DESIGN, MODELING, FABRICATION AND TESTING OF A MEMS CAPACITIVE BENDING STRAIN SENSOR

J AEBERSOLD1, K WALSH2, M CRAIN2, M VOOR3, M MARTIN2, W HNAT1, J LIN2, D JACKSON2 and J NABER2

1Mechanical Engineering Department, University of Louisville, Louisville, Kentucky, 40292, United States
2Electrical & Computer Engineering Department, University of Louisville, Louisville, Kentucky, 40292, United States
3Department of Orthopaedic Surgery, University of Louisville Medical School, Louisville, Kentucky, 40292, United States

E-mail: julia.aebersold@louisville.edu

Abstract. Presented herein are the design, modeling, fabrication and testing of a MEMS-based capacitive bending strain sensor utilizing a comb drive. This sensor is designed to be integrated with a telemetry system that will monitor changes in bending strain to assist orthopaedic surgeons with the diagnosis of spinal fusion. ABAQUS/CAE version 6.5 finite element analysis (FEA) modeling software was used to predict sensor actuation, capacitance output and the avoidance of material failure. Highly doped boron silicon wafers with a low resistivity were fabricated into an interdigitated finger array employing deep reactive ion etching (DRIE) to create 150 μm sidewalls with 25 μm spacing between the adjacent fingers. For testing, the sensor was adhered to a steel beam, which was subjected to four-point bending. This mechanically changed the spacing between the interdigitated fingers as a function of strain. As expected, the capacitance output increased as an inverse function of the spacing between the interdigitated fingers, beginning with an initial capacitance of 7.56 pF at the unstrained state and increasing inversely to 17.04 pF at 1571 με of bending strain. The FEA and analytical models were comparable with experimental data. The largest differential of 0.65 pF or 6.33% occurred at 1000 με.

1. Introduction

Modern medical science has emerged with a need to monitor physiological functions (i.e. intravascular pressure, intraocular pressure, etc.). A variety of these monitoring devices require that their tasks be performed wirelessly and implanted for indefinite terms to allow for patient mobility, continuance of daily activities and avoidance of costly surgeries to remove the systems after utilization is complete. One area of need is a system that will assist orthopaedic surgeons with the diagnosis of Spinal Fusion. Over a period of six to twelve months, grafted bone applied during surgery is expected to fuse with adjacent vertebrae to form a collective bone segment. Spinal instrumentation is often implanted across the affected vertebrae to provide stability and to promote fusion development. As a result, strain exhibited on the instrumentation can be monitored to evaluate the formation of fusion.

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The discussion presented, henceforth, is the design and development of a MEMS (Micro-Electro-Mechanical Systems) capacitive bending strain sensor to be eventually incorporated with a battery-less implantable telemetry system. The sensor design utilized a comb-drive or interdigitated fingers to generate a variable capacitance. This is normally actuated by electrostatic actuation or frequency tuning, rather than mechanical actuation, which have become integral parts of RF and wireless communications [1-5]. Due to dimensional limitations of the housing the sensor could not be longer than 10 mm or wider than 4 mm and capacitive transduction was preferred to minimize power consumption. Telemetry components required a minimal resting capacitance of 5 pF at zero bending strain and the sensor output should not exceed 100 pF at the maximum anticipated strain of 1000 με.

2. Sensor Capacitance Relationships and Initial Design

The capacitance relationship for a parallel plate system is given by

\[
C = \frac{\varepsilon_0 \varepsilon_r A}{d}
\]

where \(C\) is the generated capacitance in farads (F) and \(\varepsilon_0\) is the dielectric constant of free space equal to \(8.85 \times 10^{-14}\) F/cm [6, 7]. The second dielectric constant, \(\varepsilon_r\), is the relative permittivity for the medium between the two plates and is equal to 1 for air. The overlapping area between the two plates is \(A\) and \(d\) is the distance between the two plates [7]. From this relationship, increasing or decreasing the overlapping area of the plates would produce a linear difference in capacitance, whereas, adjusting the spacing between the two plates would result an inverse response. The sensor’s response can be amplified by increasing the distance from the neutral axis of the rod to the sensor’s interdigitated fingers. Based upon this approach an initial design was developed as shown in 1.

