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# Wireless temperature microsensors integrated on bearings for health monitoring applications

S. Scott
*Birck Nanotechnology Center, Purdue University*

Andrew Kovacs
*Birck Nanotechnology Center, Purdue University*, akovacs@purdue.edu

Lokesh A. Gupta
*Birck Nanotechnology Center, Purdue University*, lgupta@purdue.edu

J. Katz
*Birck Nanotechnology Center, Purdue University*

Farshid Sadeghi
*Birck Nanotechnology Center, Purdue University*, farshid.sadeghi.1@purdue.edu

***See next page for additional authors***

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**Authors**

S. Scott, Andrew Kovacs, Lokesh A. Gupta, J. Katz, Farshid Sadeghi, and Dimitrios Peroulis

# WIRELESS TEMPERATURE MICROSENSORS INTEGRATED ON BEARINGS FOR HEALTH MONITORING APPLICATIONS

*S. Scott, A. Kovacs, L. Gupta, J. Katz, F. Sadeghi, and D. Peroulis*
Purdue University, Birck Nanotechnology Center, West Lafayette, Indiana, USA 47907

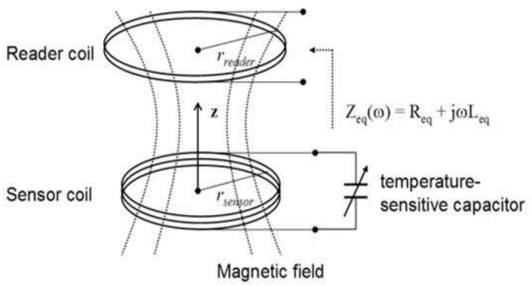
## ABSTRACT

This paper reports the performance of a wireless MEMS bimorph temperature sensor integrated on a bearing for component health monitoring applications. The sensor consists of a robust array of bimorphs consisting of gold and thermally-grown oxide operable to at least 300°C. Fabrication details are included, as well as the hermetic packaging information. Speed of actuation results from a high-speed camera is included showing the actuation time is less than 600 µs. Reliability testing of the bimorph array up to 400 million thermal cycles is also shown, after which the bimorphs still yield consistent behavior. Finally, dynamic testing is performed showing actual bearing temperature values at different speeds on a real-world helicopter bearing.

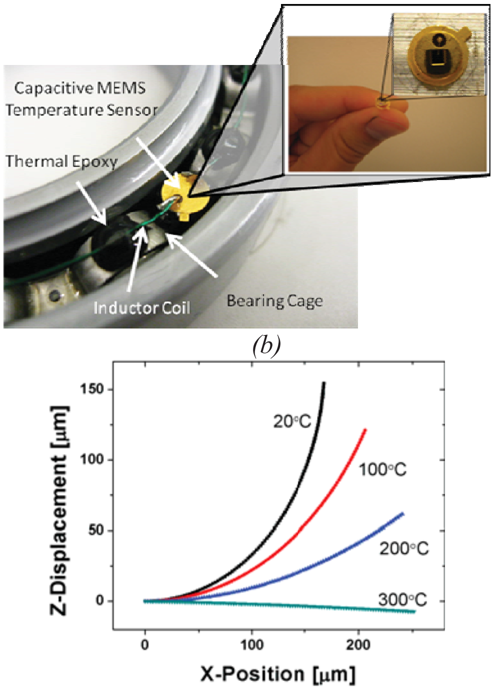
## INTRODUCTION

### Bearing Background

When a bearing is at a specific speed, it should be at a certain temperature, indicating that it is “healthy”. When damage to a bearing occurs, the rotating component will often have increased friction, which results in an increased temperature. Knowing this increased temperature value can be extremely valuable in preemptively detecting bearing failure [1]. Unfortunately, little is known about actual bearing temperatures today. Typically, a thermocouple is placed on a bearing housing, a large distance from the cage, or actual rotating component of the bearing. This temperature is very slow to respond to condition changes inside of the bearing. It has been shown [2] that an *LC* resonator containing a capacitance value which is sensitive to temperature change can be integrated directly on the bearing to detect temperature, as in Figure 1a-b. Unfortunately, commercially-available capacitors do not meet the three necessary specifications: small in size, high in temperature operation (up to 300°C for some applications), and monotonic throughout its range.



*(a)*



*(b)*

*(c)*

*Figure 1: An inductor and temperature-sensitive capacitor are connected, and the resonant frequency is interrogated wirelessly (a). The inductor and capacitor are integrated directly on the cage of a roller bearing (b). A MEMS sensor which has been shown to operate to 300°C is used (c). The beams are pre-stressed and deflect upwards at room temperature, deflecting down as temperature increases.*

### MEMS Bimorph Background

The authors have previously demonstrated a capacitive bimorph MEMS sensor and its resonant frequency versus temperature up to 300°C when integrated on a static bearing [3]. The bimorphs made use of thermally grown oxide, which allowed for higher temperatures than a PECVD oxide (Figure 1c). It was stated that the reliability was improved as well, but no data was shown as proof. This work focuses on performance of the bimorphs, including speed of actuation measurements performed under a high-speed camera, electro-thermal cycling measurements of the bimorphs, and dynamic tests performed on an actual helicopter tail-rotor bearing.

