Calibration technique for MEMS membrane type strain sensors

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Abstract— A MEMS based piezoresistive strain sensor was designed, fabricated and calibrated. A single strip of doped n-poly-silicon sensing material was patterned over a thin Si$_3$N$_4$/SiO$_2$ membrane. The silicon wafer was etched beneath this thin membrane. The intent of this design was to fabricate a flexible MEMS strain sensor. A calibration technique for measuring the strain sensor performance is described. The sensor calibration technique (to find the relationship between change in resistance and strain) entails developing a repeatable relationship between the change in sensor resistance and the strain measured at the sensor. The sensor sensitivity is evaluated by embedding the sensor in a vinyl ester epoxy plate and loading the plate. This calibration technique captures the effects of strain transfer to the stiff silicon wafer.

1. Introduction

In a separate project, a MEMS strain sensor was fabricated for remotely monitoring of the structural health of a fiber reinforced laminated composite structure. The overall sensor system consists of a strain sensor, a signal conditioning and telemetry circuit, and an antenna. The entire system is to be embedded in the composite structure. This sensor holds two distinct advantages over conventional metal foil strain gages in that the overall sensor system does not require a wire connection to the interrogation systems and is able to be cofabricated on a single chip by using MEMS technology. These completely integrated devices are well suited for composite aircraft components (door panels, fuselage), bridge and ship structures. Detection of excessive loads can help avoid catastrophic failure of these structures.

Critical to this application is the sensor sensitivity. The MEMS strain sensor must be sufficiently sensitive to measure strain up to 2000\textmu e in the structure. Three different MEMS based piezoresistive strain sensors were already developed by Hautamaki et al at the University of Minnesota [1]: a piezoresistive filament fabricated directly on the wafer, a rectangular cantilever beam and a curved cantilever beam. Typical sensor sensitivity to a uniaxial tensile strain of 1000\textmu e ranged from 1.0 to 1.5\% of the nominal resistance change (\Delta R/R), corresponding to a gage factor of -10 to -15 (Negative gage factor indicates that resistance decreases with increasing strain.). Hautamaki et al [1] found that the strain transfer from the polymer composite to the sensor was only on the order of 30-50\%. That is, for 2000\textmu e load on the structure, only 600-1000\textmu e occurred in the silicon wafer. These researchers concluded that MEMS strain sensor response must be sensitive so as to produce the desired resolution for subsequent signal processing.

In this paper, a method for evaluating strain given the change in sensor resistance is presented. The method, referred to as a calibration technique, is based on experimental data and follows accepted standards for metal foil strain gage calibration. In the subsequent sections, strain gage calibration is described, MEMS strain sensor calibration is described, and test data for MEMS strain sensor are presented.

2. Background

Standard calibration for metal foil strain gages is experimentally and statistically based. Several gages for each lot are tested to determine the sensitivity for the entire lot. ASTM E251-92 [4] is the standard test method for performance characteristics of metallic bonded resistance strain gages. The sensitivity of a strain gage is characterized by a gage factor. The gage factor GF is related to the nominal resistance $R$, the change in nominal resistance $\Delta R$ and the strain $\varepsilon$ as follows

$$GF = \frac{\Delta R}{R} / \varepsilon$$  \hspace{1cm} (1)

According to ASTM E251-92, there are three separate test methods for calibration of the gage factor: (1) Constant bending moment beam test method; (2) Constant stress cantilever beam test method; and (3) Direct tension or compression test method. Every method has its typical mechanical system and specimen, but all have the same procedure. In each, the strain gage is mounted on a metal specimen and calibrated by mechanically loading the specimen. It is important to recognize that since strain gages are part of a complex system and cannot be reinstalled, gage
factors are stated only on a statistical basis. Current calibration techniques assume that strain gages from the same fabrication lot will have the same gage factor as the devices that are mounted and tested.

