LOCALIZED STRAIN SENSING USING HIGH SPATIAL RESOLUTION, HIGHLY-SENSITIVE MEMS RESONANT STRAIN GAUGES FOR FAILURE PREVENTION

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ABSTRACT
Experimental measurements of the first-ever MEMS double ended tuning fork (DETF) resonant strain gauge, successfully bonded to steel by rapid inductive heating are presented in this paper. The localized strain-sensing results are compared with a finite element model. With a gauge length of just 200µm, the MEMS strain gauge enables higher spatial resolution and improved localized strain detection in comparison with commonly used metal-foil strain gauges, which average strain measurement over the entire metal-foil area. This sensing improvement enables the accurate detection of localized strains and may help improve crack propagation detection, and prevent catastrophic failures in structural elements.

KEYWORDS
Localized strain, strain sensor, failure prevention

INTRODUCTION
As it is impossible to completely eliminate stress concentrations in the design of machines and structures, there is a need for reliable monitoring methods to prevent catastrophic failures arising from defects such as cracks. Metal-foil strain gauges are commonly chosen in industry for such applications; however they average their strain measurement over the entire area of the metal-foil and lack the accuracy that is made possible by MEMS strain gauges. The high resolution and high bandwidth abilities of the MEMS double-ended tuning fork (DETF) resonant strain gauge have been demonstrated previously by resolving on-chip, electrostatically actuated strains[1, 2].

This paper sets forth the direct successful implementation of the MEMS DETF resonant strain gauge bonded to steel and a comparison of MEMS DETF resonant strain gauges with the Vishay metal-foil gauge under-predict localized strain due to averaging over metal-foil area and may not detect impending failure.

The surface of a 1095 steel parallel, 1 in wide, 6 in long, and 0.0325 in thick was roughened with 400-grit sandpaper to remove any surface oxides and cleaned with acetone. A stenciled metal screen-printing shim was used to deposit a repeatable 46 µm layer of 96.5Sn-3Ag-0.5Cu lead-free solder paste, (S3X58-M405, Koki Company Ltd.), on the steel parallel in the precise bonding location for the sensor. The sensor substrate was placed on the solder paste and an Ameritherm Nova Star 1M induction heating module with an eight-turn copper induction coil, 16 mm in outer diameter, and 3.25mm pitch, was operated at a power of 500 W and a frequency of 11.7 MHz at a distance of 9.05 mm above the bond location. A bonding temperature of 220 °C was achieved in nine seconds.

To fairly compare the two sensors, a blank double-side-polished silicon die was bonded in the same position as the MEMS DETF resonant strain gauge on an identical steel parallel. The Vishay metal-foil strain gauge repeatable induction bonding process, presented previously, was implemented [3]. The MEMS DETF strain gauge was designed with a 200 µm gauge length, 4.67 µm beam width, and 10.6 µm thickness, with a substrate die size of 5 mm x 5mm x 300 µm and was fabricated on a silicon (100) orientation wafer using a four-mask Robert Bosch GmbH commercial micromachining process. An adhesion layer consisting of 25nm Ti/400nm Ni/10nm Au was deposited on the backside of the MEMS DETF resonant strain gauge substrate using electron beam evaporation.

Figure 1: MEMS resonant sensors with micro-scale gauge lengths enable accurate local strain measurements on structural components for improved real-time monitoring and catastrophic failure prevention. Commonly used metal-foil strain gauges under-predict localized strain due to averaging over metal-foil area and may not detect impending failure.

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was then bonded on top of the blank silicon die with M-Bond 610 epoxy as directed by Vishay’s product bulletin “B-130-15”. In this configuration, the metal-foil strain gauge would be exposed to the identical strain experienced at the anchors of the MEMS DETF resonant strain gauge.

**Strain Testing**

Two loading setups were fabricated to compare the MEMS DETF resonant strain gauge with the metal-foil strain gauge. Firstly a well-characterized cantilevered diving-board setup was used to correlate strain measured by the MEMS DETF resonant strain gauge with the strain measured by the metal-foil strain gauge. A displacement was applied to the cantilevered steel parallel with a screw, capped with a rounded acorn-nut to reduce contact area, while a dial indicator with 0.001 in markings was used to record the displacement. The edge of the substrate was positioned 18.25 mm away from the clamp and the load screw was located 95.0 mm away from the clamp, directly centered over the parallel.

