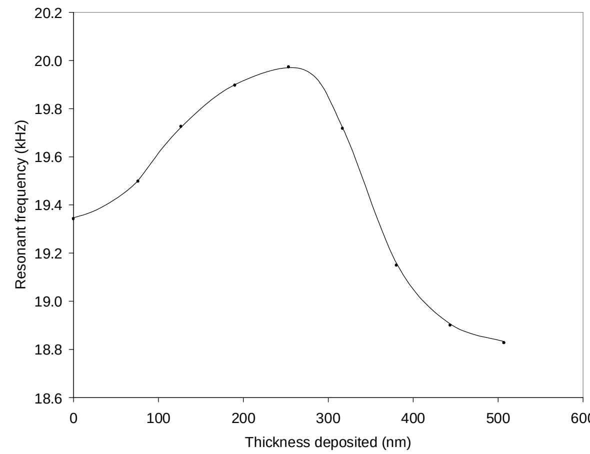

Figure 4. Resonant frequency vs. thickness deposited with arms exposed.

We surmise that the stiffness and the mass of the device were increasing simultaneously during the first half of the deposition, and that the stiffness of the device was increasing faster than its mass, causing an increase in the resonant frequency. Inspection of the MgF_2 film on the arms after deposition revealed cracks. Cracking in the film causes a decrease in the stiffness of the device. Since the mass of the device is still increasing while this cracking is occurring, the resonant frequency begins to decrease. This helps explain the nonlinearity of Fig. 4. In an attempt to make the resonant frequency dependent only on the mass of the device (and hence the thickness of the deposited material), the arms of the device were masked off. This had the desired effect, as shown in Fig. 5.

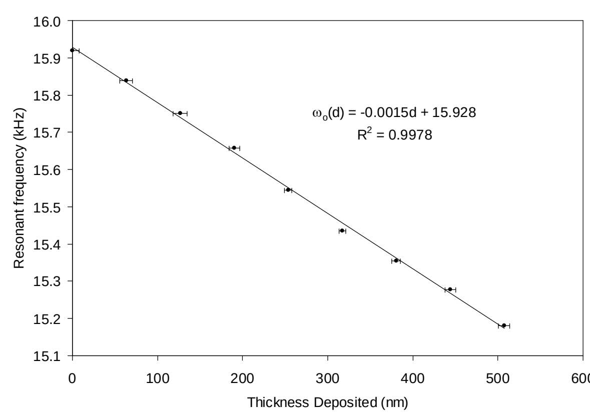

Figure 5. Resonant frequency vs. thickness deposited with arms masked.

The plot shows the variation of resonant frequency with thickness for a single CIC with only its central platform exposed during deposition, using the pinhole mask. The experimental points closely follow a decreasing straight line, as predicted by (4). Approximately 500 nm of MgF_2 was deposited, producing a 700 Hz change in resonant frequency. This gives a sensitivity of roughly 1.4 Hz/nm. Since the resonant frequency of the device at 10^{-6} Torr can be measured to within 0.1 Hz, the device's effective thin film thickness resolution is on the order of Ångstroms.

6 Conclusions

Our proof-of-concept experiment shows that the resonant frequency of a single cantilever-in-cantilever CMOS microdevice decreases linearly with the thickness of deposited material. This result agrees with what is predicted using the simple analogue of a mass on a spring. There now exists the potential for novel application of such a device as a simple, inexpensive, highly sensitive thin film deposition monitor.

Acknowledgments

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