SINGLE-MASK THERMAL DISPLACEMENT SENSOR IN MEMS

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Abstract — In this work we describe a one degree-of-freedom microelectromechanical thermal displacement sensor integrated with an actuated stage. The system was fabricated in the device layer of a silicon-on-insulator wafer using a single-mask process. The sensor is based on the temperature dependent electrical resistivity of silicon and the heat transfer by conduction through a thin layer of air. On a measurement range of 50 µm and using a measurement bandwidth of 30 Hz, the 1-sigma noise corresponds to 3.47 nm. The power consumption of the sensor is 209 mW, almost completely independent of stage position. The drift of the sensor over a measurement period of 32 hours was 32 nm.

Keywords : MEMS, thermal displacement sensor, silicon resistivity, lumped model, SOI, manipulator, precision stage

I - Introduction

The trend towards smaller and more accurate systems stimulates the use of MEMS applications with integrated actuators and sensors. An electrostatic comb-drive actuator is often used for the actuation of an elastically straight-guided stage. Position sensing in MEMS is often based on the varying capacitance between the fixed world and an actuated stage [1]. Some alternative position sensors use integrated optical waveguides [2], the piezoresistive effect [3], or varying thermal conductance [4, 5, 6]. Lantz et al. [4] demonstrate a thermal displacement sensor achieving nanometer resolution over a 100 µm range. However a multi-mask production process and manual assembly were needed to fabricate this displacement sensor together with a stage. In this work we present the design, fabrication and experimental validation of a thermal displacement sensor integrated with an actuated stage in a single-mask production process.

The thermal displacement sensor consists of two U-shaped resistive heaters in a differential configuration, as schematically shown in figure 1. A differential sensor configuration is chosen to make the sensor less sensitive to changes common to both heaters, like ambient temperature and air humidity. The temperature distribution over the heaters depends on the stage position, because an increased overlap of the heater with the stage causes increased cooling of the heater towards the stage. Heat transfer to the stage is dominated by thermal conductance through air. The electrical resistivity of silicon is highly dependent on temperature and therefore the electrical resistance of the heater is a measure for the stage position. Applying a constant voltage to both heaters, the stage displacement is measured by the difference in current through the heaters. The temperature dependent electrical resistivity of highly p-doped silicon (\(\approx 2 \times 10^{18} \text{ cm}^{-3}\)) is given by [7] and is shown in figure 2.

II - Modelling and design

A lumped-element model of the thermal sensor is created in 20-sim [8] in order to obtain a dynamic multi-physics model. The model elements, shown in figure 3, include among others the non-linear temperature dependent electrical resistivity of silicon, the temperature dependent thermal conductivity of silicon and the temperature dependent thermal conductivity of air. The elements of the model consist of a heat capacity coupled to an electrical resistance. The temperature of the heat capacity (\(^\circ\text{C}\)) determines the electrical resistance (\(\Omega\)) which in turn determines the dissipated power in the heater element. The model is used for the determination of several design parameters with respect to the sensor
sensitivity, power balance and temperature profile over the heaters. The lumped element model has been verified by finite element modelling in COMSOL Multiphysics [9].

The heater dimensions are chosen such as to maximize the power flow towards the stage with respect to the input power and the heater resistance. The length of the heater legs influences the thermal conductance and therefore the power flow towards the bondpads and directly towards the substrate. The heater legs have a length of 100 µm and the sensing part has a length of 60 µm, which limits the measurement range of the sensor. Minimum feature size and minimum trench width are both 3 µm, dictated by the DRIE process. The heater width and air-gap between the heaters and the stage therefore are 3 µm. The height of all structures is 25 µm, defined by the SOI device layer thickness.

Table 1: Power balance for the differential sensor configuration at maximum deflected position for a fixed heater voltage of 7.7 V. In maximum deflected position of the stage, one of the heaters has no overlap with the stage and the other heater has full overlap with the stage.

<table>
<thead>
<tr>
<th></th>
<th>Heater 1: No overlap (mW)</th>
<th>Heater 2: Full overlap (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage</td>
<td>0.56</td>
<td>6.29</td>
</tr>
<tr>
<td>Bondpads</td>
<td>78.93</td>
<td>77.92</td>
</tr>
<tr>
<td>Substrate</td>
<td>21.75</td>
<td>19.60</td>
</tr>
<tr>
<td>Radiation</td>
<td>0.09</td>
<td>0.07</td>
</tr>
<tr>
<td>Total</td>
<td><strong>101.33</strong></td>
<td><strong>103.88</strong></td>
</tr>
</tbody>
</table>

At an operating voltage of the heaters of 7.7 V and at maximum deflection of the stage, heater 1 at no overlap and heater 2 at full overlap, the power flow from heater 1 to the stage is 0.56 mW and the power flow from heater 2 to the stage is 6.29 mW. The power balance of the differential sensor configuration is shown in table 1. It shows that most of the power supplied to the sensor will be lost towards the bondpads and directly towards the substrate. Heat transfer due to radiation is negligible in this configuration.

Using the 20-sim lumped-element model, the temperature profile over the heater is modelled, figure 4. From no overlap to full overlap it is clear that the heat flow towards the stage increases and therefore the temperature of the heater decreases. At no overlap the maximum temperature is 712 K and at full overlap the maximum temperature is 664 K. As a result the resistance of a single heater drops from 585.1 Ω to 570.7 Ω for the given temperature profiles at no and full overlap respectively. This roughly corresponds to a sensitivity of 0.58 Ω/µm at 7.7 V heater voltage for the differential configuration.

