Analog BIST Functionality for Microhotplate Temperature Sensors

Muhammad Afridi, *Member, IEEE*, Christopher B. Montgomery, Elliott Cooper-Balis, Stephen Semancik, Kenneth G. Kreider, and Jon Geist, *Life Member, IEEE*

***Abstract*—In this letter, we describe a novel long-term microhotplate temperature-sensor calibration technique suitable for built-in self-test (BIST). The microhotplate thermal resistance (thermal efficiency) and the thermal voltage from an integrated platinum/rhodium thermocouple were calibrated against a polysilicon temperature-sensor calibration curve which drifts over time. Both of these temperature sensors, which cannot be directly calibrated, exhibit excellent long-term temperature stability and are appropriate for BIST functionality.**

***Index Terms*—Built-in self-test (BIST), calibration, microhotplate, platinum/rhodium, sensor, temperature, thermocouple.**

I. Introduction

MICROHOTPLATE-BASED conductance-type gas sensors have been under development for at least two decades. Monolithic array implementation, low-power consumption, and low thermal time constant (around 1 ms) make these devices suitable for low-cost gas-sensor applications [1], [2]. Cavicchi *et al.* [3] exploited the short thermal constant of the microhotplate to identify different gas species from the response signature of a single microhotplate gas sensor during a series of rapid temperature steps. This technique provides tunable selectivity from a single microhotplate to complement other dimensions of selectivity available from the pattern of response obtained over an array of microhotplates having different gas-sensor film compositions. However, the potential of this technique and more recent approaches [4] can only be realized if the same temperature profile is used every time. This demands excellent long-term (over a year) stability from the microhotplate temperature sensor. Barrettino *et al.* [5] identified the importance of the microhotplate temperature sensor and replaced the commonly used polysilicon temperature sensor with a platinum temperature sensor because the calibrations of polysilicon temperature sensors drift over time. While this offers a good solution, it does not address built-in self-test (BIST) functionality, which requires at least two stable temperature sensors. Furthermore, it is our experience that aluminum, which, like polysilicon, is available in a standard CMOS process, is also unsuitable as a temperature sensor at temperatures much above 300 °C.

For the system integration and mass production of microhotplate devices, BIST functionality is a must to ensure reliable long-term operation. BIST usually validates critical system specifications during manufacturing and in the normal use of the system. In case of microhotplate-based gas-sensor systems, microhotplate temperature validation is a critical system specification. The BIST strategy envisioned in this letter requires two long-term stable microhotplate temperature sensors based on different thermoelectric mechanisms. In this case, microhotplate temperature-sensor BIST consists of comparing the temperatures reported by the two different sensors. As long as the absolute value of the difference remains below an application-specific threshold value, the average of the two temperatures is considered reliable. However, if the absolute value of the difference exceeds the threshold, the system will report an error. The feasibility of this strategy is demonstrated with a novel two-step long-term calibration technique.

II. Microhotplate Device Structure

Fig. 1 (left) shows a microhotplate test device containing four microhotplates, and an enlarged view of one of these structures is shown on the right. This type of microhotplate, which has been described previously [1], is a trampoline-type structure that has four supporting legs to suspend and thermally isolate the microhotplate. The 100 μm × 100 μm active area of the microhotplate has a Kelvin-type polysilicon serpentine heater (underneath and not visible in Fig. 1) with two current leads and two voltage leads. The four-contact arrangement makes it possible to use the polysilicon as a heating element through the current leads and also to utilize a portion of it (which occupies the active area) as a temperature sensor by measuring the voltage across the voltage leads.

To calibrate the polysilicon temperature sensor, a 100-μA dc bias current, which is sufficiently low so as to avoid Joule heating, is applied through the current leads. The voltage is then measured via the voltage leads to give the resistance of the active area of the microhotplate heater excluding the legs. Therefore, it is possible to directly calibrate the microhotplate

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M. Afridi and J. Geist are with the Semiconductor Electronics Division, NIST, Gaithersburg, MD 20899 USA (e-mail: afridi@nist.gov; jon.geist@nist.gov).

C. B. Montgomery and S. Semancik are with the Process Measurements Division, NIST, Gaithersburg, MD 20899 USA (e-mail: christopher.montgomery@nist.gov; stephen.semancik@nist.gov).

E. Cooper-Balis is with the Department of Electrical and Computer Engineering, University of Maryland, College Park, MD 20740 USA (e-mail: ecc17@umd.edu).

K. G. Kreider is with the Chemical Science and Technology Laboratory, NIST, Gaithersburg, MD 20899 USA (e-mail: kenneth.kreider@nist.gov).