## FABRICATION

The fabrication is performed similar to in [3], but the process has been updated to achieve higher values of capacitance. First, a thermally-grown oxide is deposited on a low-resistivity silicon wafer (Figure 2a). This oxide is then patterned (Figure 2b), and sputtering of an adhesion layer of

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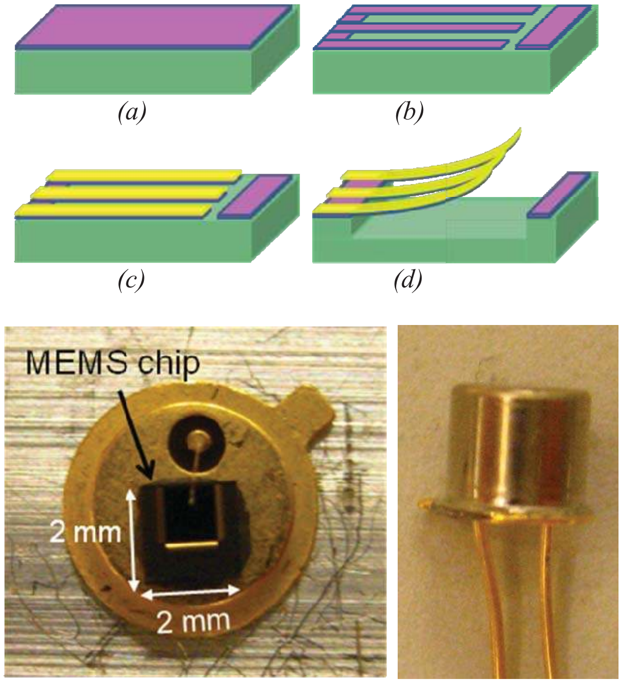
Ti, and a thicker Au layer commences (Figure 2c). $XeF_2$ gas is then used to do a dry-etch of the silicon substrate, releasing the beams (Figure 2d). Residual stresses cause the cantilevers to naturally deflect upwards at room temperature. The wafer is then diced, and the sample is mounted on a commercially-available transistor outline (TO) header, and a wire-bond is placed from the pad to the pin of the package (Figure 2e). Finally, the package is hermetically sealed by placing a cap on the header and using a resistance welder (Figure 2f), and a 50 hour anneal at 200°C is completed.



*(a)* *(b)*

*(c)* *(d)*

*(e)* *(f)*

*Figure 2: MEMS sensor fabrication. First, an oxide is grown (a) and patterned (b) on a lo-res wafer. Next, a metal layer of Ti/Au is sputtered and patterned (c). Then, the beams are released using $XeF_2$ gas (d). The chip is then mounted and wire-bonded (e) on a commercial transistor outline (TO) header, which is finally hermetically sealed using a resistance welder (f), and a 50 hour anneal of the sample at 200°C is performed.*

The sensor fabricated in this fashion consists of the typical MIM capacitor, where the top electrode is actually the moving bimorphs, the insulator is the thermally-grown oxide, and the bottom electrode is actually the low-resistivity substrate. Because the wafer is low-resistivity, and is in contact with only the metallic header and conductive adhesive, the chip is grounded to the header. Thus, capacitance is sensed between the grounding pin and the isolated second pin, which is attached to the chip by the wire-bond. The large wire-bond pad allows for a static offset capacitance to achieve the desired resonant frequency when integrated with the inductor.

## BIMORPH PERFORMANCE

### Capacitance-Temperature Response

The capacitance response to temperature shown in Figure 3 is measured by placing the sensor in an oven while leads are connected to a capacitance meter. Knowing the capacitance range of the sensor allows the designer to approximate the resonant frequency of the sensor with inductor.