Secondly, a clamped-clamped setup was developed to compare the localized-strain sensing abilities of the MEMS DETF resonant strain gauge with those of the metal-foil strain gauge as shown in Figure 2. The clamps were positioned 2.5 in apart and the left edge of the substrate was positioned 0.65 in away from the left clamp. The top edge of the substrate was bonded 0.290 in from the edge of the steel parallel. This setup was designed to enable two clamped-clamped loading conditions in which the displacement-applying load screw could be positioned either directly beneath the center of the sensor substrate or positioned 2 mm from the edge of the sensor. These conditions simulate different strain distributions which resemble the presence of a crack and the approach of a propagating crack. These two clamped-clamped loading conditions generate strain distributions that result in significantly different average strains over the area of a metal foil strain gauge while maintaining a different-from-the-average local strain at the precise location of the MEMS device, thus demonstrating the ability of the MEMS DETF resonant strain gauge to detect localized strains in an area where strain averaging would not accurately predict the formation or propagation of cracks.

**FINITE ELEMENT METHOD MODELING**

**The Model**

A finite element analysis was developed in ANSYS 12 to simulate the clamped-clamped, non-uniform strain experimental setup and to determine the anticipated strains measured by the sensors along their sense axis. The material properties of the 1095 steel parallel, the 96.5Sn-3Ag-0.5Cu solder layer, and the silicon die were taken from literature and the steel and solder were best assumed to be isotropic while the silicon was modeled with anisotropic (100) wafer orientation mechanical properties [4, 5, 6]. Solid186, a high-order structural solid element, was used for meshing and generating the components. The entire beam from clamp to clamp was modeled due to a lack of symmetry. The steel parallel was modeled with the silicon substrate bonded on top of the solder layer, which was directly atop the steel parallel. The elements used for meshing in the vicinity of the silicon substrate were 250 µm by 250 µm in area and their thicknesses, depending on which material layer they were located, corresponded to one-third the thicknesses of the respective steel, solder, and silicon.

![Figure 2: A) Schematic of the experimental setup used to impart a prescribed localized strain field to the sensor. Electronics board and dial gauge omitted for clarity. B) Trimetric view of experimental setup. C) Close-up view of MEMS resonant strain gauge. D) Loading screw is capped with rounded acorn-nut to ensure point-contact. Dial gauge measures displacement of loading screw.](image-url)

Constraints of zero degrees-of-freedom were placed at the ends of the beam to simulate clamping. These boundary conditions were placed distantly enough away from the area of interest to ensure a well-developed strain field in the proximity of the silicon die. The displacement imparted by the rounded-acorn nut was simulated as a point displacement of 0.010 in at the node where the screw contacted the steel parallel, both below the center of the sensor substrate and 2 mm offset from the upper edge of the substrate as shown in Figure 3.

**Model Results**

The strain field intensities along the sense-direction of the sensors resulting from the two different clamped-clamped non-uniform loading conditions are shown in Figure 3. In the first centered loading case, the maximum strain is located at the center of the silicon substrate with the strain intensities decreasing with
distance from the center of the substrate. The second case of loading 2 mm above the substrate edge shows the peak strain occurring at the center of the top of the substrate, with sense-direction strain intensities decreasing radially away.

For the loading condition located directly beneath the center of the substrate, the 0.010 in displacement generated a strain of 845 microstrain (µε) at the location of the MEMS DETF resonant strain gauge along the sense direction. By averaging the strain over the area of the metal-foil gauge, a strain of 565 µε was calculated.

In the second configuration the 0.010 in displacement, offset 2 mm from the top edge of the substrate, yielded a strain of 698 µε at the MEMS DETF resonant strain gauge location while a strain of 434 µε was calculated as the average strain over the metal-foil area.

**Experimental Results**

**MEMS DETF Resonant Strain Gauge Sensitivity**

The strain sensitivity of the MEMS DETF resonant strain gauge was required to determine the frequency response of the gauge due to applied strains. A custom built circuit board was wire-bonded to the MEMS and +12 V and -12 V potentials were applied to the board to drive the resonator while a 40V pull-in bias was applied to lock-in the resonant strain gauge. With zero externally applied strain, the bonded MEMS DETF resonant strain gauge had a natural frequency of 212.825 kHz. The metal-foil gauge was connected to a Vishay 2100 strain gauge conditioner to determine measured strain. Using the cantilevered setup, a 0.300 in displacement from the load screw generated a frequency shift of 13.770 kHz in the MEMS DETF resonant strain gauge and a strain of 663.5 µε measured by the metal-foil strain gauge, yielding a strain sensitivity of 20.75Hz/µε as shown in Figure 4. This strain sensitivity is the highest recorded strain sensitivity to date for bonded silicon MEMS DETF resonant strain gauges [7].

