TEMPERATURE COEFFICIENTS OF MATERIAL PROPERTIES USING DIFFERENTIAL CAPACITIVE STRAIN SENSORS

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ABSTRACT

This paper demonstrates the use of micromachined differential capacitive strain sensors for determining the temperature dependence of the thermal expansion coefficient, Young's modulus, and residual strain of microstructure materials. The device and methodology presented are suitable for both tensile and compressive materials and can be used before or after packaging the device. It is shown by this method that for a particular set of fabrication conditions for electroplated nickel devices, the thermal expansion coefficient is 11-13 ppm/K over 23-50°C; the residual strain changes from neutral to -880 microstrain over 23-100°C; the Young's modulus has a temperature coefficient of -1590 ppm/K with an estimated value of 35 GPa at room temperature; consequently, the residual stress changes from neutral to -29 MPa over 23-100°C. Using passive bent beam strain sensors, the thermal expansion coefficient is found to increase from 13.5-16.5 ppm/K over 50-150°C.

I. INTRODUCTION

Monitoring the mechanical properties of structural materials is a critical challenge in MEMS research and manufacturing. Device performance parameters are sensitive to variations in Young's modulus, residual strain, residual stress, and the thermal expansion coefficient of structural materials. Unfortunately, these properties can vary with manufacturing, packaging, and deployment conditions. Diagnostic microstructures for rapid characterization of these material properties are useful for monitoring processes. Additionally, if these structures provide electronic readout, they can be integrated within device packages, improving overall performance by offering post-deployment calibration capability.

In past efforts to electronically determine material properties, electrostatic forces have been used to cause out-of-plane deflections of cantilevers, beams, and plates [1-4]. However, a number of sensors and actuators are based on lateral deflections that occur parallel to the plane of the substrate. A laterally deflecting test device is preferred for characterizing the materials used in these devices, which may be anisotropic and may exhibit different properties for in-plane and out-of-plane deflections. The differential capacitive strain sensor [5] is a suitable tool for such measurements. It provides the added benefit of a wide dynamic range, being able to accommodate not only tensile stresses, but also compressive stresses that are exploited in certain actuator applications [6].

In the differential capacitive strain sensor, a series of ribs, suspended above the substrate by bent-beams, support interdigitated tines, forming sidewall capacitors (Fig.1). The suspensions and tines are arranged such that the capacitance on one side of a rib increases as the other decreases. The residual strain in the structural material is determined from the differential capacitance, defined as $\Delta C =$

$C_{AB} - C_{AC}$, which is >0 in tension, and <0 in compression. The Young's modulus of the material is determined from the curvature of the plot of C_{AB} (or equivalently, C_{AC}) versus an applied bias voltage between elements A and B (or C). The bias voltage applies an electrostatic force, resulting in a displacement that is measured by the change in capacitance. The displacement is related to the stiffness of the suspension, which is proportional to the Young's modulus. The curves obtained are referred to as CV curves.

In this effort, a procedure is presented for determining the temperature dependence of the Young's modulus, residual strain, residual stress, and expansion coefficient of microstructure materials, using differential capacitive strain sensors. It is demonstrated using electroplated metal strain sensors fabricated on a silicon substrate.

Fig. 1: Schematic of the differential capacitive strain sensor and definition of bent-beam dimensions.

II. MODELING

The modeling approach was conceptually similar to those described in [2-4]. The capacitance between tines was numerically modeled using FastCap™ [7]. The capacitance was determined for a range of separations between tines, and stored in a look-up table. The net mechanical spring constant of the bent-beam suspensions was calculated as noted in [6]. Starting with the zero-bias gap, spacing between the tines was decremented in small intervals. At each position, the capacitance was determined from the look-up table, while the corresponding bias voltage was determined from force balance by equating the electrostatic attractive force to the mechanical restoring force:

$$k_{eff} y = \frac{V_{Bias}^2}{2} \frac{\partial C_{AB}}{\partial y} \quad (1)$$

where k_{eff} is the effective mechanical spring constant of the system, and y is the in-plane displacement from the zero-bias position. Figure 2 shows calculated CV curves obtained by this method, assuming $L=198 \mu m$, $W=5 \mu m$,

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$\phi=0.1$ rad., $4.4 \mu\text{m}$ thickness, and 10 pairs of tines exist with $167 \mu\text{m}$ interdigitated length. The sidewalls of the tines were assumed to have a re-entrant profile that was 22° off vertical for reasons described in the following section. The zero-bias gap between the upper edges of adjacent tines (where the tines were closest) was $1.85 \mu\text{m}$. The tines were assumed to be $2.2 \mu\text{m}$ above the substrate.

