CMOS Micromachined Capacitive Cantilevers for EFM-Based Mass Data Storage

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Abstract—This work presents the CMOS capacitive cantilevers intended for detecting charge-induced electrostatic force in an EFM-based data storage device. The cantilever can be electrostatically actuated and perform capacitive sensing of the resonant amplitude. Force detection in the nN range can be achieved through the sharp tips placed in close proximity with respect to the storage medium when reading a bit. The static characterization shows a measured capacitive sensitivity of \(2.4 \times 10^5 \) V/m at a gap of 1.6 µm, equivalent to an input-referred noise force of 0.054 nN/Hz\(^{1/2}\). The dynamic measurement shows the resonant frequency shift due to the increased electrostatic force averages 56 Hz/nN.

Keywords- cantilever; CMOS; capacitive sensing; tip

I. INTRODUCTION

Electrostatic force microscopy (EFM) and magnetic force microscopy (MFM) are the key techniques for direct imaging and manipulation of electric and magnetic domain structures at the nanoscale. Both techniques, when implemented as a scanning probe array, could lead to development of ultrahigh-areal-density storage devices. Prior work has explored various mechanisms based on tunneling [1], atomic force microscopy (AFM) [2], magnetic force microscopy (MFM) [3], and magnetoresistive effect [4]. EFM explores the electric field gradient and potential on the surface of a sample. Electrons or holes can be injected into a thin dielectric medium as stored bits and be read back by detecting the motion of the scanning probe resulting from the near-field force [5]. The force magnitude, based on the Coulomb’s law, is in the order of \(10^{-9}\) N for electrons or holes separated by a distance of tens of nanometers to a probing tip. Gwo [5] used a dual-modulation technique where the scanning cantilever was operated in the resonant mode, in order to distinguish between the charge-induced electrostatic force and other near-field forces.

Following the dual-modulation scheme presented in [5], this work adopts the CMOS MEMS technology for convenient integration of the sensing and actuation elements, leading to development of an EFM probe array with enhanced data throughput. Prior work has reported CMOS micromachined AFM cantilevers with integrated piezoresistive sensing and thermal actuation [6]. Our design uses capacitive detection due to its high sensitivity as a result of monolithic integration. Electrostatic actuation is used as a better option for driving cantilevers to resonance rather than electrothermal actuation. A higher storage density could be achieved with the high-aspect-ratio probe tips, which are better than the conventional conical or pyramidal shaped tips.

II. DEVICE FABRICATION

The TSMC 0.35-µm 2P4M CMOS process is used for device fabrication. As shown by the cross-sectional view in Fig. 1 [7], an anisotropic reactive ion etch with the top metal as the etch-resistant mask is first performed to remove the inter-metal dielectric layers until the silicon substrate is exposed. Then the structure was released by an isotropic silicon etch using the XeF\(_2\) gas. Sharp platinum tips are fabricated on the probe pad by electron-beam deposition. This serial process is performed in a combined focused ion beam/electron beam system (FEI Nova 200), in which a thin gas feed tube is placed in close proximity to the chip and within the scanning field of the electron. The probe pad has to be electrically grounded to provide a discharging path. The incident electron beam causes fragmentation of the precursor gas which leads to the deposition.

![Figure 1. Cross-sectional view of the CMOS micromachined process.](attachment:image.png)
III. DESIGN

The side-view schematic in Fig. 2 depicts the charge-reading mechanism in the EFM-based data storage device. The top silicon substrate is coated with a thin dielectric layer for storing positive or negative charges as the written bits. The cantilever below has dedicated metal plates for capacitive actuation and sensing with respect to the top electrode. For operation, the cantilever is first driven to resonance at the frequency $\omega_N$. A modulation signal at $\omega_c$ is applied to the top electrode for avoiding coupling feedthrough to the sensed signal. The sensed signal of the resonant amplitude, after demodulations at the frequencies of $\omega_c$ and $\omega_n$, represents the near-field tip-sample contact force. This signal is used for closed-loop feedback to maintain a proper tip-sample spacing. Another a.c. signal at the frequency $\omega_{EFM}$, which is lower than the resonant frequency $\omega_n$, is also applied on the top substrate to drive the cantilever. The interaction between the tip and stored charges affects the resonant amplitude at $\omega_{EFM}$, depending on the charge polarity, and forms the EFM read signal. The amplitude change at $\omega_{EFM}$ is much smaller than the previous signal at $\omega_n$, therefore closed-loop feedback is not required. Fig. 3 shows the top-view schematic of the cantilever design. The sharp tip would be located in the 5 $\mu$m $\times$ 5 $\mu$m probe pad. Each of the actuation and sensing plate has a size of 50 $\mu$m $\times$ 16 $\mu$m, producing a capacitance of 1.77 fF at a 4-$\mu$m gap with respect to the top electrode. Finite-element simulation [8] as shown in Fig. 4 is used to calculate the resonant frequency and spring constant of the microstructure, giving 36 kHz and 36.2 N/m for the cantilever with 3-meander springs, and 22.5 kHz and 15 N/m for the 7-meander case.

