MEMS Sensing in an In-Cylinder Combustion Environment

Sarah Wodin-Schwartz*, **M.A. Hopcroft, D. G. Senesky, A. P. Pisano**
Mechanical Engineering, University of California at Berkeley, Berkeley, USA
*Presenting Author: swodin@berkeley.edu

Abstract: In this research, platinum thermoresistors are tested within a combusting 1000-Watt Chicago Generator engine modified with a sensor access port to provide direct sensor exposure. Two methods, a Ni based Cotronics high-temperature conductive adhesive and Al wire bonds, were used to electrically connect the thermoresistors to modified low-resistance sparkplugs. Thermoresistors were calibrated using an IR lamp and real time temperature response traces for the thermoresistors within the firing cylinder were measured. A temperature differential between the intake and exhaust strokes of 6°C was measured. Soot residue was found to form on the engine when running at a cold start however no residue was observed the engine was running with a warm start.

Keywords: In-cylinder, engine monitoring, thermoresistors

INTRODUCTION

The goal of this research is to show that MEMS sensors can obtain usable data from within an octane combusting cylinder. To achieve this goal, platinum thermoresistors were fabricated to measure in-cylinder temperature. A small engine was modified with an access port for the sensor and feedthrough system. The thermoresistors were bonded to modified sparkplugs to collect the temperature data in real-time. This set-up is shown schematically in Figure 1.

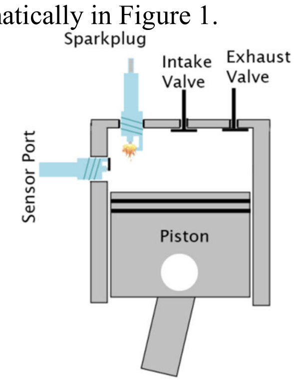

Figure 1- Graphic of piston/cylinder with MEMS sensor port, spark plug, and valves. The MEMS sensor is directly exposed to the spark front.

ENGINE THEORY

Thermal Modeling

Before sensor testing, a basic environmental characterization model of the combustion environment was generated. This model gives a general idea of the heat at the engine wall where the sensors are located.

To determine the heat at the surface of the sensors during a full engine cycle, heat transfer coefficients from both Annand are Woschni models are used to solve for the heat flux, $\frac{\partial Q}{\partial \theta}$. The overall energy balance for then engine, shown in Equation 1, shows that change in internal energy in the system is equal to the heat flux less the system work.

$$\partial Q - \partial W = \partial U \qquad (1)$$

Internal energy and work are solved for and the derivative is taken relative to crank angle, shown in Equation 2.

$$\frac{\partial Q}{\partial \theta} - \left(1 + \frac{c_v}{R}\right) P \frac{\partial V}{\partial \theta} = V \frac{\partial P}{\partial \theta} \frac{c_v}{R} \qquad (2)$$

This equation is solved using both Woschni and Annand models for the convection term used to solve for pressure at each crank angle shown in Figure 2.

The Woschni heat flux trace is used to make a 1D conduction model of the sensor mounted within the engine. This approximates that the sensor surface will be approximately 560°C (Figure 3).

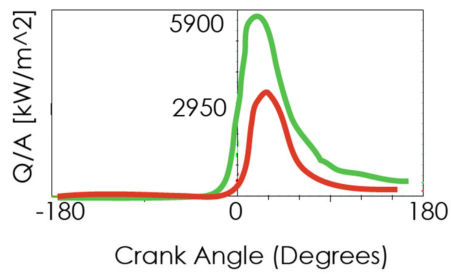

Figure 2- Heat flux trace for the Chicago Generator engine. These traces show both the Woschni (red) and Annand (green) models for the heat transfer coefficient versus crank angle [1].

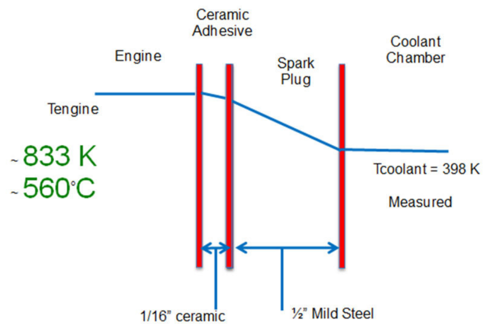

Figure 3 - 1D conduction model for die holder and ceramic adhesion layer.