Figure 1. An illustration of the elevated comb drive or interdigitated finger capacitive design with two independent anchors.

Based upon an initial capacitance requirement of 5 pF for the telemetry system and the anticipated change in the sensor’s length, dimensional characteristics could be determined. The initial gap between the interdigitated fingers was 25 μm and the finger sidewall height was 150 μm; resulting an overlapping length of 1705 μm. The anchor height was changed by adding a glass pad to achieve larger actuation, higher sensitivity and to provide a large surface area for attachment to the rod. The final design included an array of 89 interdigitated fingers. The large gap between the fingers was required to maintain a 10:1 aspect ratio needed for the DRIE process to create the interdigitated array. Based upon this dimensional information and ignoring fringing effects, the initial capacitance was calculated to be 8.01 pF.

3. Finite Element Analysis & Qualitative Results

Finite element analysis (FEA) using ABAQUS 6.5 (Providence, RI) was performed to model actuation of the sensor to calculate capacitance output and avoid fracture of the materials due to developed stresses in the silicon or glass pads. Displacement of the interdigitated fingers was used to calculate capacitance. Analysis of the system began by properly constraining the beam to produce a continuous magnitude of strain across its surface while undergoing bending. The sensor was modeled by
positioning Borosilicate (7740) glass to the bottom of the anchors and attaching the assembly to a beam using tie constraints. This was performed to reduce stress concentrations and to provide ample area to apply adhesive for final attachment to the rod.

The final small gap between the interdigitated fingers was 4.3 μm, whereas, vertical displacement of the endmost fingers was 26.14 μm. These results were used to predict a capacitance of 10.11 pF at 1074 με compared to the initial calculated capacitance of 8.01 at 0 με, as shown in figure 2. Adjusting the height of the borosilicate glass pad increased actuation of the sensor by augmenting the distance from the neutral axis of the beam to the sensor’s plane of interdigitated fingers. The height of the borosilicate glass pads is 300 μm.

Figure 2. Illustration of the maximum principal stresses developed in the glass pads and sensor while attached to a beam undergoing 1074 με of bending strain. The beam is not shown.

4. Fabrication Process

The fabrication process used double-sided polished 2”, 300 μm thick silicon wafers and a borosilicate glass wafer 300 μm thick. The wafers were highly boron doped (p+) with a low resistivity of 0.001 – 0.005 Ω⋅cm to replicate a metallic substrate and to avoid sputtering or electroplating a metallic layer. The glass wafer was diced into 3 mm squares before fabrication. Processing began with base cleaning of the wafer to remove organic materials and wet oxidation to develop an oxide thickness layer approximately 1 μm thick, as seen in figure 3a. One side of the oxidized wafer was patterned using a buffered oxide etching (BOE) solution to create the sensor’s anchors. The remaining oxide from the top surface was removed and potassium hydroxide (KOH) was used to reduce the overall thickness of the wafer, excluding the anchors to 150 μm, as shown in figure 3b.

The wafer was wet oxidized again, as seen in figure 3c, to an oxide thickness of 1 μm, which served as a mask for deep reactive ion etching (DRIE) on the front side of the wafer. Oxide was removed from the back side of the wafer and the 3mm glass pads were anodically bonded to the anchors, as seen in figure 3d. The top of the wafer was patterned using front to back alignment and silicon was etched in a Surface Technology System’s Multiplex Advanced Silicon Etcher DRIE (Imperial Park, Newport, UK) system until the elevated interdigitated fingers were free, as seen in figure 3e without altering the glass pads. Figure 3f demonstrates attachment of the wire leads and figure 3g is the sensor applied to a beam with the tethers broken. Tethers were incorporated in the design to maintain alignment of the interdigitated fingers until application to the substrate. Figure 3h is the completed sensor adhered to a beam and ready for testing.
Figure 3. Fabrication process of the MEMS capacitive bending strain sensor. (a) Wet oxidation (b) Wet etching the bottom of the wafer to form the anchors. (c) Re-oxidation of the wafer. (d) Anodic bonding of the glass pads to the anchors (e) Deep reactive ion etching of the interdigitated fingers from the top side of the wafer. (f) Attachment of wire leads. (g) Application of the sensor to the substrate and breaking of the tethers. (h) The completed sensor.

