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MEMS-based embedded sensor virtual components for system-on-a-chip (SoC) ☆

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Abstract

The design and implementation of a monolithic micro electro mechanical systems (MEMS)-based gas sensor virtual component is described. The gas sensor virtual component encloses the sensor and its associated analog circuitry into a digital shell so that all interface connections to the virtual component are digital. The system architecture supports an array of gas sensor elements. System response time is limited by the sensor and is complex. Example gas sensor characterization results are presented showing isothermal response to carbon monoxide molecules with detection sensitivity better than 100 nanomoles/mole.

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1. Introduction

Chemical microsensors using microhotplates represent one important application for micro electro mechanical systems (MEMS) technology. Microhotplate devices belong to the MEMS family and can be fabricated in commercial CMOS technology using micromachining techniques [1,2]. Such micromachined structures offer many potential advantages for sensing applications including low power consumption, low fabrication cost, high quality, and reliability. A conductance type gas sensor system can be implemented in a cost effective manner using MEMS technology. These types of sensors often need an elevated temperature to activate the sensing mechanism. The microhotplate is a perfect platform for such devices because of its small size and ease of fabrication using standard commercial CMOS technology, and the microhotplate's high thermal efficiency, short thermal time constant, and small size, which makes it very attractive to build an array of micro-gas-sensors for complex gas sensing environments. Array implementation of the micro-gas-sensor system demands an efficient way to measure data from each array element. CMOS technology enables monolithic integration of microhotplate and interface circuitry to comprise a conductance type gas sensor system [3]. There are numerous applications available for the low cost monolithic gas-array-sensors. For example, these sensors could be used to detect the freshness of food products, the leakage of toxins in chemical manufacturing facilities, or dangerous chemical agents in public places.

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Advances in MEMS-based sensors bring a new challenge for system-on-a-chip (SoC) design integration where analog and digital circuits coexist on a common substrate with the actual sensing platform. Integration of these MEMS-based sensors into an SoC requires a sensor core, or virtual component (VC), that is compatible with the digital design strategy for a larger system design. At present, there are no sensor VCs in CAD libraries for SoC integration. The purpose of this paper is to introduce a gas sensor VC that is compatible with SoC design methodology.

