SOI CMOS-Based Smart Gas Sensor System for Ubiquitous Sensor Networks

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This paper proposes a compact, energy-efficient, and smart gas sensor platform technology for ubiquitous sensor network (USN) applications. The compact design of the platform is realized by employing silicon-on-insulator (SOI) technology. The sensing element is fully integrated with SOI CMOS circuits for signal processing and communication. Also, the micro-hotplate operates at high temperatures with extremely low power consumption, which is important for USN applications. ZnO nanowires are synthesized onto the micro-hotplate by a simple hydrothermal process and are patterned by a lift-off to form the gas sensor. The sensor was operated at 200°C and showed a good response to 100 ppb NO_2 gas.

Keywords: SOI CMOS-based gas sensor platform technology, USN, micro-hotplate, ZnO nanorods, NO_2 gas sensing.

Manuscript received Feb. 22, 2008; revised Apr. 2, 2008; accepted May 2, 2008.

The work was supported by the Ministry of Information and Communication, Rep. of Korea, under project no. 2006-S-006-02.

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I. Introduction

Ubiquitous sensor network (USN) technology has attracted a great deal of attention as a means to collect environmental information to realize a variety of functions through a large number of compact wireless sensor nodes that are widely distributed [1]. Indeed, it is a researchers' dream to build USNs for agriculture, ecology protection, indoor air conditioning, pollution monitoring, disaster management, and so on by developing a compact sensing platform which can simultaneously monitor light, temperature, humidity, barometric pressure, vibration, and bio-chemicals. In order to satisfy this compact multifunctional sensor design rule, it is necessary to integrate optical, mechanical, and bio-chemical sensors, as well as actuators and other functional micro-electro-mechanical systems (MEMS) with CMOS circuits for signal processing and communication.

As the compact sensor nodes must operate for long periods of time using mini-batteries or energy harvesting tools, they must also be designed to be extremely energy efficient [2]. Another key issue in sensor platform design is the sensitivity of the sensors. Monitoring of the atmosphere, for example, requires chemical sensors to detect target gases. Commercially available environmental gas detection systems can be classified into 2 types: large systems (~cm^3) with high sensitivity and small systems (~mm^3) with low sensitivity. As chemical gas sensing is expected to become a basic core function of various USN applications, the development of highly sensitive compact gas sensing devices is crucial.

One promising way to design a highly sensitive compact gas sensing device is to use solid-state semiconductors as sensing elements instead of presently available low sensitivity electrochemical cells. The layout of this sensor basically comprises a gas sensing layer on a membrane embedded with interdigitating electrodes and a heater. The reason for incorporating heaters into sensors is that solid-state semiconductors generally react with gases at high temperatures (300 to 600°C). This is the significant drawback of commercial solid-state sensors, as the heating elements consume too much power (200 mW to 800 mW) [3], [4]. There have been previous reports of resistive heaters operating with low power consumption [5]-[10]. However, the process is not fully CMOS compatible, so it has the disadvantage of a higher fabrication cost, and it does not offer the possibility of circuit integration. CMOS compatible sensors were successfully fabricated by Suehle and others [11]. These sensors are based on oxide Al micro-hotplates and poly-silicon heaters. The use of Al, however, hinders high temperature operation due to electro-migration, and it also causes power loss. Resistive sensors based on a poly-silicon also tend to suffer from a significant shortfall. The high doping levels required to increase the resistivity of the heater put high stress on the membrane, and they possess poor long term thermal stability at temperatures above 300ºC. Udrea and others suggested a possible solution to this problem by employing silicon-on-insulator (SOI) technology [12].

By adopting the design of a micro-hotplate using SOI technology, gas sensors can operate at much higher temperatures (up to 600°C) than would normally be expected for CMOS materials. Moreover, the sensing elements are fully integrated with CMOS circuits and other sophisticated structures vulnerable to high temperatures. This also reduces the cost of fabrication, producing high quality repeatable heater structures.

SOI CMOS technology offers crucial advantages over other CMOS technologies. It provides superior characteristics and has higher temperature capability. Moreover, it offers excellent electrical and thermal isolation between different blocks and is thus able to eliminate electrical or thermal cross-talk between the sensing element on one side and the drive and transducer on the other. Therefore, SOI CMOS technology can become a common platform technology for smart mechanical and chemical sensors, which makes it ideal for USN applications [13].

