Corrosion Enhanced Capacitive Strain Gauge at 370ºC

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Abstract—In this paper a silicon carbide passivated capacitive strain sensor is proposed which continuously and accurately measures strain in corrosive ambient and operates up to 370ºC in air. The analytical model of this low-mechanical noise, high-resolution and high-gain capacitive SiC coated sensor predicts 45 aF/µε sensitivity, which is in a good agreement with finite element analysis (within 12%) over the intended full-scale range of 1-1000 µε. The gauge is fabricated using silicon-on-insulator and coated with a thin (~ 60nm) pinhole-free 3C-SiC layer. The integrity of the passivation layer is tested using a hot KOH bath followed by SEM inspection which shows no defects or damage. A localized-heating, high-temperature testing setup has been built using an infra-red lamp to heat the gauge up to 370ºC while maintaining the electronics at significantly reduced temperatures. Experimental results show the strain gauge successfully continues to operate at 370ºC.

I. INTRODUCTION

Complex mechanical systems designers have turned to embedded sensor systems to provide higher performance, reliability and level of safety demanded of these systems. Failure to maintain the intended design under various environmental conditions could result in catastrophic events in industries such as automotive and aerospace. A real-time knowledge of strain is a reliable means to individually monitor the physical state of industrial components [1]. Currently different types of strain gauges are used to monitor structures in the field [2] or conduct laboratory research in mechanics of materials. However, state-of-the-art strain sensors are not capable of operating in harsh environments such as corrosive ambient and high temperature. Metal foil [3] and resonant strain gauge [4] measurements drift due to their temperature sensitivity. High-temperature encapsulation of Bragg-grating strain sensors has enhanced their operation in intense environments [5]. However they are sensitive to temperature and also its size and development costs limit their application and adoption. However, capacitive sensing mechanism is intrinsically temperature insensitive and exhibits higher performance stability and reliability for long-term application purposes. In addition to temperature, wear and corrosion could degrade the integrity of sensors’ materials. SiC as a structural material has shown significant resistance against corrosion and oxidation [6],[7]. However, Silicon Carbide (SiC) deposition for MEMS applications is expensive. The in-house state-of-art SiC deposition requires material characterization to deal with issues such as high-stress gradient and surface roughness. The commercial alternatives such as SiC-on-insulator do not qualify for high-volume production. Material degradation due to corrosion always starts from the outer surface and penetrates deeper into the structure. Therefore, if an LPCVD SiC deposition can form a conformal encapsulation layer around previously released microstructures [7], it will impart the inert characteristics of SiC at the interface of the device material with the surrounding environment.

In this effort, a poly-SiC coated capacitive strain gauge, working in air is presented, which measures strain in the range of 1-1000µε with 45 aF/µε at room temperature. A composite-beam analysis is performed which is consistent with ANSYS finite element analysis (FEA) (within 12%). A corrosion test is performed with subsequent visual evaluations which show the encapsulated device layer integrity. A temperature testing setup is designed to apply temperature as high as 370ºC while the gauge continuously operates and measures the applying strain using an on-chip strain actuator.

II. CAPACITIVE STRAIN GAUGE

Fig.1 shows a schematic of the MEMS capacitive strain gauge employed in this work. It is designed and fabricated to measure strain in the range of 1-1000µε in the sense-axis while attenuating cross-axis strain signals. The strain field in the industrial component is transferred to the sensor through bonding layer and eventually deforms the sensing structure. The device structure is similar to a four-point bending beam where the middle bending beam experiences deflection amplification due to rigid motion of two stiffened ends. The applied plane strain field is projected into sense- and cross-axes. The sense-axis strain generates a read-out due to middle-plate bending while the cross-axis strain effect is rejected by differential capacitive readout [8]. This sensor is fabricated from a silicon-on-insulator (SOI) substrate using a Surface Technology System (STS) Advanced Silicon Etch tool followed by a wet oxide-etch release. Experimental results show 50 aF/µε strain sensitivity, more than 90% of cross-axis strain effect attenuation and 472 Hz bandwidth which makes the gauge suitable for applications such as automotive and aerospace. The strain application is achieved.

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Fig. 1. (a) Schematic of the capacitive strain gauge device layer (top view) (b) deformed device layer due to the sense-axis strain application (c) SEM image of the strain gauge with an on-chip cross-axis strain actuator.

using an on-chip parallel-plate strain simulator for both sense and cross axes. The fabricated gauge is tested using a Commercial Off-The-Shelf (COTS) capacitive readout IC with 4 aF/√Hz resolution. A noise analysis shows the electronics noise sets the ultimate noise floor for strain resolution.

III. SILICON CARBIDE ENCAPSULATION

Manufacturing cost and repeatability is critical for industrial application of any new technology. In the last decades, Micro-Electro-Mechanical-Systems (MEMS) fabrication technology has advanced to such an extent that silicon has become vastly used in the industry. The processes for Si deposition and etch are well established and well controlled. On the other hand, its material properties limit the possibility of using Si as a structural material in harsh environments. Automotive and aerospace sensor environments typically are very hot (at temperatures higher than 300ºC) and may include exposure to corrosive fluids (such as acids or bases). Due to its chemical stability [9], [10], SiC has become a good structural material for MEMS dealing with extreme environments [11]. However, slow deposition and etch rate, high stress gradient and surface non-uniformity are on-going issues that need to be addressed in high-volume SiC sensor fabrication. The primary failure mechanism of a Si-based sensor in a harsh-environment is due to native oxide cracking and oxide propagation under mechanical and thermal cycling and structural deterioration due to the presence of etchants. A conformal SiC coating over a silicon-based gauge provides an erosion- and oxidation-resistant surface at the gauge interface with its surrounding ambient, yet enables leveraging a well established Si fabrication process.

