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Simultaneous Capacitive and Electrothermal Position Sensing in a Micromachined Nanopositioner

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***Abstract*— This letter reports a micromachined nanopositioner with capacitive actuation together with capacitive and electrothermal sensing on a single chip. With the actuation voltage of 60 V, the electrostatic actuator can achieve a maximum displacement of 2.32 µm. The displacement can be simultaneously measured using capacitive and electrothermal sensors. Both sensors are calibrated to operate at a sensitivity of 0.0137 V/V. The electrothermal sensor is found to display *1/f* noise, which affects the low frequency measurements obtained from this device. However, at higher frequencies it displays a lower noise power spectral density when compared with the capacitive sensor. The comparisons of frequency responses, power consumptions, and noise performances are presented in this letter.**

***Index Terms*-Capacitive position sensing, electrothermal position sensing, micromachined nanopositioner, sensor fusion.**

I. INTRODUCTION

High precision nanopositioners have been used extensively in many applications such as scanning probe microscopy [1], atomic force microscopy [2], and emerging ultrahigh-density probe storage systems [3, 4]. Closed-loop feedback control of the positioners is highly desirable if a high degree of displacement precision is required, and such a control system needs an accurate source of position information [5, 6]. To detect the displacement of the microactuators, capacitive and electrothermal sensing is commonly adopted in the literature. Capacitive sensing offers excellent noise performance, when operated over a low bandwidth, and low power consumption. An embedded on-chip capacitive displacement sensor was integrated in a thermally actuated positioner in [7, 8], and sub-nanometers resolutions were obtained. Recently, a thermal sensing scheme was used in a probe-based storage device [9, 10]. Micro-heaters were used to measure the motion of a MEMS micro-scanner with resolution of less than 1 nm. Compared to a comb capacitive sensor, a thermal sensor is much more compact and can be easily integrated with actuators in a MEMS device [11]. Both capacitive and electrothermal sensing can achieve a good degree of positioning accuracy. However, a thorough comparison of the two sensing techniques cannot be found in the literature.

In this letter, in order to make a fair comparison between the two sensing methods, a 1DoF micromachined nanopositioer has been constructed in which displacements of a target object are measured with both capacitive and electrothermal sensors in the same micromachined device. The positioner stage was moved 2.32 µm by electrostatic actuation under 60 V dc. The capacitive sensor consists of a series of combs to measure the capacitance change due to the displacement. The electrothermal sensor comprises of a pair of silicon hot wires, whose resistances vary with the displacement of the positioner stage [12]. The comparisons of static responses, frequency responses, power consumptions, and noise performances of the two methods are presented here. The noise power spectral density (PSD) measurement show capacitive and electrothermal curves intersect at about 3.2 Hz.

II. DESIGN

The conceptual schematic view of the nanopositioner is presented in Fig.1. This positioner consists of a stage, a comb capacitive actuator, a comb capacitive sensor and an electrothermal sensor. The stage is moved by the capacitive actuator, and the displacement is detected by capacitive sensor and electrothermal sensor simultaneously.

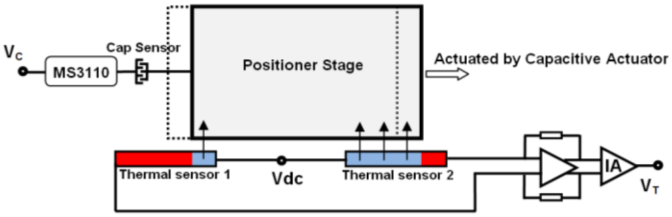

Fig.1. Schematic diagram of the nanopositioner with simultaneous capacitive sensor and electrothermal sensor.

The electrothermal position sensor consists of two beam-shaped resistive heaters made from single-crystal silicon [12]. Application of a fixed dc voltage across the heaters results in a current passing through them, thereby heating the beams. As a heat sink, a rectangular plate is placed beside the beam heaters with a 2 µm air gap. The displacement of the positioner stage can be detected by measuring the resistance difference between the two sensors. The differential changes of the resistance result in current variations in the beam resistors, and the currents are converted to an output voltage using two trans-impedance amplifiers and an instrumentation amplifier.

The displacement information is also detected by an integrated capacitive sensor. The capacitive sensor is made of a comb-shaped variable capacitor, whose capacitance is proportional to the displacement. The capacitance change is measured by a low noise capacitive readout circuit, MS3110 [13].