In this paper, we propose novel gas sensor platform technology showing extremely low power consumption and fast and high sensing response that can be used in conjunction with USN for environmental monitoring.

II. Preliminary Sensor Platform Design Layout

The preliminary sensor platform design layout is shown in Fig. 1. The micro-hotplate is integrated with the drive circuitry and analog readout circuitry. The interface electronic circuits mainly comprise the constant current mirror (to drive the micro-heater and temperature sensor), temperature control circuit, analog multiplexer and decoder circuit, sample and hold circuit, 555 timer clock for the A/D converter and successive approximation register (SAR) A/D converter. They are integrated with the micro-hotplates to complete the smart sensor system.

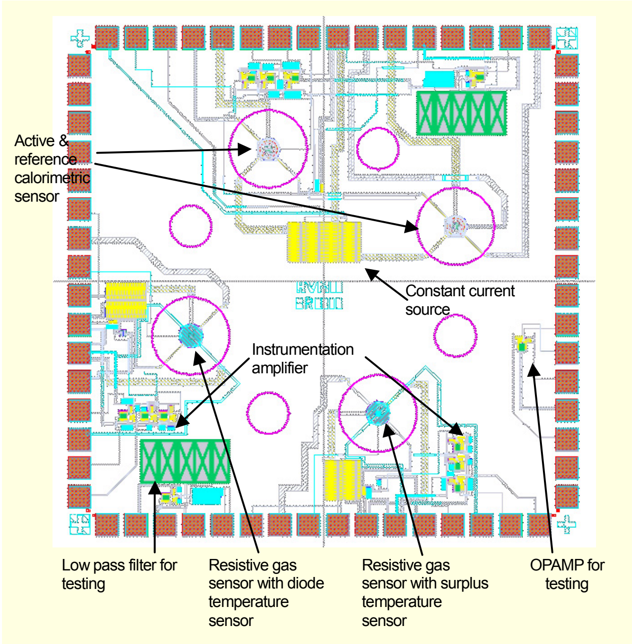

Fig. 1. Sensor platform design layout.

III. Integrated Circuit Design and Simulation - Sensor Interface and Signal Processing Electronics

The main building blocks of the associated electronic circuits for integration with gas sensors are shown in Fig. 2. The micro-controller is connected from the outside to control and monitor the chip functionality. The details of the design are discussed in this section.

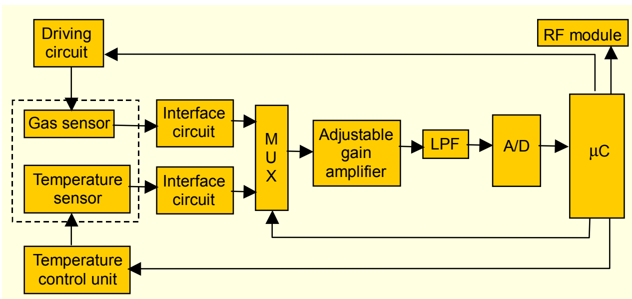

Fig. 2. Schematic diagram of complete sensor system.

1. Driving Circuit

The main driving circuit is a constant current source. It is used to drive the micro-heaters and integrated circuit (IC) temperature sensors. A constant current source modifies the voltage across its load to produce a constant current through it.

$$\frac{I_{out1}}{I_{ref}}=\frac{\left(\frac{W}{L}\right)_1}{\left(\frac{W}{L}\right)_R}$$

This equation indicates that for the simple MOSFET current mirror, the ratio of I_{out1} to I_{ref} may be scaled to any desired value by scaling the aspect ratio (W/L) of the devices. The usual method to realize I_{ref} is to introduce a constant resistance between the drain of M_R and the ground.

In our chip, a cascade constant current source has been designed for better performance (see Fig. 4) because it has greater internal resistance than the simple current mirror circuit (see Fig. 3) and, therefore, can deliver a constant current for higher load resistances. Instead of using a constant resistance at the reference arm, a MOSFET can be used to vary the current through the load. This allows the load current to be varied by applying different DC bias voltages to the gate (as shown in Fig. 5) or pulsing the gate signal to reduce the power consumption.