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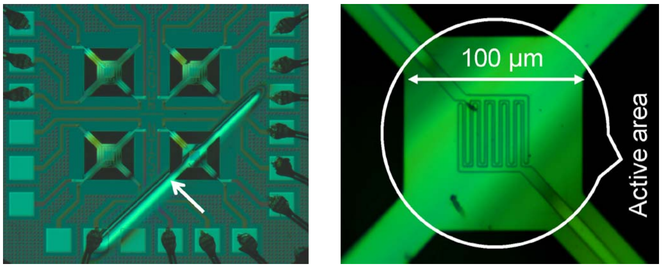

Fig. 1. (Left) Sputtered rhodium trace over the bottom right microhotplate. (Right, magnified) Exposed interdigitated platinum traces over the active area of the microhotplate.

heater as a thermometer by heating the entire chip to a known temperature [6].

The top surface of the microhotplate has exposed platinum interdigitated electrodes, as shown in Fig. 1. Originally designed for metal–oxide sensing-film conductance measurements, they were used to build a platinum/rhodium thermocouple junction in the active area by sputtering a 200-nm rhodium film line using a shadow mask. Another isolated set of sensing-film electrodes will be needed if this device were to function as a gas sensor. Fig. 1 (left) shows the deposited rhodium film line over the bottom right microhotplate indicated by the arrow. In the expanded view on the right, the rhodium film line is barely visible because of the depth of focus.

The resulting modified microhotplate has three independent temperature sensors, one based on the resistance of the polysilicon heater, another based on the thermal resistance of the microhotplate legs, and a third based on the thermal EMF of the platinum/rhodium thermocouple. However, neither the thermocouple nor the thermal resistance of the microhotplate legs can be directly calibrated as a temperature sensor by heating the entire chip containing the microhotplate. Unlike the heater resistance, they respond to the temperature difference between the microhotplate and the chip on which they are located.

The purpose of this letter is to report the results of an investigation of the long-term stability of the calibrations of these three different types of temperature sensors for potential use in microhotplate temperature-sensor BIST.

III. Long-Term Calibration Stability Study

To study the long-term stability of the three temperature sensors, 11 experiments were performed over a period of three months. Each experiment consisted of three steps.

A. Thermal-Stress Treatment

The first step of each experiment consisted of holding the temperature of a custom-built oven at 30 °C while applying a sufficient power (18 mW) to the microhotplate heater to hold it in the vicinity of 400 °C for a period that varied from 5 to 11 days. The first thermal-stress period was used to anneal the fresh microhotplate structure. The remaining stress periods simulated the thermal stress that would occur in the normal operation of a microhotplate-based gas sensor in a typical application.

B. Polysilicon Heater Resistor Calibration

The second step of each experiment consisted of calibrating the resistance of the active area of the microhotplate heater as a function of temperature from 30 °C to 220 °C by heating the entire package as described previously [6]. The uncertainties associated with these temperature measurements to calibrate the polysilicon resistor are ±1 °C. A 100-μA constant dc current was used to measure the resistance. A polynomial fit to the resistance of the active area versus temperature was obtained and extrapolated to 400 °C.

C. Thermocouple and Thermal-Resistance Calibration

The third step of each experiment was to calibrate the thermocouple and the thermal resistance (thermal efficiency) of the microhotplate. This was done by electrically heating the microhotplate from 30 °C to about 400 °C by applying known power levels to the polysilicon heater and measuring the resistance values of the active area of the microhotplate heater and simultaneously measuring the thermocouple voltages. The temperatures corresponding to the resistance values were then calculated using the polynomial fit obtained during step 2 of the experiment. The thermocouple voltages were also correlated to the corresponding temperatures at all power levels covering the range of temperatures from 30 °C to 400 °C. Polynomial fits to the microhotplate temperature versus power and the thermocouple voltage versus temperature were obtained only during the first experiment.

As mentioned previously, it was not possible to calibrate the thermocouple and thermal resistance using the oven at different temperatures because these measurements require a temperature difference across the microhotplate legs.

The three polynomial fits to the calibration data obtained during the first experiment were labeled as PHR1 (polysilicon heater resistance), TCV1 (thermocouple voltage), and TE1 (thermal efficiency). The experiment was then repeated ten more times with a modification to step 3, where no recalibration of the thermocouple and thermal resistance was performed. Only the PHR2 ... PHR11 polynomials that were obtained in step 2 were compared with the TCV1 and TE1 polynomials to verify the integrity of temperature sensors.

