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THIN SILICON MEMS CONTACT-STRESS SENSOR

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This work offers the first, thin, MEMS contact-stress (CS) sensor capable of accurate *in situ* measurement of time-varying, contact-stress between two solid interfaces (e.g. *in vivo* cartilage contact-stress and body armor dynamic loading). This CS sensor is a silicon-based device with a load sensitive diaphragm. The diaphragm is doped to create piezoresistors arranged in a full Wheatstone bridge. The sensor is similar in performance to established silicon pressure sensors, but it is reliably produced to a thickness of 65 µm. Unlike commercial devices or other research efforts [1 – 5], this CS sensor, including packaging, is extremely thin (< 150 µm fully packaged) so that it can be unobtrusively placed between contacting structures. It is built from elastic, well-characterized materials, providing accurate and high-speed (50+ kHz) measurements over a potential embedded lifetime of decades. This work explored sensor designs for an interface load range of 0 – 2 MPa; however, the CS sensor has a flexible design architecture to measure a wide variety of interface load ranges.

This first generation CS sensor is 2 mm x 2.5 mm and is 65 µm thick (Figure 1). The circular diaphragms are designed to be free of stress concentrations, making them mechanically strong and tolerant of 10x times overloading. Diaphragm thicknesses of 0.5 – 25 µm and radii of 50 – 500 µm have been produced to accommodate load ranges for various applications. The sensor electronics are designed to show no temperature or humidity dependence and be drift-free over long-term use.

The novel CS sensor packaging utilizes several layers of flexible polyimide, to fully encapsulate the silicon sensor, which mechanically and electrically isolate the sensor from its environment (Figure 2). The packaging is designed to maintain a uniform thickness, including the region where the silicon sensor is mounted. The packaged CS sensor can withstand extreme loads without failure over tens of thousands of load cycles and survives repeated cycling between -40 to 70 °C while maintaining accuracy. The package addresses a variety of stringent mechanical and electrical requirements. It reliably maintains electrical contact with the device (no solder-joint failure) while simultaneously and robustly transmitting normal contact loads to the silicon sensor and isolating it from shear loads and its environment.

Basic characterization data is presented here for a diaphragm thickness of 15 µm and radius of 50 µm, although other diaphragm geometries exhibit similar results (more detailed data across extreme environments will follow.) Figure 3 shows the CS sensor output for 10 load cycles over a load range of 0.04 – 2.41 MPa. Across the full load range of the sensor, the maximum drift after 2 hours is < 0.7 %. Figure 4 shows the calibration curve for the 10 increasing segments showing excellent linearity ($R^2 > 0.99$). The average error (the difference in the measured load and the predicted load) of the sensor is 0.04 MPa, corresponding to an average accuracy of ± 1.5 % (the average of the absolute value of the error divided by the full-scale range of the device). The CS sensors have been subjected to tens of thousands of load cycles and exhibit good stability and repeatability over time.

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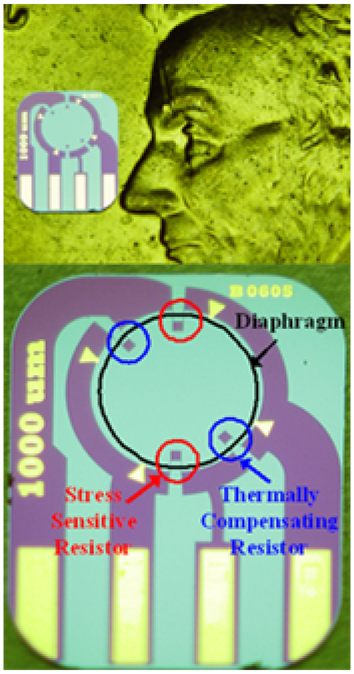

Figure 1. The top image shows the silicon MEMS CS sensor with a penny (for scale). The bottom image shows the implanted piezoresistor placement (red and blue circles) relative to the diaphragm location (black circle). Both images present a CS sensor with a diaphragm radius of 500 µm.

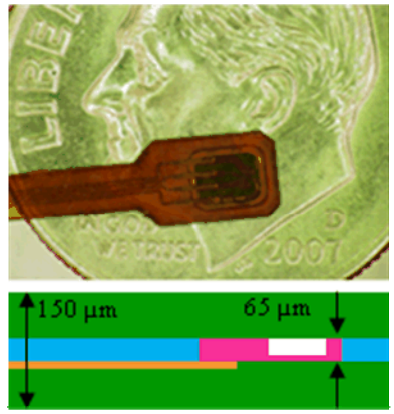

Figure 2. The top image shows a packaged CS sensor with a dime (for scale). The bottom image shows a cross-section of the packaged CS sensor (not drawn to scale). The silicon CS sensor (in red) is soldered to the package and is completely encapsulated by the polyimide (Top and Bottom Coverlays in green and Chip Shim in blue). The Bottom Coverlay has an electro-deposited copper layer (orange) for making electrical connections to the sensor and the external electronics. The package maintains a uniform thickness of < 150 µm and can be arbitrarily shaped to accommodate a variety of applications.

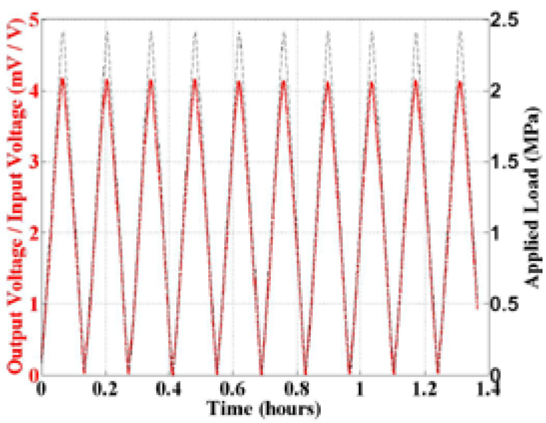

Figure 3. Graph of the CS sensor output (in red) for 10 time-varying load cycles over a load range of 0.04 – 2.41 MPa. The data shown is for a diaphragm thickness of 15 µm and radius of 50µm. Other diaphragm geometries exhibit similar results. The applied load profile is shown in black. (Note: The DC bias has been removed for clarity.)

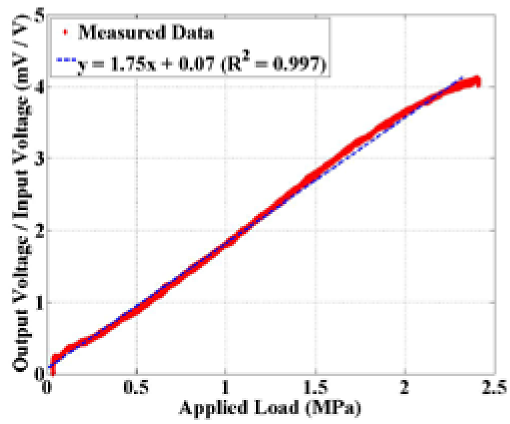

Figure 4. Graph of the linear calibration curve (in blue) for the 10 increasing load cycles (~2500 data points). Also shown is the data (in red) from a second load cycling test (7 increasing load cycles, ~1800 data points) for comparison with the established calibration data. The average accuracy for this data, compared with the calibration data, is ± 1.5 %, demonstrating the good performance of the packaged CS sensor. The data shown is for a diaphragm thickness of 15 µm and radius of 50 µm, although other diaphragm geometries exhibit similar results. (Note: The DC bias has been removed for clarity.)

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