Characterization System for Embedded Gas Sensor Systems-on-a-Chip[1]

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Abstract: *A characterization system is presented for evaluating critical functions of a microhotplate-based embedded gas-sensor for system-on-a-chip applications. The system uses a virtual instrument interface to control parts-per-billion (ppb) gas concentration levels and microhotplate temperature control registers and acquires temperature and gas sensor data. The system is easily reconfigurable to measure chips with various combinations of analog and digital inputs and outputs.*

Keywords: Microhotplate; MEMS; Embedded Gas Sensor; CMOS; System-on-a-Chip (SoC).

Introduction

A characterization system is being developed for embedded gas-sensor systems on a chip (SoC). The SoC, which is based on conductive metal-oxide films that are deposited on microhotplates [1], will have the architecture shown in Fig. 1. SoC-level external communication is through an RS232 serial port connected to a microcontroller, which in turn, communicates with the gas-sensor virtual component (VC) through the system bus.

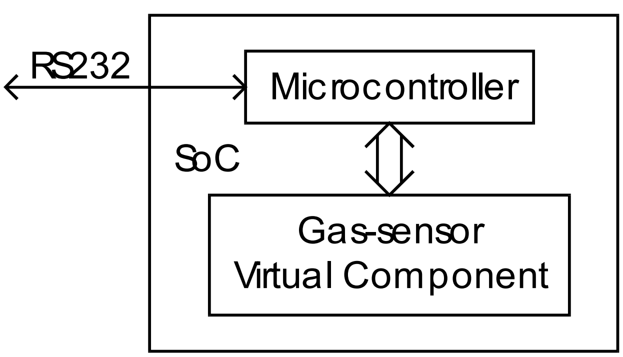

Figure 1. Gas-sensor SoC system architecture.

The gas-sensor VC [2] encloses the gas-sensor cells (Sensor) and their associated analog circuitry in a digital shell so that all interface connections to the VC are digital.

Figure 2 shows a block diagram of the gas-sensor VC. The circuit topology shown is for an array of n gas-sensor cells. Each gas-sensor cell is a microhotplate with a resistive polysilicon heater (left side), a resistive polysilicon temperature sensor (bottom), and a metal-oxide semiconductor sensor film (right side). Registers associated with digital-to-analog converters (DAC 1 ... DAC n) control the heater power for heating the corresponding sensors through amplifiers (Amp 1 … Amp n). The microhotplates [1] are made by post-processing structures fabricated in the same standard CMOS process used to fabricate the SoC microcontroller and VC circuit elements.

A register associated with the multiplexer (MUX) selects the temperature sensor or the gas sensing film signal of any desired sensor. A register associated with a digital gain control (DGC) amplifier controls its gain and a register associated with the analog-to-digital controller (ADC) stores the temperature or gas sensing film conductance data from the selected sensor. The DGC amplifier (Amp) is used to provide the dynamic range needed for different multi-sensor applications.

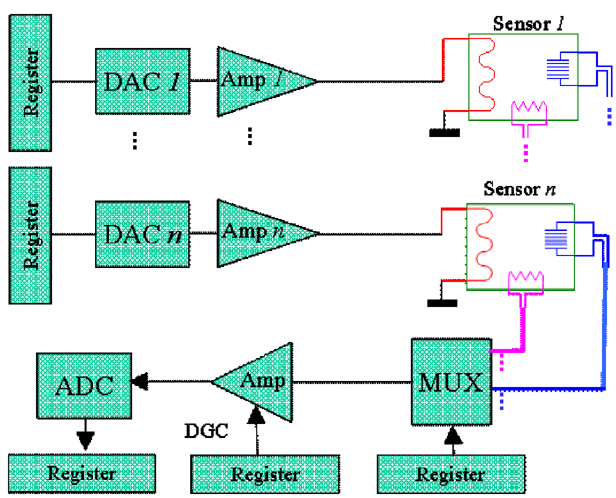

Figure 2. Gas-sensor Virtual Component (VC).

Typical output signals for the various sensor cells of the gas-sensor VC shown in Fig. 3(a) are given in Figs. 3(b)-3(d). Figure 3(b) shows a thermal efficiency of about 10 °C/mW for the microhotplate. Figure 3(c) depicts a typical metal-oxide gas sensor response as carbon monoxide (CO) is alternately applied in various concentrations for 200 s and purged for 300 s. The data show that the gas-sensor is capable of sensing 100 ppb of CO. Figure 3(d) shows a typical temperature-sensor voltage response, which is quite linear and easily corrected by the on-chip microcontroller.