THERMORESISTOR DESIGN

A set of platinum thermoresistors of varied geometries, with a titanium adhesion layer, was fabricated on Si dies in the UC Berkeley Microfabrication laboratory. Post fabrication the sensor resistances were compared with the theoretical calculations. The actual resistances of the sensors at room temperature are shown in Figure 4. The as-deposited resistance is higher than theoretical resistances based on the geometry which was verified using a profilometer and microscope. Once annealed, the resistance decreased. This indicates that the resistivity of the sputtered platinum is higher than that of bulk platinum. This is not unexpected, as many papers have studied the resistivity of sputtered platinum films based on the sputtering parameters[2]. This is due to the fact that at the thin film scale, resistance can be affected by grain boundary scattering which is neglected in bulk material analysis [3][4][5][6] and [7].

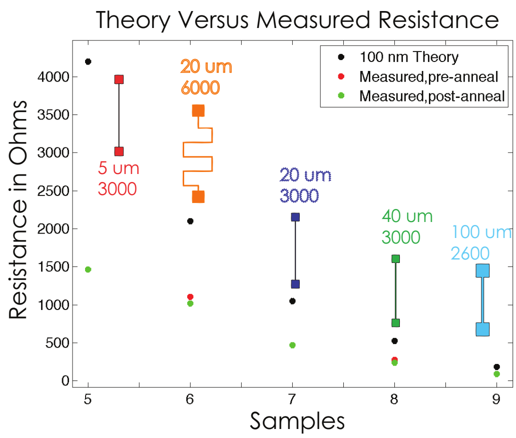

Figure 4- Resistance of platinum samples at room temperature versus the theoretical resistance for five samples drawn on the plots.

WIRE FEEDTHROUGH AND SENSOR BONDING

To collect the thermoresistor signal from within the cylinder, a 1 ohm resistance sparkplug (from ACCEL Ignition) was modified to create an inexpensive feedthrough capable of surviving pressures and temperatures encountered within the engine. The initial electrical connections from the sensor bond pads to the sparkplug electrodes were made with Cotronics nickel resbond adhesive (Figure 5).

Aluminum wire bonds, shown in Figure 5, were also used as a connection method between the thermoresistor and the sparkplug feed through. This connection method required separate mechanical and electrical connections at the interface. The mechanical attachment was made using a ceramic adhesive.

Figure 5 – Image of Pt thermoresistor mounted to a sparkplug with Ni resbond used as electrical contact (left) and Al wirebonds connect the sensor (right).

ENGINE MODIFICATION

A Chicago Generator engine (Figure 6) was modified to be used as a testing platform for the MEMS sensors. The cylinder head was removed and a hole was drilled as an access port for sensors as shown in Figure 7. The top of the hole was planarized to make a smooth mating surface for an adaptor plate. Two adaptor plates were machined, one for the modified sparkplug and one with no access hole to allow the engine to fire without a mounted sample

Figure 6- Image of Chicago Engine Generator which was modified for MEMS sensor testing.

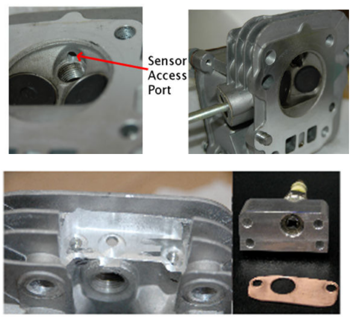

Figure 7- Modified Chicago Generator Chicago Generator Engine test engine cylinder head (Top), the black circles are the valves. SiC MEMS Sensor access port (Lower-Left) into the Sparkplug adapter block with Pt sensor and copper gasket (Lower-Right).

CALIBRATION

A calibration test was performed to observe the thermoresistors response to temperature variations. These tests were conducted using an IR lamp with samples mounted on sparkplugs shown in Figure 8. The lamp intensity was cycled to observe the thermoresistors resistance change with temperature. This setup was able to track the behavior of the whole test device including the spark plug packaging. The response of one sample is shown in Figure 9. This test setup was able to show that the thermoresistors have a linear response with temperature.

Figure 8 - IR lamp test setup. The modified sparkplug with a surface mounted thermoresistor.