The sensing circuit as shown schematically in Fig. 5 contains two p-channel source followers that provide a voltage gain close to one. The circuit area is 130 $\mu$m by 40 $\mu$m. The use of PMOS input transistors helps to reduce the flicker noise at low frequencies. The first source follower uses a small-size input transistor to provide a small input capacitance. Despite large transistors are commonly used in conventional low-noise circuit design for reducing the transistor thermal noise and flicker noise, in this case, they also reduces the sensed signal owing to the increased gate capacitance. To our advantage, the interconnect capacitance can be greatly reduced as the sensing circuit can be placed near the cantilever. The d.c. path at the circuit input is provided by the transistor M5 operated in the subthreshold region. The second source follower with a larger input transistor is used for driving the output pad.

IV. EXPERIMENT

Fig. 6 shows the released cantilever structure with a sub-$\mu$m platinum tip on the probe pad. The structural curl was first measured by an optical profiler (FOGALE ZOOMSURF3D), with curl-up distances of 3.1 $\mu$m and 1.6 $\mu$m for the three-meander and the seven-meander cases, respectively. Laser Doppler Velocimetry (LDV) was used to measure the mechanical dynamic responses, giving resonant frequencies at 50.25 kHz and 24.03 kHz for the three-meander and the seven-meander cases. Fig. 7 shows the measured result of the latter. The experimental values are higher than those from simulations, which could be attributed to the underestimated structural thickness.
The pre-amp input capacitance was measured at 48 fF from a test circuit [9] by using an Agilent 4395A network analyzer. The measured pre-amp input-referred pre-amp thermal noise is 0.87 µV/Hz^{1/2} (-130 dBV @ resolution BW of 30 Hz) as shown in Fig. 8.

For electromechanical characterization of the cantilever resonant frequency under different electrostatic forces, we used a commercial AFM (Veeco CPII) where the AFM cantilever was flipped over with its flat backside as the top electrode as shown in Fig. 9. The top electrode overlapped one driving plate and one sensing plate, and tilting degrees between the AFM and EFM cantilevers was carefully adjusted. A modulation signal of 3 MHz and 10 V_{pp} was applied to the top electrode as it was gradually lowered down to the EFM cantilever. The measured pre-amp output with respect to the gap separation is shown in Fig. 10. The sensitivity is 2.4 × 10^5 V/m at 1.6 µm, producing an input-referred noise displacement of 0.036 Å/Hz^{1/2}. Thus the equivalent noise force is 0.054 nN/Hz^{1/2} based on a simulated spring constant of 15 N/m for the 7-meander case.

The change of cantilever resonant frequency due to electrostatic force gradient was monitored by applying different voltages between the cantilever and the top electrode. At a gap of 2.5 µm, we first applied a.c. signals of 10 V_{pp} from 10 to 40 kHz to the 80 µm × 16 µm actuation plate, and gave different d.c. biases and a 1.5-MHz modulation signal on the top electrode. The sensed signal was observed on the spectrum analyzer as the sidebands to the modulation frequency. Fig. 11 shows the modulated pre-amp output with respect to the scanning frequency at d.c. biases of 5 V and 10 V, respectively. The resonant frequency shift is 0.6 kHz, corresponding to an electrostatic force change of 28.3 nN based on the parallel-plate assumption. The measured sensitivity is 21 Hz/nN. Next, we repeated the same experiment by applying the a.c. signals to the 5 µm × 5 µm probe pad and grounding the actuation plate. The result in Fig. 12 shows the resonant frequency shift is 0.1 kHz, which corresponds to a force change of 1.8 nN. The measured sensitivity is therefore 56 Hz/nN.
V. CONCLUSION

In this work, capacitive cantilevers for detecting charge-induced electrostatic force are fabricated by a post-CMOS micromachining process, and the tips are deposited by a serial fabrication process. For mass production of the sharp tips, this die-level serial process has to be modified into a wafer-level process by using, for example, the lift-off technique [10]. The dielectric reactive etch can use photoresist as the etch-resistant mask to define the microstructures and to protect the tips. Monolithic integration of the sensing circuit greatly reduces the parasitic effect which would otherwise negatively impact the measured signal-to-noise ratio. Detection of electrostatic force change in the nN order, as needed for EFM-based data storage, has been demonstrated. For further improving the capacitive sensitivity and increasing the data rate, it is desirable to design a cantilever with a high resonant frequency. A smaller probe pad is also desired in the future to reduce the produced force from the far field.

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REFERENCES

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