The effect of certain structural non-idealities on the CV curves is shown in Figs. 3-5. Figure 3 shows variations in the CV curve caused by changing the gap between the tines. The device dimensions are as for Fig. 2, the Young's modulus is 100 GPa , and the gap between the upper edges of the tines is varied from $1.65 \mu\text{m}$ to $2.05 \mu\text{m}$ in $0.1 \mu\text{m}$ increments. Figure 4 shows the impact of changing the sidewall angles of the tines, with the Young's modulus at 100 GPa , and the remaining parameters as for Fig. 2. Figure 5 shows the impact of upward and downward deflections of one tine in each pair. Clearly, each of these variables can have an impact on the CV curves.

III. EXPERIMENTAL RESULTS

The strain sensors were fabricated on silicon wafers insulated with $1 \mu\text{m}$ thick thermal oxide and $0.5 \mu\text{m}$ thick LPCVD nitride. A $2 \mu\text{m}$ thick sputtered Ti sacrificial layer was patterned and covered with a Cr/Ni seed layer. The devices were electroplated into a photoresist mold from a nickel sulphamate solution (which contained trace impurities.) At 54°C temperature, using $5\text{-}10 \text{ mA/cm}^2$ current density, a thickness of $4.4 \mu\text{m}$ was achieved in 9.5 min . The sidewalls of the plated structures were 22° off vertical due to resist reflow during hard bake. The photoresist mold was subsequently stripped and the sacrificial material etched away. Following this, the sample was coated with self-assembled monolayers using ODS [5]. A SEM image of a fabricated structure is shown in Fig. 6.

The coefficient of thermal expansion for the structural metal was first measured by passive bent-beam strain sensors [8] which were fabricated on the same die as the differential capacitive strain sensors. The strain was measured as a function of temperature by observing their deformation through a microscope. The dimensions of these devices were $L=198 \mu\text{m}$, $W=6 \mu\text{m}$, and bending angle $\phi=0.1$ rad. The expansion coefficient of structural metal can be written as:

$$\alpha_{\text{Metal}}(T) = \alpha_{\text{Si}}(T) - \frac{d(e(T))}{dT} \quad (2)$$

where $e(T)$ is the strain observed by the strain sensor. The expansion coefficient of silicon as a function of temperature is provided in [9]. It increases in an approximately linear manner from 2.5 ppm/K at room temperature (23°C) to 4 ppm/K at 500°C . The residual strain in the structural metal at 23°C was 1.1×10^{-10} . Its expansion coefficient as obtained by this method increased from about 13.5 ppm/K at 50°C to about 16.5 ppm/K at 150°C . This compares well with previously published results. One report indicates that the expansion coefficient of pure bulk nickel increases from 10.2 ppm/K at 20°C to 16.3 ppm/K at 300°C , and retains the latter value at 400°C as well [10]. Another report indicates that the expansion coefficient of nickel electroplated under particular conditions may increase from 8.5 ppm/K averaged over the temperature range of $25\text{-}50^\circ\text{C}$ to 15.1 ppm/K averaged over the temperature range of $25\text{-}367^\circ\text{C}$ [11]. Thus, the measured results are in agreement with prior reports, given the contextual differences.

Fig. 2: Theoretical CV curves for k_{eff} values representing Young's moduli of $40\text{-}220 \text{ GPa}$ in 20 GPa increments.

Fig. 3: Impact of gap variations between tines.

Fig. 4: Impact of variations in the sidewall angles of tines.

Fig. 5: Impact of out-of-plane deflections of tines.