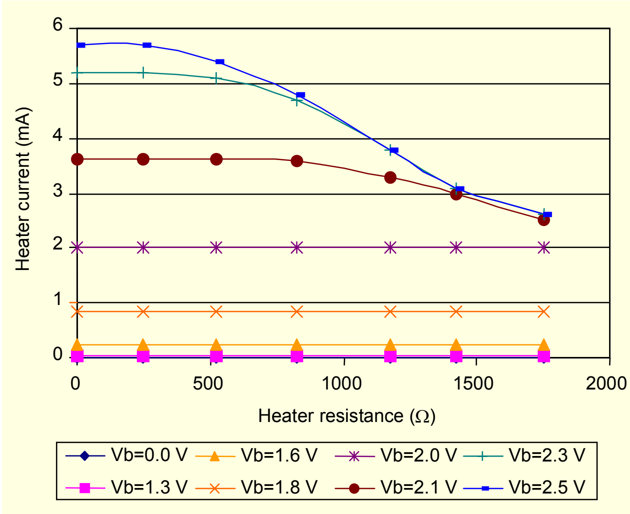

Fig. 5. Current at various bias voltages.

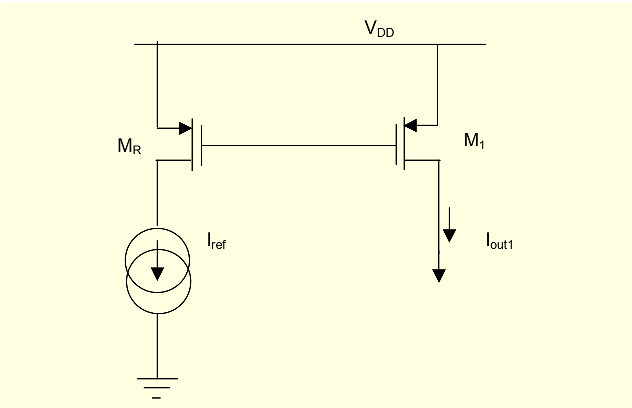

Fig. 3. Current mirror circuit.

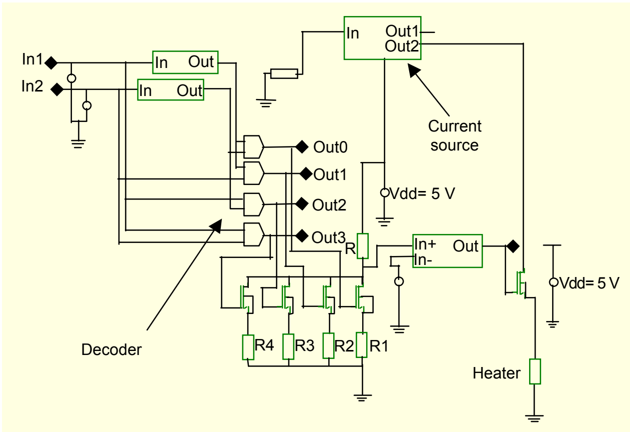

Fig. 6. Temperature control circuit.

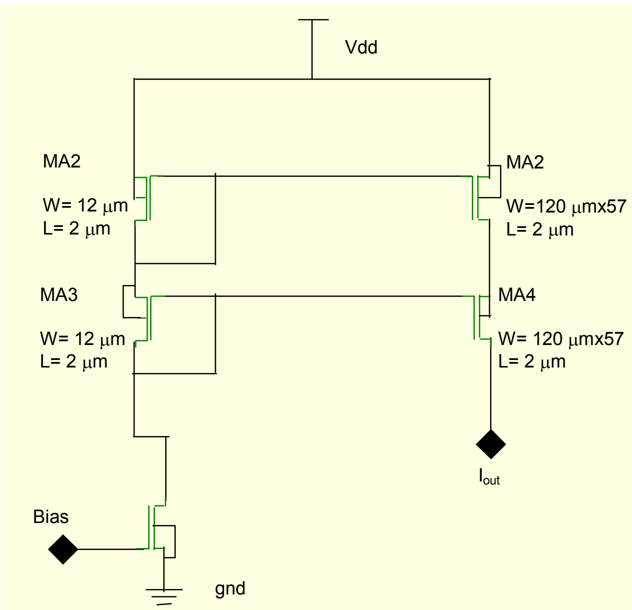

Fig. 4. Cascade current mirror circuit.

2. Temperature Control Unit

The temperature control unit is designed to control the temperature of the heater. Temperature control is important because gas sensing materials are sensitive to different gases at different temperatures. Therefore the temperature has to be controlled in order to properly identify gases.

