A Suspended Heater Wire for Low Power Gas Sensing Using the 3-Omega Technique

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Introduction:

Gas sensors have been used for nearly four decades in order to measure gas mixture composition or identify certain gases [1]. The majority of conventional gas sensors function via electrochemical detection, but electrochemical sensors face certain disadvantages, including having a low shelf-life, requiring individual sensor calibration, and containing corrosive sensor components.

Recently, a gas sensor based on the 3-Omega technique was developed [2]. In a standard 3-Omega technique, a current of root-mean-square value (RMS) $I_{\omega,\mathrm{RMS}}$ and angular frequency $\omega = 2\pi f$ is driven through a metal heater line, causing Joule heating at frequency 2ω. The resulting thermal wave penetrates the surrounding environment, causing a temperature fluctuation at the source at a frequency 2ω, but at a phase lag ϕ. The temperature oscillation causes the resistance of the heater to oscillate at 2ω. The current driven at a frequency 1ω and the resistance fluctuation at frequency 2ω causes a voltage fluctuation at a frequency 3ω across the heater-line that is dependent on the thermal environment of the sensor. The 3ω voltage amplitude and phase are directly measurable and depend on the composition of the surrounding gas. Since different gases result in different 3ω signals, the 3-Omega technique can be applied for gas sensing purposes. The purpose of this study was to fabricate heater lines that will improve the sensitivity of the technique while consuming lower power (< 1 mW) than many commercially available sensors.

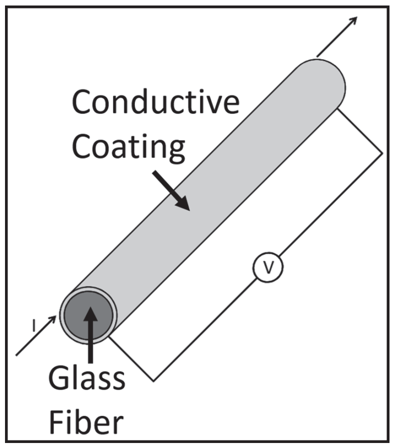

Figure 1: Schematic for cylindrical heater line geometry.

Design and Fabrication:

The 3-Omega technique is best applicable for 1-D geometries and therefore, a cylindrical geometry with Length>>Diameter is preferred. To improve the sensitivity of the technique, most of the heat generated in the heater line should diffuse through the gas medium. To satisfy both the criteria, a heater line geometry as shown in Figure 1 was designed. A thin layer (~ 50 nm) of metal (e.g., gold) deposited on the circumference of an insulating core (e.g., glass fiber) of larger dimension (~ 50 µm) served as the heater line.

In this study, borosilicate glass fiber was used as the insulating core and gold, platinum, and copper were deposited circumferentially onto the core. The fibers were cleaned in acetone, deionized water, and isopropyl alcohol prior to deposition. The fibers were then suspended across a deposition lathe designed to rotate and provide a uniform circumferential coating, as shown in Figure 2. The metal coating of desired thickness was achieved by placing the lathe within a vacuum sputtering system. The rotation of the lathe was controlled by the planetary motors of the sputtering system. An 8 nm thick titanium layer was first deposited as the adhesion layer, and was followed by a 300 nm thick layer of the metal.

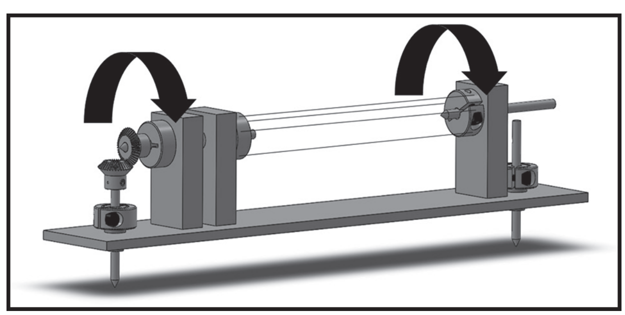

Figure 2: Rotating deposition lathe designed for vacuum sputtering system.