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III. EXPERIMENTAL RESULTS AND DISCUSSION

The device is micro-fabricated from single-crystal silicon using a commercial bulk silicon micromachining technology-SOIMUMP in MEMSCAP [14]. This process has a 25 µm thick silicon device layer and a minimum feature/gap of 2 µm. The Scanning Electron Microscope (SEM**)** image of the whole device and a zoomed image of the electrothermal sensor pair are provided in Fig.2.

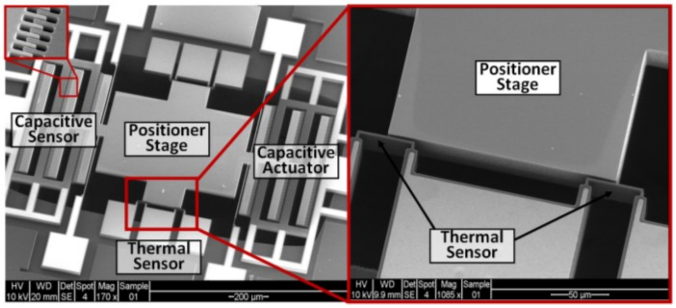

Fig.2. SEM images of the micromachined nanopositioner.

The nanopositioner was calibrated using a Polytec^{TM} Planar Motion Analyzer (PMA). Digital image capture and analysis methods were used to determine the displacement of the positioner stage. The static actuation voltage vs. displacement results are illustrated in Fig.3. With the actuation voltage of 60 V, the actuator can achieve a maximum displacement of 2.32 µm. The fitted linear curve shows that the actuator has a sensitivity of 39.6 nm/V. The linear relationship between displacement and actuation voltage is due to the combined effects of positive quadratic response of the comb actuation and negative quadratic response of the fixed-fixed beam when operated at large displacements [15].

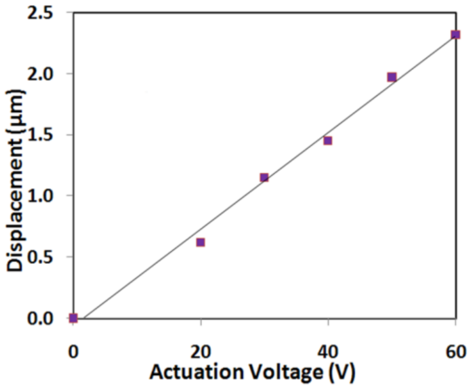

Fig.3. Experimental calibration results: positioner stage displacement versus actuation voltage.

The sensors are calibrated by measuring the two sensing signals simultaneously. In order for the two sensors to have identical sensitivities, the testing circuit's parameters were adjusted such that the overall gains of the two sensors were identical. As illustrated in Fig.4, both capacitive and electrothermal sensors display extremely similar static responses. The fitted linear curve shows that the sensor's sensitivity is 0.0137 V/V. As the electrothermal sensors are biased by a dc voltage of 4.8 V, the dc current passing through the resistive sensors causes a power consumption of 102 mW. By contrast, the capacitive sensor itself consumes almost zero energy since no dc current passes through the sensing capacitor.

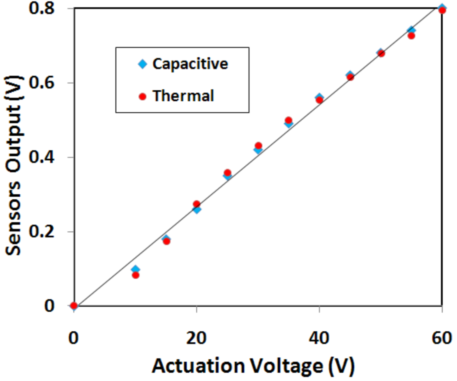

Fig.4. Experimental calibration results: sensor outputs versus actuation voltage.

The dynamic characterization of the device was conducted using a HP35670A spectrum analyzer. A voltage of 9.7 V dc plus 0.3 V ac was applied to the actuator and swept sinusoidal measurements were obtained from 10 Hz to 10 kHz. The frequency responses obtained from the capacitive and electrothermal sensors are plotted in Fig. 5. This figure illustrates that both sensors detected the first mechanical resonance frequency of 1.59 kHz. In electrothermal sensing, the effect of 50 Hz environmental noise can be observed in the frequency response curve. This, however, does not seem to appear in the capacitive sensor's frequency response. The reason is that the MS3110 board, used in conjunction with the capacitive sensor, adopts modulation/demodulation techniques to eliminate the low frequency noise. In particular, the capacitor output is first modulated by a 100 kHz carrier signal, followed by a low pass filter with 8 kHz cut-off frequency to eliminate the low frequency noises, including 1/*f* noise and 50 Hz noise, and then synchronously demodulated to recover the sensing signal only [12].