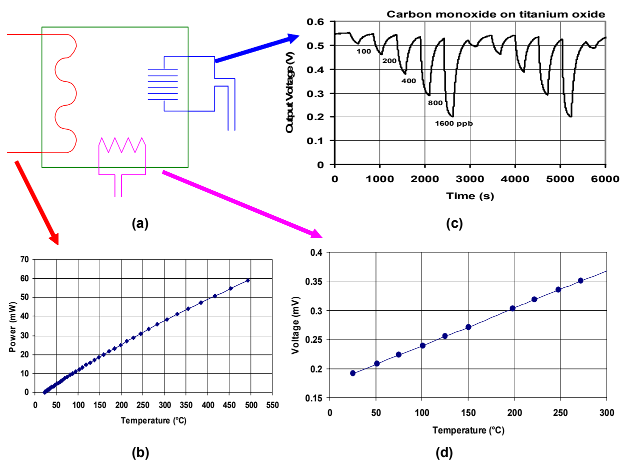

Figure 3. Gas-sensor SoC-calibration requirements.

During development of the SoC it is necessary to carry out analog measurements at the gas-sensor VC level, digital measurements at the register level, and serial measurements at the SoC level on test chips containing various VC and SoC subsystems. The characterization system must also be capable of delivering known concentrations of test gases to the device under test and be capable of heating the test chip externally to at least 220 ºC for temperature-sensor calibrations. In the following sections, temperature-sensor calibrations, microhotplate efficiency measurements, and gas-sensor DC response calibrations will be described.

Temperature-Sensor Calibration

Figure 4 shows an end view of a packaged chip mounted on an aluminum block containing a heater and calibrated thermocouple. Screws (not shown) on each end of the aluminum block hold the chip in tight physical contact with the block, which is coated with heat-sink compound. Gold flying-lead connectors are attached to the package gold-pins on each side of the block. The heater and the thermocouple also make good thermal contact to the aluminum block through heat-sink compound that was placed inside the heater and thermocouple wells. The characterization system has connections for the heater leads, thermocouple leads, and flying-lead connections to the package pins. The temperature of the aluminum block can be raised in programmable step intervals. When the block temperature stabilizes to the desired set point through a PID controller, the output voltages from the microhotplate temperature sensors are recorded both with and without temperature-sensor bias current. The voltage measured with no bias current is the thermal emf error. The difference between these voltages is the voltage drop across the temperature-sensor resistor due to the bias current. Large thermal emf corrections were encountered with low-resistance temperature-sensors.

An upper bound for the difference between the temperature of the aluminum block and a microhotplate in a packaged chip was measured by attaching a calibrated surface thermometer to the top of a package and comparing its readings with the recorded block-temperature readings. The differences were less than 2 °C up to 220 °C.

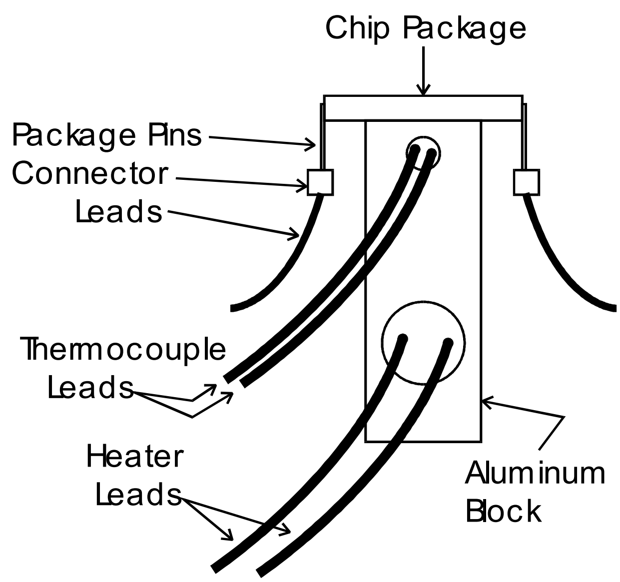

Figure 4. Microhotplate temperature-sensor calibration.

The National Instruments[2] CVI programming environment is used to develop a virtual-instrument graphical user interface (GUI) for automatic data acquisition and device characterization. Figure 5 shows the user interface for the temperature sensor calibration. A Keithley 2400 is used as a programmable constant current source and a JC Systems Model 600A is used as a programmable temperature controller.

[2] Reference to commercial equipment is provided to fully describe the experimental procedure and does not constitute an endorsement by NIST nor a representation that the equipment is the best for the purpose.

