Displacement Sensing With Silicon Flexures in MEMS Nanopositioners

Abstract—We report a novel piezoresistive microelectromechanical system (MEMS) differential displacement sensing technique with a minimal footprint realized through a standard MEMS fabrication process, whereby no additional doping is required to build the piezoresistors. The design is based on configuring a pair of suspension beams attached to a movable stage so that they experience opposite axial forces when the stage moves. The resulting difference between the beam resistances is transduced into a sensor output voltage using a half-bridge readout circuit and differential amplifier. Compared with a single-piezoresistive flexure sensor, the design approximately achieves 2,22, and 200 times improvement in sensitivity, linearity, and resolution, respectively, with 1.5-nm resolution over a large travel range exceeding 12 μm.

Index Terms—Displacement sensor, nanopositioning, SOI-MEMS, piezoresistivity.

I. INTRODUCTION

Recent advances in micro-electromechanical systems (MEMS) such as scanning probe microscopy, probe-based data storage, microgrippers, and gyroscopes necessitate rapid development of in-situ sensors with reduced footprint, noise, and drift and increased bandwidth and dynamic range [1]–[3].

The piezoresistive effect refers to variations of the electrical conductivity in a material due to the mechanical stress. Semiconductor piezoresistivity has extensively been used to measure various physical quantities such as pressure, shear stress, acceleration, velocity, deflection, and displacement. However, fabrication of the requisite sensors usually involves expensive custom processes to create piezoresistors in selectively doped zones [4]. Few works have been reported on solid-state piezoresistive displacement sensors fabricated by standard micro-machining processes, where custom fabrication steps are not available to incorporate the conventional piezoresistors into the flexures. In [5], piezoresistive position transducers were fabricated through standard micro-machining processes in a variety of polysilicon beam shapes, where considerable nonlinear behavior was reported for bending beam sensors. In [6], a piezoresistive sensor was micro-machined adjacent to an electrothermal micro-actuator using a standard process with n-type polysilicon. Since the piezoresistors in [6] experience similar stresses, the sensor exhibits a nonlinear response. In [7] and [8], piezoresistivity of T-shaped flexures were used to detect vibration of the resonators fabricated through standard SOI-MEMS processes over extremely small displacement ranges.

This letter reports the fabrication of a novel displacement sensor in a flexure-guided MEMS nanopositioning through a standard single-crystal silicon SOI-MEMS fabrication process (SOIMUMPs [9]) based on the differential piezoresistive effect, where two piezoresistors experiencing axial forces with opposite signs are simultaneously employed. The piezoresistors also serve as structural flexures to suspend a scan table. Thus, the sensor footprint is almost zero. The proposed differential approach utilizes orientations of the suspension beams to exert opposite stresses on the piezoresistor pair rather than the differential method in [8], where piezoresistors have similar stresses and an interface circuit cancels the feedthrough signal from actuator to sensor. In contrast to the traditional sensors that use stresses generated on the surface of implanted piezoresistors [10]–[12], we employ the inherent axial forces generated in the existing suspension beams. This removes the need for doping certain zones to generate the piezoresistive effect. Note that in the few works using piezoresistors with axial forces, the displacement direction is in parallel with the axial force, significantly limiting the travel range [7], [8], [13]. However, the axial force and displacement directions are almost orthogonal to each other in the proposed design, allowing much larger strokes. Compared with the sensing method reported in [6], the differential operation demonstrates considerable improvement in sensitivity and linearity as well as lower noise and drift. Furthermore, our design benefits an electrostatic actuation mechanism with a larger stroke and a higher bandwidth without the adverse effect of thermal coupling from the actuator. Using an advanced Micro-System-Analyzer (MSA), we investigate the dynamic response of the sensor and compare it with the actual displacement.

II. SENSING MECHANISM

Figures 1(a) and (b) show SEM image and schematics of the proposed sensor in a nanopositioner, where two straight suspension beams, designated as piezoresistors $R_{p1}$ and $R_{p2}$, differentially measure the x-axis displacement of the stage. The stage is movable along the x-axis in both directions by comb drives. As shown in Fig. 1(b), the undeflected sensing beams have an angle of $\delta = 0.86^\circ$ with respect to the y-axis in opposite directions so that the lower ends of the piezoresistors are oppositely displaced by $\Delta = 15 \mu m$ along the x-axis, which is more than the expected stroke limits of $\pm10 \mu m$. This inclination was selected to allow for a large travel range and avoid buckling suspensions. As the stage is displaced, one piezoresistor experiences axial tensile force while the other is compressed; see Fig. 1(b); thus, their resistances change, oppositely. The resistance difference is amplified as the measured displacement by the readout circuit in Fig. 2. A pair of similar suspensions on the other side of the stage serve to complete the guidance mechanism along the x-axis. On top of these suspensions and the stage, we opted to deposit a 500 nm gold layer to electrically ground the moving combs and the lower ends of the piezoresistors. A pair of similar piezoresistors are available on the chip as dummy resistors, which experience no mechanical stresses and complete the Wheatstone bridge legs in the readout circuit.