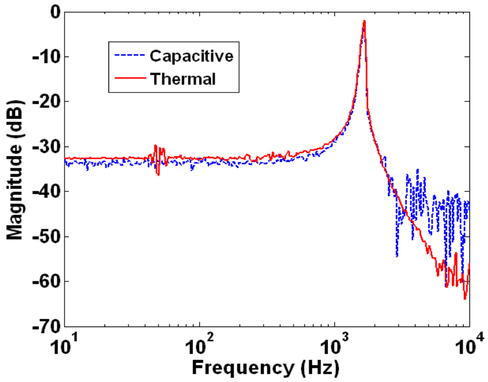

Fig.5. Nannpositioner frequency response measured by capacitive sensor and electrothermal sensor.

To characterize the noise properties of the two sensors without any interference from the actuation circuitry, the actuator was electrically grounded. Then the power spectral densities (PSD) of the two sensors were measured by a HP35670A spectrum analyzer from 1 Hz to 200 Hz. The resulting PSD plots are illustrated in Fig.6. The capacitive sensor's PSD is fairly flat due to the use of the modulation/demodulation technique and the filtering of the low frequency noise. This means that the wider the bandwidth over which this sensor is used, the more noticeable sensor noise will be. The electrothermal sensor displays a similar property at high frequencies. However, at low frequencies it is susceptible to significant 1/f noise. Power spectral density of the capacitive sensor was measured as 0.76 nm/√Hz. Also, beyond the frequencies over which the effect of 1/f noise is significant, the electrothermal sensor's PSD approaches 0.14 nm/√Hz. The two PSDs cross over at about 3.2 Hz, as shown in Fig.6.

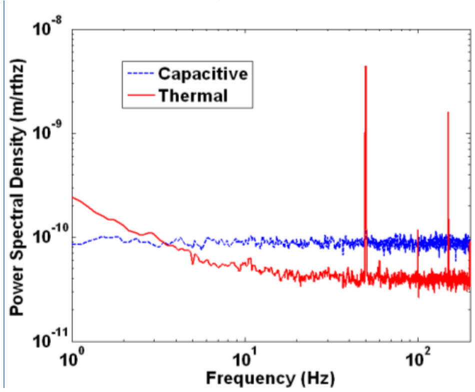

Fig.6. Measured power spectral densities of capacitive and electrothermal sensors.

The different noise profiles of the two sensing mechanisms presents an interesting possibility. At high frequencies, the electrothermal sensor is clearly the better sensing device, as far as sensor noise is concerned, However, at very low frequencies, the capacitive sensor is a better choice. Thus, both measurements can be combined, e.g. using a Kalman filter as described in [16] to obtain a "virtual sensor" that has a better noise profile than either of the two sensors. Such a sensor fusion scheme would use the capacitive sensor measurements at low frequencies and the electrothermal sensor readings beyond the cross-over frequency of 3.2 Hz.

To this end it is important to point out that electrothermal sensors can only be used over a limited bandwidth. Typically, beyond 10 kHz, electrothermal sensors are rather ineffective [17]. Capacitive sensors, however, can be used at much higher frequencies.

IV. CONCLUSIONS

A novel micromachined silicon nanopositioner with on-chip electrostatic and electrothermal sensors was designed to compare the two types of displacement sensing. Both sensors illustrated good position measurement capabilities. The comparisons of static responses, frequency responses, power consumptions, and noise performances were given. The electrothermal sensor was found to have a better noise profile at high frequencies. However, at low frequencies it is susceptible to significant flicker noise. The measurements obtained from the two sensors can be combined, in a sensor fusion framework, to obtain a virtual sensor with excellent noise properties.

To this end, we point out that the comparison presented here is limited to these two specific sensors. For other sensing methods, e.g. piezoresistive sensing, the noise properties would be different and dependent on the front-end electronics and sensor's geometry. A less noisy circuit may reduce the noise levels associated with both sensors. However, for electrothermal sensing, the 1/f noise will persist. Only the cross-over frequency may be lower or higher.

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