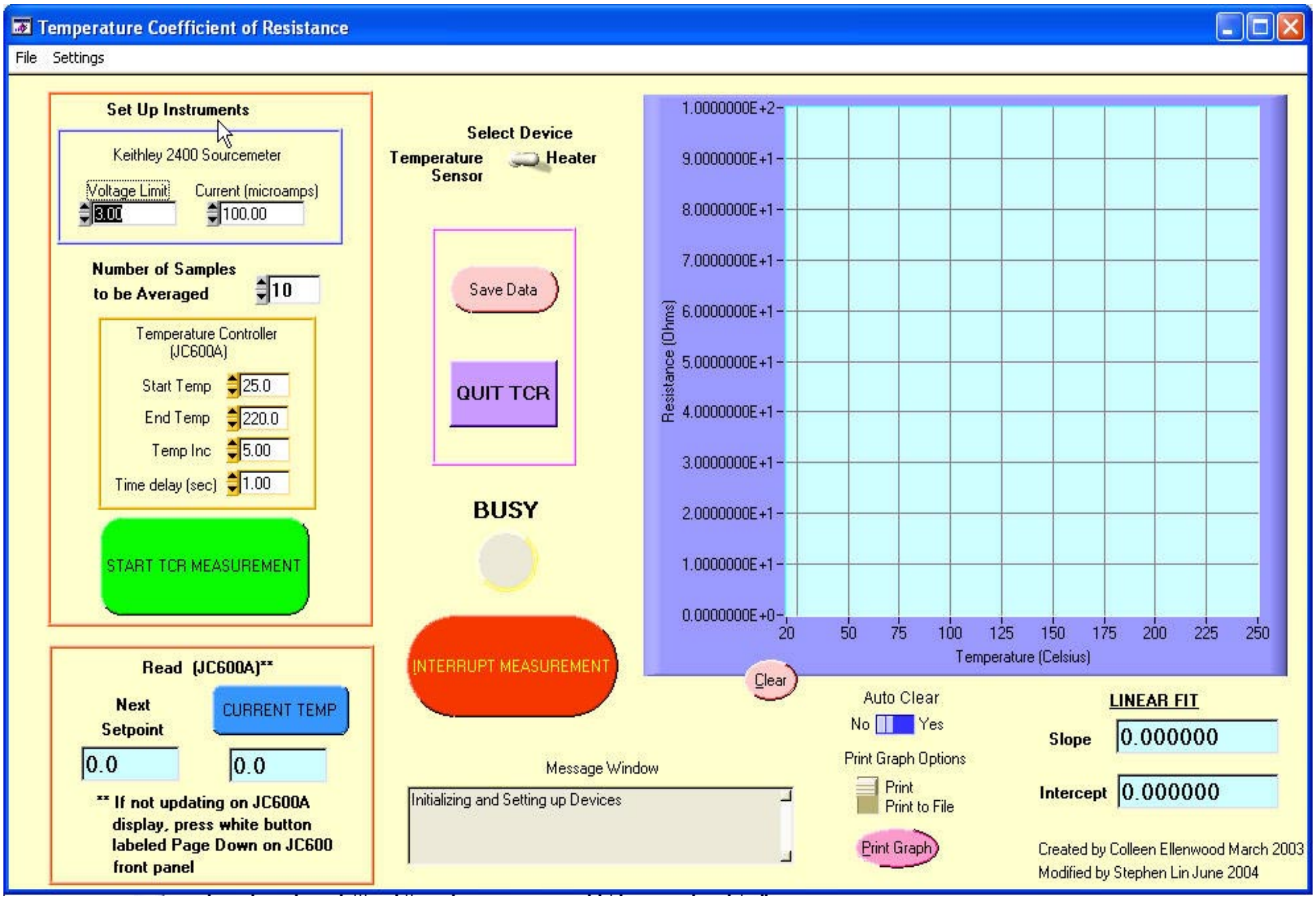

Figure 5. Virtual instrument user interface for microhotplate temperature-sensor and heater calibration

Microhotplate Thermal Efficiency

The characterization system provides the option to characterize the temperature response of either the microhotplate heater or the temperature-sensor. The measured temperature coefficient of resistance (TCR) for the polysilicon-resistance data shown in the Fig. 3(d) is 1.02×10^{-3}/°C.

The thermal efficiency of the gas-sensor microhotplate is determined by heating the microhotplate polysilicon resistor with known power steps and measuring the corresponding temperature-sensor resistance. The measured resistance is then related to the corresponding TCR calibration or an equation fit to the measured data during the temperature sensor calibration.

Microhotplate thermal efficiency is an important system parameter because portable equipment is one potential application of the gas-sensor SoC. In this application, microhotplate power may be the dominant power loss.