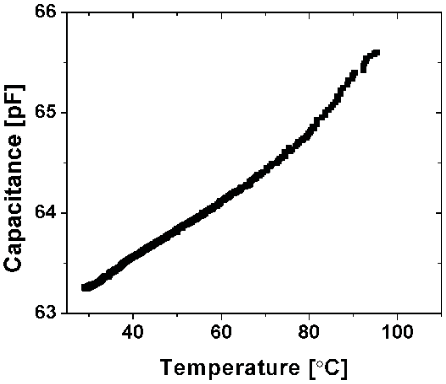
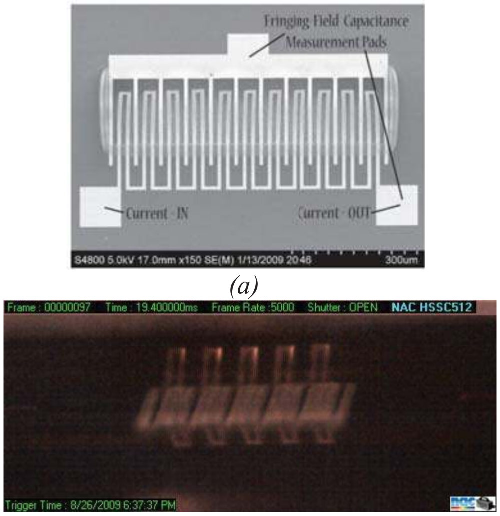


*Figure 3: Measured sensor capacitance vs. temperature calibration curve obtained by placing the packaged MEMS sensor in an oven while measuring it with a capacitance meter.*

### Speed of Actuation

Thermal ovens typically take a large amount of time to reach a desired temperature, as well as to cool off again. To quickly actuate the beams, a different method of heating is used. Adjacent beams were connected at the tips, and the next at the anchors in a meander fashion, as shown in Figure 4a. The beams can then be actuated with a precision current supply. The Keithley 6221 is used, which has a maximum response time of 100 µs, and a typical fast response time of 2 µs [4]. Two frames from a high-speed camera are shown 600µs apart in Figures 4b-c.



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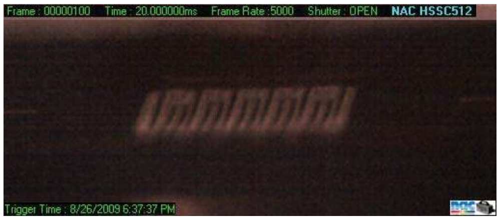


*(c)*

*Figure 4: Meandered structure used for actuating MEMS beams (a) and sensor speed of actuation determined by viewing sample under a high-speed camera (5,000 Hz sampling) and electro-thermally actuating. Frames (b) 97 and (c) 100 show the beams actuating in under 600 µs, much faster than the necessary response time in the application.*

### Reliability

To complete the maximum number of cycles possible in a short amount of time, the beams were placed as they were in the previous measurement. This allowed us to actuate the beams using Joule heating supplied by a 500Hz square wave. The samples were then scanned with a LEXT confocal microscope [5] both unbiased (at room temperature) and biased to a deflected, or 'down,' state (~250°C). Each scan required approximately ten minutes of steady state bias. Figure 5 shows the results of both the up and down-state measurements. One can see that there is very little drift in the beam profile even for a large number of cycles. Furthermore, the perceived uncertainty increase at 1 million cycles is likely due to the need to remove the cycles and replace them in between measurements. This is because the cycling time becomes appreciable at this point (hours instead of seconds), and the equipment could not be reserved for the entire duration of the test (over a week).

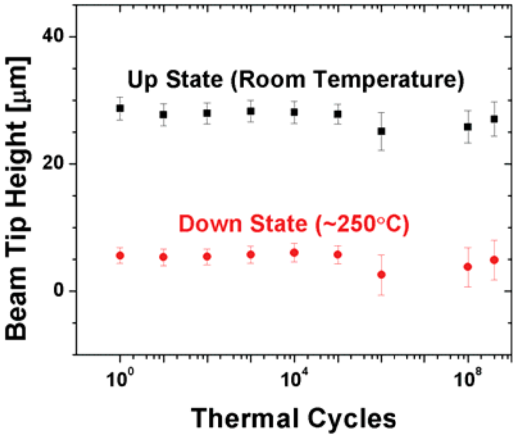


*Figure 5: MEMS beams are cycled electro-thermally for reliability and the beam heights are obtained using a LEXT laser confocal microscope. These results show very little drift over 400 million cycles. At even hundreds of cycles per day, this far exceeds requirements. Uncertainty increases at 1 million cycles at this point, likely because the samples under the microscope were removed and replaced each time a measurement was conducted.*

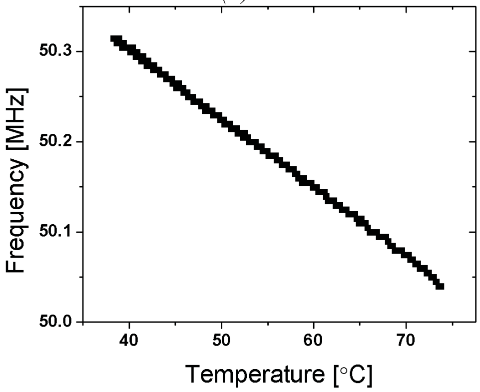
## DYNAMIC BEARING TESTING

### Static Calibration Curve

Typically, one would use a network analyzer to measure the resonant frequency and extract temperature. For practical applications and field measurements, this method cannot be used as network analyzers are bulky and costly. A small, intelligent detector circuit that can measure the temperature and send the acquired data to a computer for further analysis was developed using commercially available components.