A. Analysis

SiC deposition over a silicon-based sensor forms a composite structure which needs to be analyzed using a composite-beam model. SiC is a stiff material and it is applied far away from the neutral axis of the beam, so even though the SiC coating layer is orders of magnitude finer than Si structure, it still makes the coated structure significantly less flexible. Using the Rayleigh method the EI for the composite beam is: [10]

\[
EI_{\text{comp}} = \frac{E_{\text{SiC}} w t_{\text{SiC}}^3}{12} + E_{\text{Si}} \left( \frac{w t_{\text{Si}}^3}{2} + \frac{t_{\text{SiC}}^3}{6} \right)
\]

Where \(EI_{\text{comp}}\) is the composite beam’s EI, \(E_{\text{SiC}}\) (~490 GPa) and \(E_{\text{Si}}\) (~160 GPa) are SiC and Si modulus of elasticity, respectively. \(w\) stands for Si beam width and \(t_{\text{SiC}}\) is the SiC coating thickness. The coating does not have any significant effect on other physical dimensions or material attributes. The LPCVD SiC deposition provides a highly-conformal coating around the structure of the silicon sensor and its on-chip strain actuator (Fig.2,3). An FEA of coated strain gauge has been performed which results show a good agreement (within 12%) with the analytical model (Fig. 7).

B. Fabrication Process

The silicon-based sensor is fabricated through a one-mask process [8]. After critical point dry release of the structures, they are placed in an LPCVD poly-SiC furnace which deposits undoped SiC with 300 nm/hr growth rate at 800ºC temperature. The intended 60nm coating provides a good encapsulation over the silicon structure especially over critical features such as the bottom of the beams. (Fig.3)

Fig. 2. SEM image of the SiC coated (a) strain gauge (b) on-chip strain actuator.
The thickness of SiC coating should be increased to decrease the chance of pinholes in the film as well as extend the corrosion resistance lifetime. However, overly-thick films do not provide for adequate wirebond contact resistivity [7]. This compromise needs to be considered when designing the sensor.

C. Corrosion Resistant Test

Excellent chemical inertness of SiC qualifies it for corrosion resistant applications. Silicon nitride, well-known as an excellent insulating material could slowly be etched by HF and phosphorus acids. KOH is one of the most powerful Si etchants. In order to test the corrosion-resistance of the SiC coating over silicon structure, a hot (80°C) KOH bath is prepared. Two coated dice, one cleaved into two pieces and one full die are placed in the KOH bath for 20 minutes. As Fig. 4 shows, the exposed silicon structure start to bubble as a sign of the on-going etch process, while the full die shows no sign of any silicon-core exposure to the etchant.

The corrosion test is followed by an SEM inspection of the dipped dice. Fig. 5 shows no crack or erosion of the structures. This confirms the success of the deposition of a pinhole-free and highly-conformal coating layer.

D. High-Temperature Testing

Resonant SiC device has shown a robust performance at high temperatures without any signal attenuation due to degradation of the structural material [11]. In order to test the survival and performance of the coated device a testing setup is designed which uses an IR-lamp to heat up the gauge. The device is tested using a COTS capacitive readout with 4 aF/√Hz resolution and 5V operating voltage. An insulation barrier is designed to heat up the die while dispersing the generated heat away from the off-chip electronic circuit board. (Fig.6) The coated device is wirebonded to the circuit board through SiC coating layer.

E. Experimental Results

The predicted 45 aF/µε sensitivity by analytical model shows a good agreement (within 12%) with FEA and experimental results at the room temperature within the intended range of 1-1000 µε. The experiment was repeated several times which proves that the gauge successfully continues to operate at 370°C. The experimental results at 370°C show large variations with respect to the room temperature measurements. The heat insulation of the circuit board is designed to keep it below in the allowable range of
temperature. However further investigation indicates sensitivity of the capacitive readout chip to temperature variation in the circuit board. In addition, coefficient of thermal expansion (CTE) mismatch between SiC coating and Si device is anticipated to introduce readout error. An effort is undergone to eliminate such sensitivities to accurately measure the applied strain at the substrate.

Despite a very thin SiC coating, the resultant composite beam is stiffer than a silicon-based beam due to higher EI. In performing a vibration analysis of thin uniform beam the performance bandwidth is improved by at least 13%, compared to a silicon-based structure [8], which leads to a bandwidth of 535 Hz.

IV. CONCLUSION

A SiC coated capacitive strain gauge is fabricated, and tested to successfully operate at 370°C and survive corrosive ambient. The 60nm 3C-SiC coated gauge survived hot KOH etch after 20 minutes. A subsequent SEM inspection performed proved the coating is pinhole free. A high-temperature testing setup is designed to heat the gauge while the off-chip electronic circuit board is kept below the maximum allowable temperature. The gauge is tested using a COTS capacitive sensing chip and achieves 45 aF/µε. An additional benefit of the SiC coating is an improvement of the mechanical bandwidth by at least 13% due to the effective stiffness of the SiC coating. The strain measurements at 370°C show signs of temperature sensitivity. This sensitivity is anticipated to be due to errors introduced by the capacitive readout IC sensitivity to high temperature and CTE mismatch between the coating and device layer. Future work will include elimination of such errors to extract the signal purely due to the applied strain.

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REFERENCES