A capacitive strain sensor was then used monitor the residual strain in the structural metal on the silicon substrate as a function of temperature for several samples (Fig. 8). The measured results of show a linear increase in the differential capacitance readout as temperature is increased from 20°C to 60°C. Measurements were taken with ± 0.5 fF precision using 10 tine pairs with 168 μm overlap length and 5 μm nominal gap; for the suspensions, $L=198$ μm , $W=6$ μm , and $\phi=0.2$ rad. The response of the differential capacitance readout to increasing temperature was theoretically estimated using FastCap^{TM}. For this simulation it was assumed that the expansion coefficient of the electroplated metal exceeds that of silicon by 10 ppm/K. This result is superimposed on the measured data in Fig. 8. Based on the passive strain sensor measurements (Fig. 7) and previously published results, the expansion mismatch between nickel and silicon over 20-60°C is 6-11 ppm/K, consistent with the differential capacitance measurements. At temperatures $>60^\circ\text{C}$, however, the capacitive strain sensor was affected by out-of-plane buckling of the support ribs, and the capacitance model must be changed accordingly. As a design guideline, the lengths of support ribs should be minimized for highly compressive materials.

Figure 9 shows CV curves that were measured at various temperatures for devices with 10 tine pairs of 167 μm overlap length, and suspensions with $L=198$ μm , $W=6$ μm , and $\phi=0.1$ rad. Numerically simulated curves were fitted to measurements using the zero bias capacitance and the Young's modulus as fitting parameters. A comparison of a measured and fitted curve pair is shown in Fig. 10. The best fit of k_{eff} corresponded to a Young's modulus of 35 GPa at 23°C for the electroplated metal. Although the Young's modulus of pure bulk nickel is 208 GPa, electroplated nickel has a substantially lower modulus and can demonstrate significant variability, underscoring the need for such measurements. For pure nickel electroplated under particular conditions, a value of 150 GPa was reported in [12]. Trace levels of contamination and variations in plating conditions can significantly affect the mechanical properties of electroplated materials. For the structural material used in these experiments, the relatively low value of Young's modulus may be related to a combination of effects, including trace impurities, aging of the solution, and possibly the plating rate.

The measured temperature coefficient of the Young's modulus, which is the same as the temperature coefficient of k_{eff} , was found by fitting measured CV curves at elevated temperatures to be -1590 ppm/K. This parameter is also strongly dependent on fabrication conditions, and values ranging from -550 ppm/K [12] to -952 ppm/K [10] have been reported for pure nickel.

Using the measured values of strain and Young's modulus the thermal stress in the metal microstructures can be calculated in a piecewise linear manner. At 23°C it is essentially neutral, at 60°C it is -14 MPa, and at 100°C it is -29 MPa. In the 23-60°C temperature range, the Young's modulus of the metal and the expansion coefficients of the metal and silicon are averaged at 34 GPa, 13.5 ppm/K, and 2.5 ppm/K respectively. In the 60-100°C temperature range, these values are 32 GPa, 15.0 ppm/, and 2.8 ppm/K, respectively. These variations in mechanical properties occur within a range of temperatures commonly encountered in microelectronics and MEMS applications, and can have significant impact on device performance.

Fig. 6: SEM of a released device showing displaced tines. All tine spacings were equal before release.

Fig. 7: The thermal expansion coefficient of the structural metal as measured by passive bent-beam strain sensors.

Fig. 8: The thermal expansion coefficient of the structural metal as measured by differential capacitive for four adjacent devices. The support ribs buckled near 60°C.

Fig. 9: Measured CV as a function of temperature. The buckling temperature for this device was $>70^\circ\text{C}$.

Fig. 10: Comparison of a measured CV curve from Fig. 9 to a fitted theoretical one. $T = 60^\circ\text{C}$.

IV. CONCLUSIONS

In summary, a procedure for determining temperature dependent mechanical properties of microstructure materials using differential capacitive strain sensors was presented in the context of electroplated nickel microstructures fabricated on a silicon substrate. For the fabrication conditions used, it was found that the thermal expansion coefficient was 11-13 ppm/K over $23\text{--}50^\circ\text{C}$; the residual strain changed from neutral to -880 microstrain over $23\text{--}100^\circ\text{C}$; the Young's modulus had a temperature coefficient of -1590 ppm/K with an estimated value of 35 GPa at room temperature; consequently, the residual stress changed from neutral to -29 MPa over $23\text{--}100^\circ\text{C}$. Using passive bent beam strain sensors, the thermal expansion coefficient was found to increase from 13.5-16.5 ppm/K over $50\text{--}150^\circ\text{C}$.

Theoretical calculations indicate that CV measurements can be affected by variations in device dimensions. In most commercial processes, however, these are held to tight tolerances. Within these constraints, differential capacitive strain sensors offer a wide dynamic range that spans both tensile and compressive materials; electronic readout, which can be used even after packaging; and measurements based on lateral deflections.

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