5. MTS Testing & Quantitative Results

The sensors were attached to a steel beam using a cyanoacrylate adhesive (M-Bond 200, Vishay Micro-Measurements, Raleigh, North Carolina) and tested for a capacitance change in four-point bending. Conductance and capacitance of the sensor was measured using a Keithley 590 CV Analyzer. Conductance was less than 2 μS when all silicon material was clear between the fingers and a change in capacitance could be measured.

Metal foil strain gages were mounted on the beam and upon adjacent materials not undergoing bending for temperature compensation. Following shunt calibration, the strain analog signal and load cell output from the MTS were recorded using a custom virtual instrument developed using LabView version 6.1 and a National Instruments 6024 data acquisition card with a sampling rate of 6.3 samples per second. The capacitance sensor was connected to a Keithley CV Analyzer where the GPIB output was recorded with the same virtual instrument and collection rate.
A series of tests were developed to characterize the behavioral response of the sensor. The first test applied a cyclical load to generate 200 to 1010 με at a frequency of 0.0083 Hz for five hours, for a total of 150 cycles, to determine if hysteresis was present. Application of a zero load was not selected to assure that the beam did not slip in the MTS fixture. The second test statically loaded the sensor for an extended period of time to see if the capacitive output of the sensor would drift over time. Optical micrographs of the micro-machined capacitive sensor are shown in figure 4. The first photograph, figure 4(a), shows equal spacing of the fingers before loading. Figure 4(b) shows movement of the interdigitated fingers after bending was induced on the beam.

![Figure 4](image)

Figure 4. Visualization of the interdigitated fingers of the sensor (a) before bending strain is applied. (b) After bending strain is applied the spacing between the fingers changes significantly.

The sensor was tested under cycle loading and capacitance versus strain data were collected using a customized LabView program. The test was performed for a duration of five hours or 150 cycles with the sensor’s response. The data showed that the sensor had no hysteresis and was very repeatable throughout cycle testing. Three additional devices were tested and demonstrated comparable graphical behavior.

Sensor drift was evaluated by applying a static load from the MTS that generated 11.50 pF from the sensor. This value was beyond the capacitance range tested during cycle testing, but was selected due to increased sensitivity of the device where drift would become more evident. Data was recorded in a similar manner as the cyclical test, but for a duration of 10 hours. A minimal amount of change was seen during the static test; however, these small fluctuations were attributed changes in the load applied by the MTS and not due to any change from the MEMS sensor. This was supported by load cell and strain gage data recorded simultaneously from the MTS.

Maximum range of the sensor was determined by increasing loading from the MTS to the beam until maximum capacitance was achieved and conductance began to rapidly increase. This indicated that the fingers were in contact with each other and no further actuation could be achieved. Figure 5 shows the change in capacitance from the FEA model and experimental data. A small differential is noticed between the FEA model and experimental data between 500 to 1300 με, with the largest differential of 0.65 pF or 6.33% at 1000 με. This may be attributed to non-symmetric spacing between the interdigitated fingers of the sensor before application of bending strain and would explain the lower than anticipated capacitance value at 100 με. Another item not taken into account were fringe effects incorporated in the capacitance calculations from the FEA model, where the displacement data was used in a simple parallel plate model. Further capacitive calculations could be performed with the ABAQUS model, but deemed unnecessary given the encouraging results from the simple parallel plate model.
Figure 5. Graphical results of the entire capacitance range from the FEA model and experimental testing.

6. Conclusions & Recommendations
The following were derived from modeling, fabrication and testing of the sensor. First, the sensor model developed in ABAQUS simulated the longitudinal and vertical actuation of the fabricated sensor, which was verified by visual inspection of the fabricated sensor while undergoing actuation. Additionally, the sensor did not exhibit any drift characteristics during static testing or hysteresis during cycle testing. Finally, FEA modeling and experimental data results were comparable verifying efficacy of the ABAQUS model. The capacitive response of the sensor performed as expected according to the inverse relationship of the spacing of the interdigitated fingers. It is recommended that additional ABAQUS capacitive modeling be performed to account for fringe effects that were omitted from calculations to better compare to quantitative and qualitative data.

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