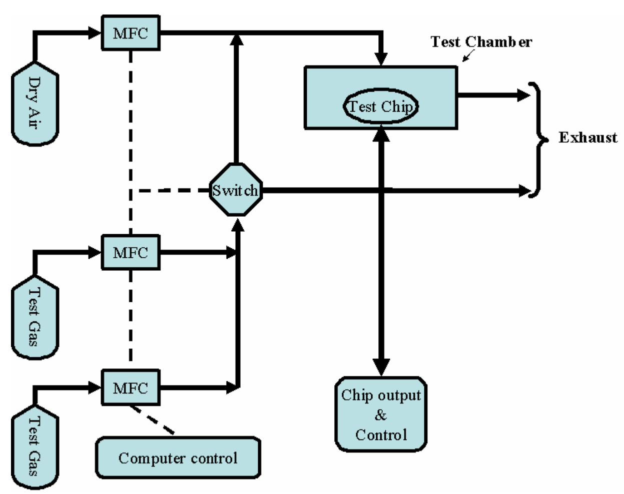

Figure 6. A schematic diagram of the gas handling capability used with the characterization system.

Gas-Senor Film Characterization

Figure 6 illustrates the gas-delivery system used with the gas-sensor film characterization system. A computer-controlled flow switch directs either a dry-air or a dry-air carrier containing known concentrations of test gases to thetest chip. The computer also controls the flow rates of the dry air and test gases through separate mass-flow controllers (MFC). The concentration of gas in the test chamber is determined by dilution via the computer-controlled MFCs.

With this setup, the sensor response to mixtures of gasses can be measured. For instance, a single bottle containing a calibrated mixture of target gases can be used. Alternatively, one bottle can contain a target gas and another bottle can contain an interfering gas expected to be present in the ambient. In this case, the relative concentrations of the target and interfering gases can be varied independently, to develop a detailed signature for distinguishing the target gas from the interfering gas.

As the gas-sensor VC-development process continues, the chip interface changes and different characterization-system inputs and outputs are used. For instance, Fig. 7 shows a schematic diagram of a typical use of the characterization system to calibrate the gas-sensor cells on a mixed-signal test-chip during exposure to different gas species and concentrations from the gas-delivery system shown in Fig. 6.

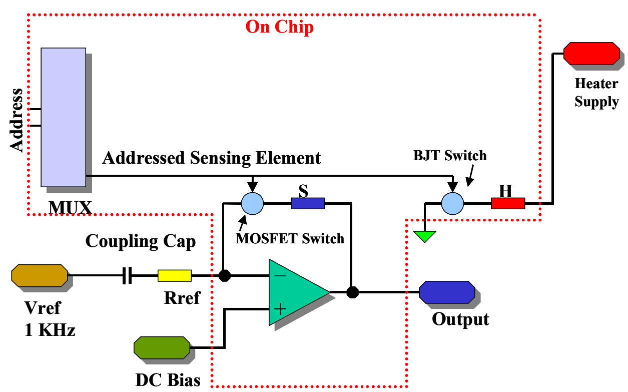

Figure 7. A schematic diagram of the gas-sensor calibration and characterization.

The virtual-instrument window used for this measurement is similar to that shown in Fig. 5. The microhotplate in each gas-sensor cell is coated with a different metal-oxide semiconductor film (S). The characterization system provides an appropriate address for the on-chip MUX to select the desired gas-sensor microhotplate heater (H) and sensor-film output. For this mixed-signal chip, the characterization system also provides a 1 kHz sinusoid for use as a reference signal and records the RMS value of the operational amplifier output. The capacitive coupling of the reference sinusoidal signals prevents DC offset and drift problems in the measurements, thus insuring symmetric clipping for maximum dynamic range.

Besides providing both analog and digital I/O, the characterization system also provides a user selectable heater voltage and power supply voltage (not shown) for the operational amplifier to support migration to lower-voltage (finer-geometry) chip-fabrication technologies. Finally, the characterization system also provides a user selectable DC bias to the non-inverting amplifier input that can be adjusted to maximize the dynamic range. Rref (see Fig. 7) is chosen to get the maximum output voltage without clipping under the various gas-sensing conditions. When an automatic gain control (AGC) circuit is added to the VC, Rref will not be needed.

Conclusions

The characterization system described here makes it practical to provide different types of gas environments and sensor controls to characterize different types of gas-sensor system outputs during the development of a fully functional gas-sensor SoC. The provision of both analog and digital inputs and the means for reading both types of outputs with easily reconfigured application-specific virtual-instrument interfaces allows different chips representing different levels of integration to be characterized. Specifically, the characterization system has been used to test various portions of the gas-sensor VC digital shell with various portions of the gas-sensor cell during the on-going VC development process. The versatility of the characterization system will be essential for continued progress in adding increased functionality to the gas-sensor VC

References

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