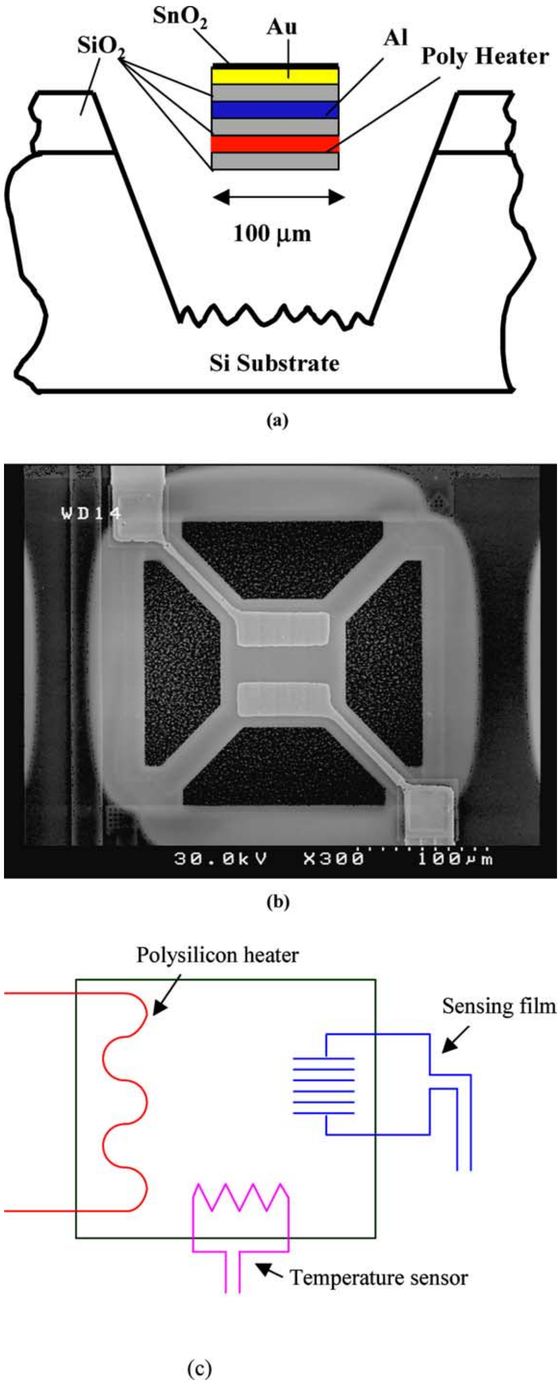
2. Gas sensor platform

The microhotplate is the basic MEMS structure used as a building block for the gas sensor VC. This microhotplate is fabricated using micromachining technology and includes a polysilicon heating element, a polysilicon or aluminum temperature sensor, and a metal-oxide sensing film to form the gas-sensing platform. Fig. 1 shows a post-processed microhotplate gas-sensing element. Fig. 1(a) shows a cross sectional sketch and Fig. 1(b) is an scanning electron microscope (SEM) micrograph. The two gold electrodes can be seen in the SEM micrograph, and the sensing films are grown over the entire heated surface of the microhotplate. The sensing films thus straddle the area between the gold electrodes, and this portion of the film determines the response of the sensor. Fig. 1(c) is a schematic symbol for the gas sensor platform. Because silicon is a good heat conductor, it must be removed from underneath the microhotplate to achieve high thermal efficiency. Localized removal of silicon from desired places is accomplished by using bulk micromachining techniques [4]. Xenon difluoride (XeF_2) can be used as a silicon etchant in this post-CMOS process. The small size (100 × 100 μm) and resulting thermal isolation of the microhotplate allows it to have a short (1 ms) thermal time constant as measured both by an infrared thermal microscope [5] and a van der Pauw sensing structure [10].

An array of gas sensor elements is fabricated with different sensing film characteristics by controlling heater temperature during film deposition [6,7]. In this work a gas sensor VC with an array of four sensing elements is presented.

The metal oxide-based thin film gas sensors typically require elevated temperatures (~200 to 400 °C) to detect gas species [8]. The high thermal efficiency and short thermal time constant suggest using the microhotplate to implement a metal oxide-based gas sensing system. Their small size also makes it practical to implement an array of gas sensors by replicating the microhotplate design.

Gold electrodes are fabricated on the top of the microhotplate by coating the CMOS chip with 200 Å of chromium and 4000 Å of gold. The chromium is used as an adhesion layer for gold because gold does not adhere well to the SiO_2 dielectric. Before the sputter deposition



(a)

(b)

(c)

Fig. 1. Microhotplate—(a) cross section of layer structure, (b) SEM micrograph of the suspended microhotplate structure with the post-processed gold gas-sensing electrodes and (c) Schematic symbol.

of the chromium and gold on the chip, the chip is in situ ion-beam cleaned with argon to remove aluminum oxide from the pads that make contact to the post-processed gold electrodes.

In order to make a direct comparison between the sensing characteristics of two different metal oxide thin films, SnO_2 and TiO_2 films are grown over post-processed gold sensing electrodes by low-pressure chemical vapor deposition (LPCVD) using tin(IV) nitrate and titanium(IV) isopropoxide as the precursors [9]. The precursor temperatures are 25 and 28 °C for the tin(IV) nitrate and titanium(IV) isopropoxide, respectively. Argon is used as the carrier gas with a flow rate of 10 sccm. The reactor pressure is 0.5 Torr. Sensing films are deposited at 250 and 300 °C for SnO_2 and TiO_2 films, respectively. Deposition times are 15 min.