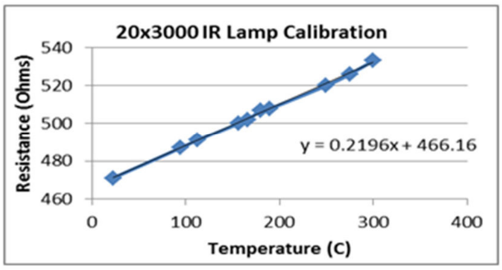

Figure 9 –Calibration temperature response for one of the thermoresistors from the heated probe station. The linear regression equation is shown on the plot.

SENSOR TESTING

The first test sensors were attached both mechanically and electrically with the nickel resbond adhesive. A simple data collection circuit was designed to acquire engine data. The output voltage was measured with a virtual instrument (LabView) and a data acquisition card (National Instruments). Data was sampled at 10 kHz so that the 3600 RPM engine speed could be observed in the temperature readings. As the engine is a 4 stroke system, the observed frequency is at 1800 RPM.

The Ni resbond attachment method failed to maintain its electrical integrity for more than a few minutes within the combustion environment. The results from one sensor, which failed after about 10 seconds of engine runtime, are shown in Figure 10.

The Aluminum wire bonded samples were able to collect data from within the engine for 20-minute tests without connection failure. The filtered real time temperature response traces for one of the sensors in

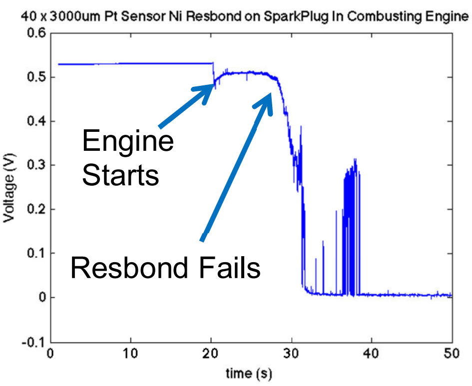

Figure 10- The Ni resbond broke down after about 10 seconds of engine run time.

the firing cylinder, shown in Figure 11, has a temperature differential between intake and exhaust strokes of 6°C. This value is between 5°C and 9°C depending on the sensor design. The thermoresistor is not able to measure the instantaneous flame temperature or the true temperature of the intake air due to its thermal mass; however the average temperature is centered around 565°C. Four different thermoresistor designs measured average engine temperatures of 560, 570, 575 and 600°C. All of these measured temperatures are within 7% of the theoretical 1D conduction model temperature of 560°C.

The thermoresistors that were tested within the engine were in one of two engine environments, "cold" or initial running state before the engine was warmed up, and "hot" or once the engine had been warmed up. In the cold engine environment, an oil residue similar to that seen in previous work adheres to the silicon surface [8]. This residue coated both the Si surface and the Pt trace on the sample. The samples tested once the engine was warmed up did not have this oil residue layer adhering to the surface of either the Si or the Pt. One sample from each of these testing conditions can be seen in Figure 12.

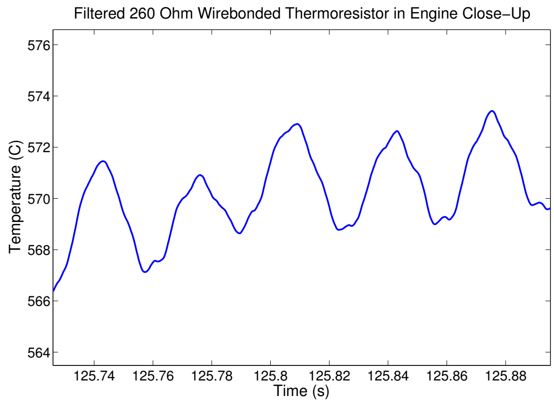

Figure 11 - Temperature response for one thermoresistors during a 10-minute test within the engine. The 3600 RPM (as rated by the generator manufacturer) is shown with an 1800 RPM signal. This data is filtered using a moving average to reduce high frequency noise.

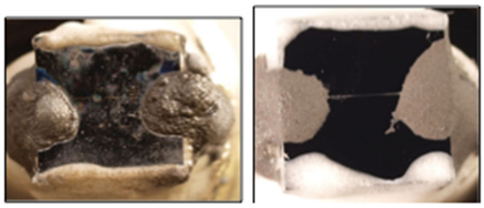

Figure 12- A Pt thermoresistor run in a cold start environment (left) and a warm start environment (right). The cold die sample has a thicker oily surface which clouds the Pt line from view. No oil is observed on the surface of the hot sample.