A differential actuation mechanism allows us to compensate for the quadratic nonlinearity in the electrostatic force-voltage characteristics of the comb drives [14], [15]. Since the stage and rotor combs are electrically grounded, we augment the actuation signals $\pm v_a$ by
III. CHARACTERIZATION

For static characterization of the sensor output voltage $v_o$ versus the MSA measured displacement, we apply a slowly varying triangular waveform as the actuation signal with $v_q = 30$ V and $v_b = 4$ V. The voltage-displacement characteristics corresponding to rising and falling periods of the triangular actuation are shown in Fig. 3. Note that the sensor output voltage linearly changes with the displacement in a travel range exceeding 12 microns with no hysteresis.

To confirm that the linear response of the sensor is achieved by the differential sensing, we bypass one of the piezoresistive suspensions in the Wheatstone bridge. Since the piezoresistive suspensions are not removable, we apply a constant voltage source to one midpoint of the bridge to null any voltage variation due to piezoresistivity at the amplifier’s non-inverting input, as indicated in Fig. 2. For this experiment, we opted to use primary cells as the constant voltage sources of the bridge. Using two switching power supplies in the bridge creates excessive noise at the sensor output due to their uncorrelated switching noises, which are amplified by the readout circuit. With a bias voltage of $v_b = 6.3$ V for the modified bridge, the resulting static characteristic of the sensor is shown in Fig. 3, where that of the original bridge biased by the same cells is also included. Clearly, the differential sensing significantly improves the linearity and sensitivity of the sensor.

As a reference for dynamic characterization, we measured the frequency response of the stage from the differential actuation signal $v_a$ to the actual displacement detected by the MSA, directly. Fig. 4 shows the results along with those of the differential piezoresistive sensor output with $v_b = 4$ V, where similar actuation signals were used during both tests. As the frequency is increased, the sensor response closely follows the displacement up to 7 kHz, indicating a sensing bandwidth well above the useful mechanical bandwidth of the nanopositioner, which is below its 3 kHz resonant frequency.

As the frequency increases, the sensor response gradually deviates from the displacement as indicated in Fig. 4. This is mainly due to non-zero resistance of the suspensions with gold layers ($\approx 5\Omega$) connecting the piezoresistors to the ground and also the reduction of comb drive impedances with increasing frequency. To confirm this assertion, we switched off the bias voltages ($v_q = 0$) in the differential actuation system to keep the displacement virtually zero while measuring the sensor response to the actuation signal. As shown in Fig. 4, the frequency response of the sensor under the zero
displacement condition matches well with the original sensor data beyond the sensor bandwidth. Hence, the deviation is mainly due to the electrical coupling from the actuator to the sensor rather than a dynamic relationship between the displacement and the axial forces in the piezoresistors. Similar electrical couplings from electrothermal or piezoelectric actuators to built-in piezoresistive sensors are reported in [6] and [17].

Fig. 5 shows the time histories of the sensor output with zero actuation signal using the differential and non-differential sensing approaches with the bridge biased by the foregoing batteries. The sensitivities and resolutions of these sensors are reported in Table I. Compared with the non-differential method, the differential approach reduces the sensor noise and drift and improves on sensitivity and resolution, considerably. Furthermore, due to the highly doped nature of the top layer of the SOI chip [9], [18] and the sensing bridge being fabricated through standard micro-machining SOI-MEMS processes.

IV. Conclusion

A built-in differential displacement sensor with almost zero footprint was presented based on the piezoresistivity of entire suspension beams employed in a flexure guided nanopositioner, which can be fabricated through standard micro-machining SOI-MEMS processes. The differential action was achieved through a novel design of a flexure pair experiencing opposite axial forces orthogonal to the measured displacement while avoiding buckling. Compared with the non-differential approach, considerable improvement on linearity, sensitivity, resolution, and reduction of noise and drift are obtained by the differential method. Although, electrical coupling from actuator to sensor limits the sensor bandwidth to 7 kHz, it is well above the mechanical bandwidth of the device.

TABLE I

<table>
<thead>
<tr>
<th>Sensor Settings</th>
<th>Sensitivity (mV/μN)</th>
<th>3σ-Resolution(μm)</th>
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<tr>
<td>Differential-6.3V Cells</td>
<td>172</td>
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<tr>
<td>Non-differential-6.3V Cells</td>
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<td>319</td>
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<td>Differential-4V Supply</td>
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REFERENCES