3. Gas sensor virtual component design

The gas sensor VC encloses the sensor and its associated analog circuitry into a digital shell so that all interface connections to the VC are digital. Fig. 2(a) shows a block diagram of the gas sensor VC. The circuit topology shown is for an array of *n* gas sensors. Registers associated with digital-to-analog converters (DAC 1… DAC *n*) control heater power for the corresponding sensor's heating element through an amplifier. A register associated with the multiplexer (MUX) selects the temperature sensor or gas sensing film signal of any desired sensor. A register associated with the digital gain control (DGC) amplifier controls its gain, and the register associated with the analog-to-digital controller (ADC) contains the temperature or gas sensing film conductance data of the desired sensor. A DGC amplifier is used to improve dynamic range. Fig. 2(b) shows the layout of the gas sensor VC with an array of four gas sensing elements, decoders, ADC, and amplifiers, all of which are fabricated in 1.5 μm standard CMOS technology. Finally, post-processing is performed to realize the MEMS gas sensing structures.

Characterization results of the various components of the sensor of Fig. 3(a) are given in Fig. 3(b)–(d). Fig. 3(b) shows the thermal efficiency of approximately 10 °C/mW of the microhotplate. The slight curvature in the graph is due to the fact that SiO_2 becomes less thermally conductive at higher temperatures and hence the thermal efficiency of the microhotplate increases at higher temperatures. Fig. 3(c) depicts a typical metal-oxide gas sensor response as gas is alternately applied in various concentrations for 200 s and purged for 300 s. Fig. 3(d) shows a typical temperature–sensor voltage response using a square aluminum van der Pauw structure for the measurement [10]. The sensor is biased with a 10 mA constant current in the source legs (northwest and northeast corners of the square) and voltage is measured across the sensing legs (southwest and southeast corners of the square).