DISCUSSION AND CONCLUSIONS

This research project consisted of fabricating platinum thermoresistors for testing within an octane combustion environment. To meet this goal, high temperature/high pressure feedthroughs were fabricated from low resistance sparkplugs, two separate wiring systems were tested, an engine was modified, and the thermoresistors were calibrated. The modified low resistance sparkplugs proved to be effective, inexpensive two lead feedthroughs for the interim wiring system. While these feedthroughs provided a temperature and pressure seal for the engine compartment, die attachment to the feedthrough proved difficult. Of the two wiring systems, nickel resbond and Al wire bonds, the wire bonds were the most robust. The Ni resbond was prone to cracking due to the temperature and pressure fluxuations within the engine. The wire bonds were sufficient to connect the thermoresistor signal to the modified spark plug for short duration testing. A more advanced die attachment method such as direct chip attachment [9] is necessary for longer duration testing within this harsh environment until the RF technology exists to transmit the signal wirelessly.

The thermoresistors were tested within the combustion environment. While the thermoresistors were not designed to behave as optimized sensors within the engine, they did provide a test to demonstrate the survivability of the materials and the feedthrough system. The thermal mass of the thermoresistor prevented the measurement of the combustion gasses, however an average temperature with small fluxuations can be measured.

This work shows that, when warmed up, this test set-up can be used for testing MEMS sensors within an octane combusting environment. It also shows that platinum on Si can survive within this small sized engine. For large, higher temperature engines, the silicon could be replaced with silicon carbide (SiC) to enable survival within the harsh environment.

FUTURE WORK

The next steps in this research will be to pattern Pt on SiC for testing, reinforce the electrical and physical connection between the sensor and the feed through, reduce the noise from the sensor when collecting data from inside the engine, and conduct longer tests to observe oil residue deposition within "hot" engine. The final steps will be to develop RF technology to transmit the sensor signals wirelessly and fabricate more advanced engine sensors.

ACKNOWLDEGEMENTS

The authors would like to thank Matthew Chan, David Myers, Fabian Goerioke, and UC Berkeley Microfabrication Center for all of their help with this work.

REFERENCES

[1] University Of Colorado. "Finite Heat Release with Heat Transfer." 26 June 2000. Web. 28 Nov. 2009. http://www.engr.colostate.edu/~allan/thermo/page8/page8.html

[2] S.P. Murarka, R.F. diode sputtered platinum films, Thin Solid Films, Volume 23, Issue 3, p. 323, October 1974,

[3] K. Fuchs, The conductivity of thin metallic films according to the electron theory of metals, Mathematical Proceedings of the Cambridge Philosophical Society , Volume 34 , Issue 01 , pp 100, Jan 1938.

[4] E. H. Sondheimer, in Advances in Physics, edited by N. F. Mott (Taylor and Francis, Ltd., London, 1952), Vol. 1, p. 1.

[5] A.F. Mayadas, M. Shatzkes, Electrical-Resistivity Model for Polycrystalline Films: the Case of Arbitrary Reflection at External Surfaces, Physical Review 1970, Vol. 1, p. 1382.

[6] P. Sheng, "Electronic transport in granular metal films ", *Philos. Mag. B*, vol. 65, pp. 357. 1992.

[7] N. Artunc, Z.Z. Ozturk, Influence of grain-boundary and surface scattering on the electrical resistivity of single-layered thin copper films Journal of Physics: Condensed Matter 1993, p.559.

[8] S. W. Schwartz, D. R. Myers , R. K. Kramer, S. Choi, A. Jordan, M. B. J. Wijesundara, M. A. Hopcroft, A P. Pisano, "Silicon and Silicon Carbide Survivability in an In-Cylinder Combustion Environment," PowerMEMS 2008, Sendai, Japan, pp 477-480, 9-12 Nov 2008.

[9] Okojie, Robert S., Ender Savrun, Phong Nguyen, Vu Nguyen, and Charles Blaha. "Reliability Evaluation of Direct Chip Attached Silicon Carbide Pressure Transducers." 3rd IEEE International Conference on Sensors (2004). Print.