III - Fabrication

The designed sensor was micromachined in a SOI wafer with a highly boron-doped (≈ 2·10¹⁸ cm⁻³) device layer of 25 µm thickness and a buried oxide layer of 1 µm. Aspect-ratio controlled deep-reactive-ion etching (DRIE) was used to etch through the full device layer of the wafer. The directional etching and resulting high aspect ratios are particularly useful for good mechanical behaviour of the leafsprings used for straight guiding the stage, resulting in low driving stiffness and high transversal and out-of-plane stiffness. A minimum trench width of 3 µm is used, restricted by the used DRIE process. A maximum trench width of 50 µm is used to prevent large variations in etch loading. Etch loading effects influence the etch rate and the subsur-
face profile development [11]. For this reason several etch compensation structures are included in the design.

After reactive ion etching, the structures were released from the substrate by isotropic etching of the buried oxide with vapour-HF. Thin structures (<10 µm) and perforated bodies are released from the substrate in this way. Large structures will stay mechanically fixed to the substrate, while being electrically isolated from the substrate due to the oxide layer. The resulting design is shown in figure 5. The fabricated devices are glued and wire bonded with thin aluminium wires to a PCB for measurement.

Figure 5: Top view, optical microscope image of the fabricated sensor with the stage in its rightmost position. ‘Etch structures’ are incorporated to increase the DRIE quality.

IV - Experimental results

A constant voltage is applied across both heaters. Due to varying stage overlap, the heater resistances and the resulting heater currents will change. The two heater currents are amplified using two equal current-to-voltage amplifiers. The second amplifier stage consists of a differential voltage amplifier in combination with a low-pass filter to reduce common noise. The stage deflection as a function of actuation voltage is measured by stroboscopic video microscopy measurements, performed with a Polytec MSA400 and its Planar Motion Analyzer software. Interpolation of the measurement data provides accurate information about the actual stage position at a specified actuation voltage. For a deflection of 25 µm an actuation voltage of around 80 V is required.

At a heater voltage of 9 V the displacement versus sensor amplifier output voltage was quasi-statically measured, shown in figure 6 (top). The sensor output varies between -0.776 V and 4.316 V, with an offset of 1.770 V due to an initial resistance mismatch of the two heaters. The resistance variation of a single heater over the measurement range of 48 µm is determined to be 25.3 Ω. In a differential configuration this results in a sensitivity of 1.056 Ω/µm.

Figure 6 also shows the nonlinearity of the measurement signal with respect to stage displacement. Considering the non-linear effects in the electrical resistivity of silicon as a function of the temperature and the fairly large temperature fluctuation over the sensing part of the heaters, the sensitivity of the sensor decreases slightly towards the outer boundaries of the measurement range, at large deflections of the stage.

Figure 6: Quasi-static measurement of the amplifier output voltage as a function of stage displacement at a heater voltage of 9 V (top). The bottom figure shows the deviation from a linear fit (106 mV/µm) of the amplifier output voltage with respect to the stage displacement.

Figure 7 shows that the measured sensitivity is highly dependent on the heater voltage. A maximum sensitivity was reached at a heater voltage of 10 V, 1.247 Ω/µm. The measured sensitivity curve is related to the resistivity curve of silicon as a function of temperature (figure 2) in two ways: a) the power flow from heater to stage and b) the resulting change in electrical resistance. The power flow from heater to stage (a) is determined by the temperature difference between heater and stage and therefore the temperature ‘setpoint’ on the resistivity curve. The change in electrical resistance (b) as a result of the power flow from heater to stage is dependent on the slope of the resistivity curve at the temperature setpoint.

Figure 7: The measured sensor sensitivity as a function of the applied heater voltage.
Figure 8 shows the resistance of a single heater when a step voltage is applied from 0 V to 5 V. A change in resistance from 435.3 Ω to 474.9 Ω was measured. A first order exponential was used to make an approximation of the thermal time constant of the heater. The behavior of the sensor matches really well with a first order fit with a time constant of 165 μs. A second time constant of 30 ms was measured, most likely caused by local heating of the substrate underneath the heater. Constant usage of the sensor prevents this time constant from showing up in the measurements. A startup time of around 200 s is necessary for the complete system to reach a thermal equilibrium. Since the power dissipation of the differential sensor configuration is nearly independent on stage position, the thermal steady state situation of the complete system will not be affected and will therefore not have any influence on the measurement.

A drift measurement was performed with the differential sensor. Without the control of ambient temperature and air humidity, the drift of the sensor was determined to be 32 nm over a measurement period of 32 hours. A run-in time of several days was required to remove long-term drift. For example thermal oxidation [7] and thermal activation of oxygen [12] are effects that can change the thermal and electrical properties of the silicon material. Both effects will stabilize in a time period of multiple days.

V - Conclusion

We have designed, fabricated and validated a thermal displacement sensor in MEMS. The sensor principle is based on the temperature-dependent electrical resistivity of silicon and the heat transfer by conductance through a thin layer of air. The sensitivity of the sensor is highly dependent on the applied heater voltage: sensitivities up to 1.247 Ω/µm were measured. The sensitivity of the sensor is determined by the power flow towards the stage, due to the temperature difference between heater and stage, in combination with the slope of the resistivity curve of silicon. The 1-sigma noise of the measurement signal corresponds to 3.47 nm at a measurement bandwidth of 30 Hz and with a power dissipation of 209 mW. The time response of the heater structures was determined to be 165 μs, allowing a higher measurement bandwidth. The major advantage of the presented thermal displacement sensor is that it can be easily integrated in the device layer of a SOI-wafer together with, for example, an elastically guided stage and electrostatic comb-drive actuation.

References