The principle of operation is similar to a scalar network analyzer performing single port measurements. A commercially available voltage-controlled oscillator (VCO) is used to power the device under test. The VCO generates a frequency sweep that is connected to the sensor through a matching network. An RF power detector circuit detected the signal level before the matching network using a T connector and generated equivalent DC output. Knowing the amplitude of the RF signal at every frequency step, the resonant frequency of the inductor and MEMS capacitor was measured versus temperature in a hot oil bath (Figures 6a-b).

*(a)*



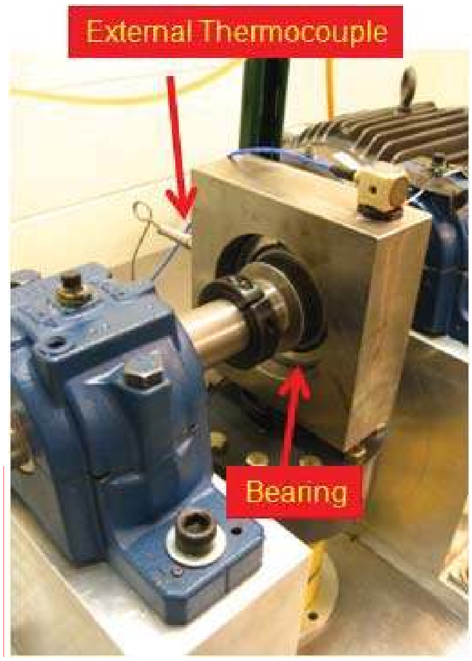
*(b)*

*Figure 6: Calibration curve measurement: (a) hot oil bath with MEMS sensor and receiver coil and measured bearing resonant frequency vs. temperature calibration curve (b).*

**Dynamic Test**

The test rig used to validate the sensor in real-world operation is custom-made to resemble the tail rotor shaft of helicopters (Figure 7a). It consists of a stainless-steel housing that the bearing is press-fit into, and a shaft of hardened steel that is also press-fit into the inner race of the bearing. Both ends of the shaft are fixed by pillow block bearings to the table, and the motor is connected to one end of the shaft by way of a belt and pulley system. Underneath the metallic housing, a load cell with hydraulic jack is used to create a radial load on the bearing. The rotational speed and radial load can both be changed independently to create different conditions that the sensor can be tested under. On the bearing itself, the sensor is installed with the receiver taking the place of a snap-ring. On the metallic housing, there is a small hole that goes all the way through to the outer race of the bearing. A thermocouple is installed in this hole so that it directly contacts the outer race. This allows a direct comparison between the outer race of the bearing and the cage temperature inside the bearing. An accelerometer is attached to the top of the housing for vibration analysis, which is beyond the scope of this paper.

The bearing is started at static, ambient condition, and the resonant frequency is noted. The rig is then run at 500 RPM intervals up to 2,500 RPM. Figure 7b shows the results from both the MEMS sensor's extracted temperature value and the housing thermocouple's reading.



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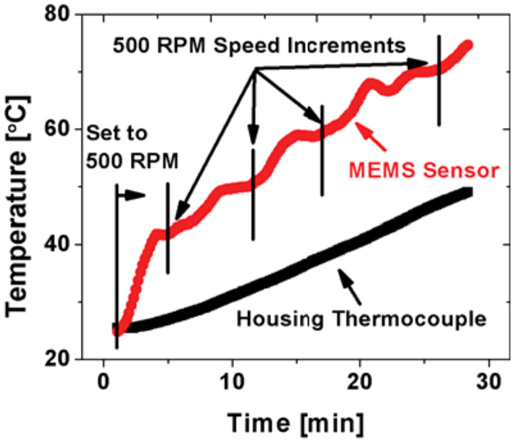

*(b)*

*Figure 7: Dynamic bearing testing rig (a) and bearing temperature vs. time (b) as measured by a MEMS sensor on the cage and a thermocouple on the outer race (existing monitoring method). As speed is increased, the MEMS sensor detects the change in temperature much more quickly than the thermocouple.*

## CONCLUSION

A robust, high-temperature MEMS sensor for component health monitoring applications has been presented. The speed of actuation results and cycling data have shown the sensor responds in under 600µs repeatedly at least 400 million times. The capacitive sensors calibration curve has been generated and the resonant frequency calibration curve shown when integrated on the bearing. Finally, successful dynamic testing of the MEMS sensor on a bearing has been completed to 2,500 RPM. The MEMS sensor proves to be a valuable and reliable instrument in component monitoring and failure detection.

## ACKNOWLEDGEMENT

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