Because the sputtering system deposited metal in a rectangular plane while the lathe was rotating in a cylindrical motion, the actual thickness on each fiber was theoretically calculated to be $300/\pi = 95.5$ nm. The factor of π results from the ratio of the fiber's actual surface area (πDL) to the area projected onto a horizontal plane (DL).

Since the deposition process was set to a custom calibrated run for the lathe, the thickness and uniformity of the metal layer had to be characterized. The cross section of the fiber was analyzed under a scanning electron microscope (SEM) for two configurations. The first configuration involved embedding the fiber in a solidified epoxy, which was then sliced and polished before imaging. The second configuration involved vertically placing the coated fibers onto the SEM stand via double sided copper tape. The second configuration yielded better images as the presence of epoxy interfered with the imaging process.

Energy dispersive x-ray (EDX) tests were performed to verify the presence of metal coating on the surface of the sensor. It was observed that gold and platinum coatings were uniform, whereas copper showed inconsistency. Figure 3 shows the measured thickness of the metal layer in small region of the cross-section. The average thickness in this region was determined to be 82.5 nm with a standard deviation of 11.6 nm, which was lower than the theoretical value of 95.5 nm. Further depositions are required to calibrate sputter deposition rates.

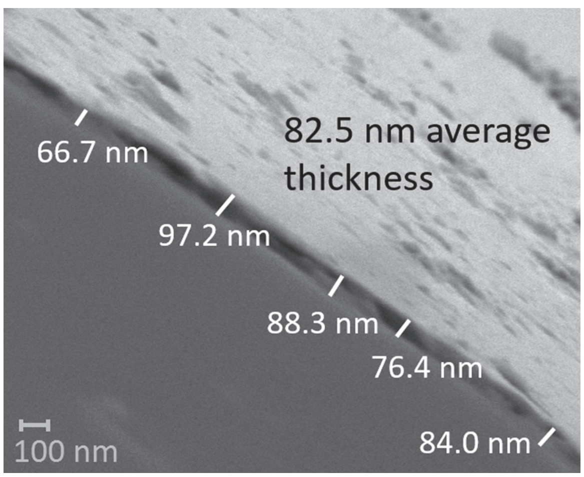

Figure 3: Thickness analysis on an SEM of Au coated fiber.

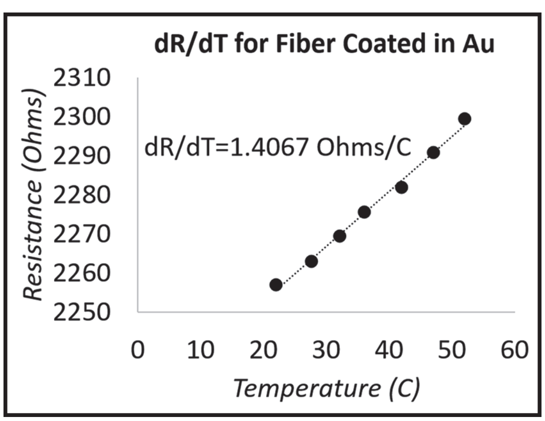

Figure 4: dR/dT *measurement of Au coated fiber.*

Experiments:

The first test was to determine the rate of change of resistance with temperature, dR/dT, as it plays a vital role in analyzing the 3-Omega signal. The fibers were suspended across a dual in-line chip package (DIP) and connections to the pins were established using gold wires. The gold wire was connected to the fiber using conducting silver paste, which was cured at 60°C for a period of 36 hours, and the other end was wire bonded to the pin. The sensor was placed in an oven, and resistance was measured across a range of temperatures. Figure 4 shows the variation of resistance with temperature and the value of dR/dT. 3-Omega measurements were taken with the sensor placed in ambient air to verify the functionality of the sensor.

Future Steps:

To fully characterize the sensor, experiments need to be carried out in the presence of different gas mixtures. The resulting 3-Omega data will be used to determine the sensitivity. An iterative study involving the deposition parameters and input current will be performed to optimize the sensitivity and power consumption of the sensor.

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References:

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[2] S. Kommandur, A. Mahdavifar, P. Hesketh, S. Yee, A microbridge heater for low power gas sensing based on the 3-Omega technique, Sensors and Actuators A: Physical, 233(2015), 231-238.