A similar approach can be applied to experimentally calibrate MEMS strain sensors. Several MEMS strain sensors from the same lot must be tested and calibrated. The MEMS strain sensor is fabricated on a stiff silicon wafer. Like the metal foil strain gage, the strain is transferred to the MEMS strain sensor through an adhesive bond (i.e. the strain sensor is either bonded or embedded in the structure). Silicon has such a high modulus compared to the surrounding adhesive that strain transfer is poor [1]. Near the sensor, there is a mismatch between the stiffness of the silicon and the adhesive that bonds the sensor to a specimen or encapsulates the sensor in an embedded specimen. One way to characterize this effect is to introduce the terms nearfield and farfield strain [3]. Nearfield strain is the actual strain which is measured at the MEMS strain sensor. Farfield strain is the strain which would occur at that location had there been no silicon wafer to disturb the strain field. The silicon introduces nearfield (sensor) strain disturbances. The nearfield strain can be as small as 30% of the farfield strain.

For conventional metal foil strain gages on a flexible polyimide backing, the strain transfer between the specimen and sensor is perfect. The ASTM E251-92 standard assumes that the mechanical (farfield) strain that is determined from the applied load is the same as the (nearfield) strain that is transferred to the strain gage. This procedure is not valid for the stiff silicon backed MEMS sensor. The calibration procedure must be modified to account for the strain transfer to the MEMS sensor. The outcome of sensor calibration is a gage factor, which is used to relate the change in resistance to the nearfield strain at the sensor. In order to calibrate a MEMS sensor fabricated on a silicon wafer, the nearfield strain at the sensor must be known.

3. Sensor design and fabrication

The MEMS strain sensor resembles a picture in a frame. The frame is a 10mm long x 10mm wide x 0.5mm thick silicon wafer. The picture is a thin Si$_3$N$_4$/SiO$_2$ membrane with n-polysilicon pattern, as shown in Figure 1. The sensing material is patterned over the thin membrane. A 1100µm x 1100µm window of the silicon wafer is etched beneath the thin membrane. The thin membrane provides a flexible backing for the sensing material. The intent of this design is to fabricate a flexible MEMS strain sensor, similar in function to a flexible metal foil strain gage. A scanning electronic microscope (SEM) for this single strip sensor is shown in Figure 2. The detailed fabrication steps for this sensor are described in [4].

4. Experimental procedures

For calibration (i.e. determine the gage factor), the windowed single strip sensor was embedded in a vinyl ester epoxy plate. Vinyl ester epoxy was selected because it is a room temperature cure, transparent polymer. Room temperature adhesive properties of vinyl ester are comparable to typical adhesives used to mount strain gages. Two specimens were constructed: i) a strain gage specimen with an embedded commercial strain gage (EA-00-125AD-120) mounted on a blank 10mm x 10mm x 0.5mm silicon wafer; and ii) a MEMS specimen with an embedded MEMS single strip sensor of 10mm x 10mm x 0.5mm overall dimensions. The specimen material (vinyl ester epoxy) and geometry (160mm x 30mm x 6.0mm) are identical. The strain gage mounted on a blank silicon wafer in the strain gage specimen had the same
size and geometry as the MEMS strain sensor. For each specimen, the embedded device was placed at a height one quarter the overall thickness and at the end of the specimen, as shown in Figure 3. This location was selected to ensure good sensor response in bending. In addition to the embedded devices for either MEMS strain sensor or strain gage on silicon, a conventional strain gage (EA-00-125AD-120) was bonded to the outside of each specimen, directly above the embedded sensor. The surface strain from the applied load to the specimen was measured with the exterior strain gage. The farfield strain was calculated from linear transformation of the surface strain for bending by using

\[ e_{\text{farfield}} = e_{\text{surface}} \frac{(T/2-h)}{T/2} \]  

(2)

where \( h \) is the distance from the surface mounted strain gage to the embedded sensor and \( T \) is the overall thickness of the specimen. The farfield strain was calculated from the surface strain for tension by using

\[ e_{\text{farfield}} = e_{\text{surface}} \]  

(3)

Two different loadings were applied, bending and uniaxial tension. A cantilever beam method was used to apply to the bending load [6]. The specimen was held rigid at one end. A bending load, ranging from 0 to 11.8kN, was applied to the free end of the specimen. Bending tests were run in both tension and compression bending by turning over the specimen. The same specimen was loaded in tension on a MTS Test-QT/10 machine. A tension load, ranging from 0 to 1.6kN, was applied.