IV. Calibration Stability Results

Fig. 2 shows the differences between the temperatures determined from the very first polynomial fit to the polysilicon heater resistance calibration curve (PHR1) and the remaining ten more polynomial fits (PHR2 ... PHR11). It shows that the polysilicon heater resistance calibration drifted over a range of about 25 °C at 400 °C during the calibration stability study. This drift seems to have been caused by the prolonged exposure of the microhotplate heater to temperatures in the vicinity of 400 °C during the thermal-stress treatment.

Although not evident from the figure, the drift shown in Fig. 2 was not a monotonic function of time during the three-month thermal-stress period. Instead, the temperature-difference curves shown in the figure drifted up and down

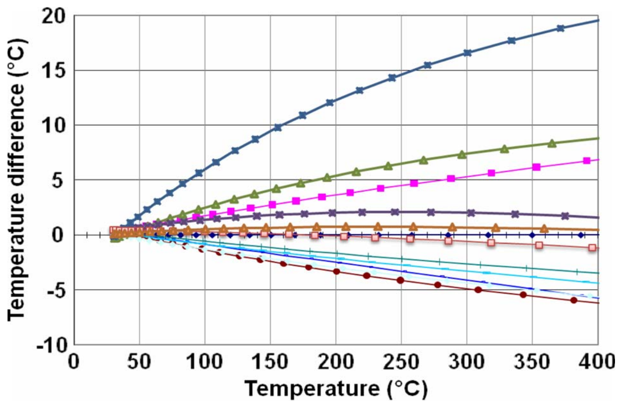

Fig. 2. Apparent errors in microhotplate temperature measurements based on a long-term calibration of the microhotplate heater in Fig. 1 as a resistance thermometer at 11 different times during a period of three months.

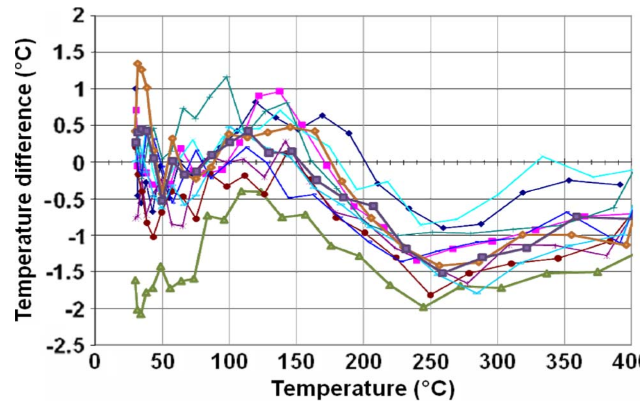

Fig. 3. Differences between the microhotplate temperatures based on the long-term calibration of the platinum/rhodium thermocouple and those based on the long-term calibration of the thermal resistance of the heater legs at 11 different times during a period of three months.

erratically during the stability test. It is clear that the lack of temperature-measurement reproducibility evident in Fig. 2 could seriously degrade the ability to distinguish between different gas species and to quantify the concentrations of known gas species in temperature-programmed gas-sensing applications.

On the other hand, the long-term stability of temperature measurements based on the thermocouple and thermal efficiency of the microhotplate was more than adequate for the temperature-programmed gas-sensing applications. Fig. 3 shows the difference of the microhotplate temperatures determined from the thermocouple polynomial (TCV1) and from the thermal efficiency polynomial (TE1) calibration curves for the 11 experiments. Notice that the range of these differences is 3.5 °C but that, at any given temperature above 100 °C, the range is about 1.5 °C. This level of reproducibility would appear to be more than sufficient for microhotplate-based temperature-programmed gas sensing.

The fact that the differences between the temperatures reported by two temperature sensors that rely on completely different physical properties did not change by more than 1.5 °C strongly suggests that neither of the sensors drifted during the stability study.

Based on the results obtained from thermal efficiency and thermocouple temperature sensors, it is quite evident that these sensors could be used to implement temperature-sensor BIST for gas-sensor applications.

In this letter, we have demonstrated a method to calibrate microhotplate temperature sensors that respond to thermal difference rather than absolute temperature against a microhotplate temperature sensor that is not stable over long periods of time. We have also demonstrated for the first time that stable microhotplate thermal efficiency can be used as a redundant temperature sensor for BIST. Finally, the first integration of a thin-film platinum/rhodium thermocouple in a microhotplate structure has been reported with stable calibration results.

Based on the results reported in this letter, we tentatively conclude that either an integrated thermocouple or the thermal efficiency of the microhotplate can be used with an integrated platinum resistance temperature sensor of the type described as the basis for microhotplate temperature-sensor BIST. Furthermore, based on these results, we further conclude that an integrated thermocouple in combination with the thermal efficiency of the microhotplate can be used with a polysilicon heater/temperature sensor as the basis for microhotplate temperature-sensor BIST.

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