**Non-Uniform Localized Strain Sensing.**

With the displacement first applied directly beneath the center of the substrate, 0.010 in of displacement yielded a MEMS DETF resonant strain gauge strain of 656 µε and a metal-foil strain measurement of 596 µε and with the displacement applied 2 mm away from the edge of the sensor substrate, the MEMS DETF resonant strain gauge measured a strain of 655 µε while the metal-foil gauge measured 392 µε. These experimental results for both loading conditions are plotted against the theoretical predictions from ANSYS in Figure 5.

The results of the experimental measurements agree reasonably with the predicted values from the theoretical model. The MEMS DETF resonant strain gauge is capable of detecting the high local strains caused by the loading condition. As predicted, the metal-foil strain gauge averages the strain over its area and thus records a lower strain than the maximum strain present. This prompts that a substrate with multiple MEMS DETF resonant strain gauges would be able to more-accurately measure and profile the strain gradient across a local area than a metal-foil strain gauge. In areas of stress concentration monitoring, this technology would be well suited to detect arising strains associated with crack formation and propagation.

In the case of the centered applied load, the strain measured by the MEMS gauge shows a discrepancy between the modeled and measured strain. A possible explanation for this phenomenon is that the tethers of the DETF have a series of release-holes used in the fabrication process; these holes deform when subjected to high strains, causing a shift in measured frequency.

For the load applied to the steel parallel, 2 mm offset from the edge of the die, the ANSYS predicted strain values for the MEMS and the metal-foil correspond well with less than 10 % error. The strains encountered by both MEMS strain gauge and metal foil strain gauge were reduced and so DETF effects such as tether deformation were reduced.

It is noted that the measured strains calculated from the frequency shifts of the MEMS DETF resonant strain gauge are within 2 µε for the two clamped-clamped
loading conditions. After the non-uniform loading tests were performed, the strain sensitivity experiments were repeated and the results were still in agreement with the aforementioned strain sensitivity. Centered-loading tests were repeated and the frequency shifts also agreed with the previously collected results.

Furthermore, in previous work, the same bond between silicon and steel has been demonstrated to survive beyond 1000 µε under cyclic fatigue testing, thus ruling out bond delamination and fatigue as the cause for the measured strain being lower than the predicted strain [3]. With further refinement of the DETF design, strain transmission loss at the anchors can be reduced and the experimental values measured from the MEMS DETF resonant strain gauge are expected to more-closely align with the predicted theoretical values from the finite element analysis.

### CONCLUSION

In conclusion, the silicon MEMS DETF resonant strain gauge offers a high spatial resolution, much higher than that of traditional metal-foil strain gauges, thus proving worthy in detection and failure prevention application. Additionally, the MEMS strain gauge is capable of higher sensitivity and resolution than traditional metal-foil strain gauges. This paper provides a detailed comparison of the MEMS DETF resonant strain gauge with the metal-foil strain gauge. A bonding method was developed to secure the MEMS resonant strain gauge and metal-foil strain gauge to steel parallels for repeatable testing; an experimental setup was fabricated to characterize the MEMS DETF resonant strain gauge and determine its sensitivity after bonding; another experimental setup was designed and fabricated to impart a non-uniform, localized strain gradient to the silicon substrate in order to compare the localized strain sensing ability of the MEMS DETF resonant strain gauge with that of the metal-foil strain gauge; an ANSYS simulation was developed for the non-uniform loading experimental setup and it was used to predict the strains encountered by

![Figure 5: Comparison of MEMS DETF resonant strain gauge and metal-foil strain gauge. Predicted strain values from ANSYS are shown. MEMS gauge consistently measures the high local strain while foil gauge inadequately estimates actual strain. The foil gauge would not have been able to sense crack development while the MEMS sensor would have sensed strain front.](image)

the MEMS DETF resonant strain gauge and the metal-foil strain gauge; and, lastly, the results from the experiments were compared with the predicted strain values from the ANSYS simulation.

The MEMS DETF resonant strain gauge offers accurate measurements of strain over a small localized area, which a conventional metal-foil strain gauge might under-predict the actual strains present. For critical applications where high strains are known to occur, an array of MEMS DETF resonant strain gauges on a single substrate would be able to accurately and locally determine the strain gradient occurring at the specified location and detect high strains before catastrophic failures take place.

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### REFERENCES


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