The schematic of the calibration procedure is shown in Figure 4. Both specimens were loaded under identical loading conditions. The strain gage specimen was tested to establish a relationship between the farfield strain and the nearfield strain in bending (bending relationship) and tension (tension relationship), respectively. The MEMS specimen was tested to obtain the farfield strain versus the sensor nominal resistance in bending (bending data) and tension (tension data), respectively. In the MEMS specimen, we cannot record the nearfield strain, only the “nearfield” resistance. The farfield strain from the MEMS specimen bending data and tension data must be converted to the MEMS nearfield strain using the two relationships. The bending data is converted using the bending relationship and the tension data is converted using the tension relationship. The response of the sensor in bending was determined by plotting the change in the MEMS nearfield strain as a function of the change in the nominal resistance. This step was repeated to obtain the MEMS nearfield tensile strain as a function of change in nominal resistance. The gage factor (Equation 1) of the sensor is the slope of each response.

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**5. Results and discussion**

Figures 5(a) and 5(b) show the bending relationship and the tension relationship between the farfield and nearfield strain in the strain gage specimen, respectively. The changes in farfield strain with the nearfield strain were linear for both bending and tension loads.

Figures 6(a) and 6(b) show the bending data (a) and tension data (b) for the MEMS strain sensor. The change in sensor nominal resistance versus the change in farfield strain is shown. The normalized resistance change increased linearly with the farfield strain as a compression bending load was applied. Similarly, the normalized resistance change decreased as a tension bending or a tension load was applied.

The bending and tension responses for the sensor (after conversion to the nearfield strain) are shown in Figures 7(a) and 7(b). The nearfield strain was determined from the strain gage specimen data that were collected under similar loading conditions. The normalized resistance change with
Figure 4. Schematic of the calibration procedure.
the nearfield strain was linear for each design. The normalized resistance change decreased linearly with increasing nearfield strain for both bending and tension loads. Gage factors for bending and tension loads are the slopes of the data shown in Figures 7(a) and 7(b). The gage factors for the single strip sensor were $-15$ in bending (a) and $-13$ in tension (b).
researchers reported gage factors of -17 in bending and -16 in tension for a monofilament sensor.

The gage factors of MEMS fabricated piezoresistive sensors on the thin membrane, which were obtained from bending and tension tests, are larger than those of conventional metal foil strain gages. Gage factors for metal foil strain gages are 2.0 [7]. The high magnitude of the gage factor indicates high sensitivity to changes in strain. Moreover, the high gage factor magnitude reduces the signal processing requirements and is compatible with lower power electronics.

6. Conclusions

A MEMS piezoresistive (doped n-polysilicon) strain sensors on a 3μm thin Si₃N₄/SiO₂ membrane were successfully designed, fabricated and calibrated. A calibration technique for a MEMS strain sensor was described. The calibration establishes a relationship between the change in nominal resistance and the change in nearfield strain. The calibration technique was based on experimental data and followed the standard procedure similar to metal foil strain gage calibration. Nearfield and farfield strain concepts were introduced to account for poor strain transfer between silicon and adhesives. The gage factors for the MEMS membrane type strain sensor design were comparable to those for the MEMS strain sensors observed by Hautamaki et al researchers [1].

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8. References

[4] Tae Song Kim, Li Cao, Susan C. Mantell and Dennis L. Polla, “Fabrication of Piezoresistive Membrane Type Strain