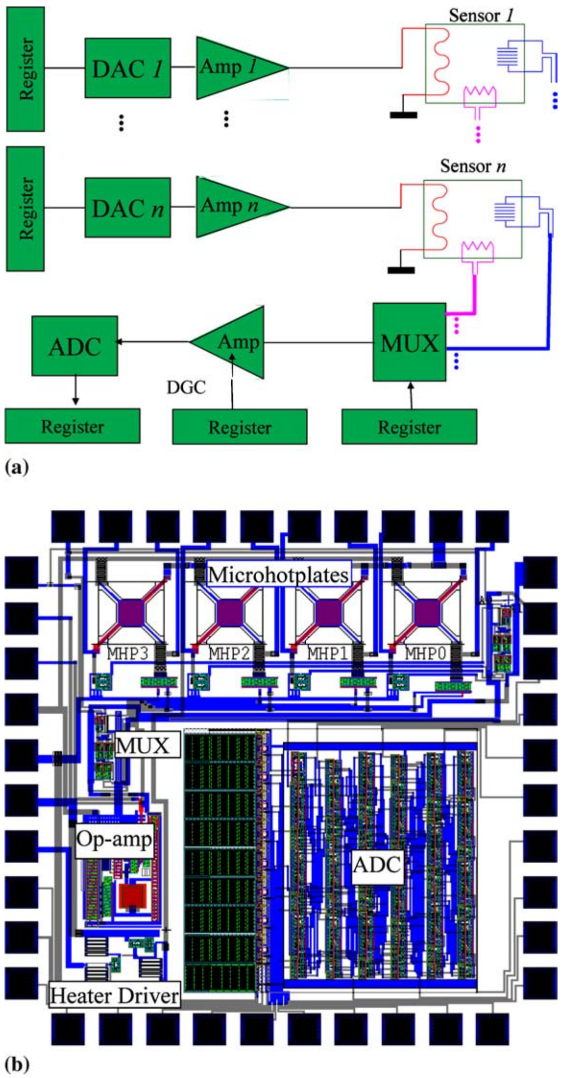
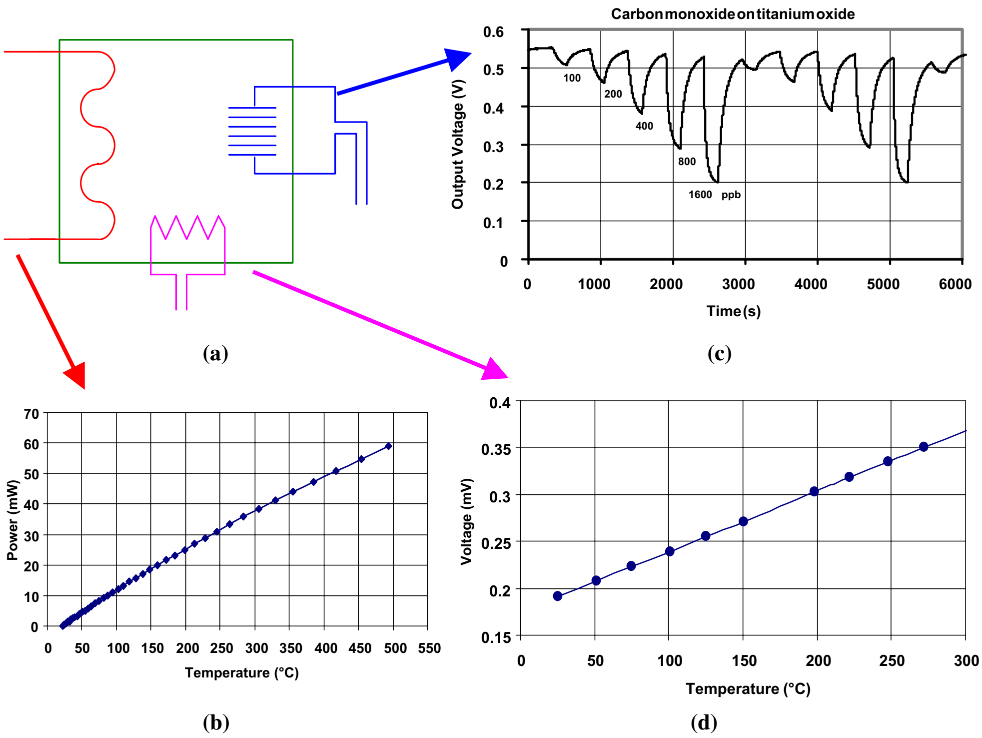


Fig. 2. Gas sensor VC (a) Block diagram and (b) Layout.

It can be seen in Fig. 3(c) that a gas concentration of 100 nanomoles/mole (ppb) of carbon monoxide is easily resolved. The results of Fig. 3(c) were obtained using the on-board op-amp and MUX, and the microhotplate was held at a constant temperature. The response time of the gas sensor is complex and is a function of the sensing film surface and material, temperature, humidity, and gas type and concentration. Detectable response times of the gas sensor system are observed to be less than a second; however, much longer times are required to saturate the sensor output as shown in Fig. 3(c). Since this is a test chip, the various components of the VC could be individually characterized and connected. The



(a) (c)

(b) (d)

Fig. 3. Gas sensor characterization results. (a) Symbol, (b) Heater efficiency, (c) Typical sensing film response to varying gas concentrations and (d) Temperature sensor response.

ADC and heater driver were characterized but not used for the results shown.

4. Conclusion

A microhotplate suitable for use as a gas sensor platform is discussed. A monolithic implementation of a MEMS-based conductance-type gas sensor virtual component is presented. An efficient digital interface compatible with CMOS design strategy is given for a gas sensor virtual component which can be easily integrated into an SoC design. It is demonstrated that by using CMOS compatible post-processing steps, a gas sensor virtual component with integrated electronics can be implemented on a common substrate with low cost and enhanced performance. Other issues regarding packaging, sensor reliability, and sensor VC availability in commercial CAD tools will need to be addressed in future work before such systems can become commercially viable.

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