The temperature control unit (see Fig. 6) comprises a decoder, a comparator, and a voltage divider circuit. The decoder is used to select one of the resistances of the voltage divider circuit by switching on a MOSFET. The comparator

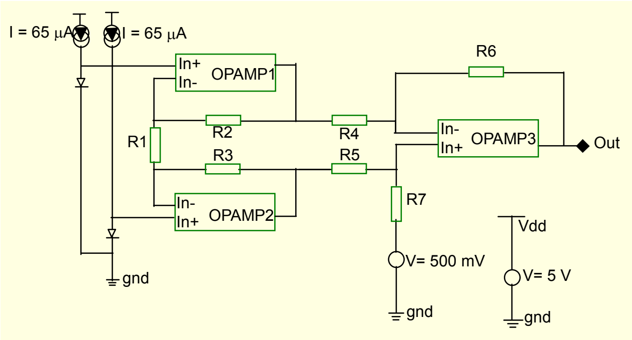

Fig. 7. Instrumentation amplifier for measuring temperature.

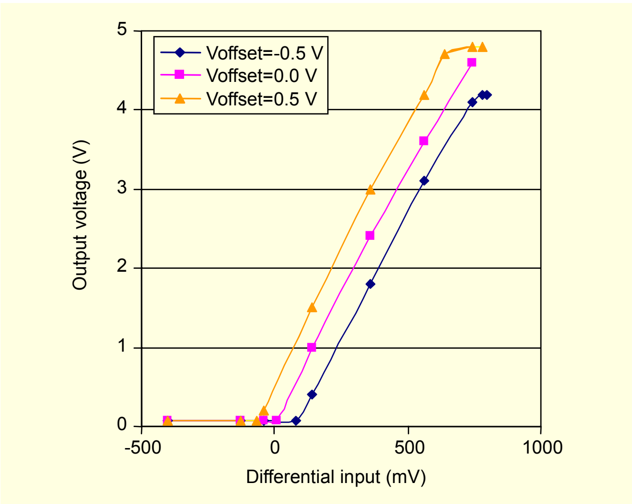

Fig. 8. IA output at different offset voltage.

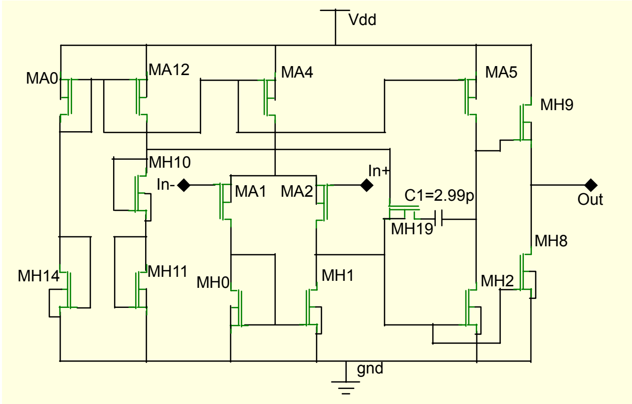

Fig. 9. Operational amplifier.

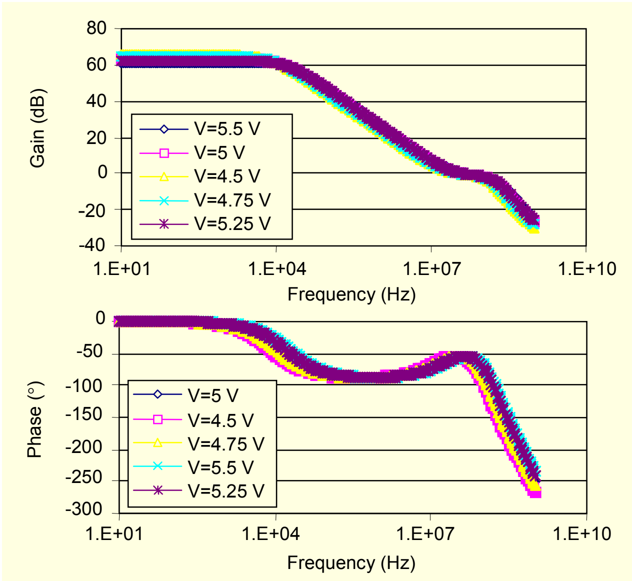

Fig. 10. Operational amplifier characteristics.

compares the voltages across the voltage divider and the temperature sensor. Thus, the comparator output controls the duration of the current through the heater. The heater temperature can be controlled depending on which resistance branch is selected by the decoder.

3. Interfacing Circuit for the Temperature Sensor

An instrumentation amplifier (IA) was designed to measure the temperature of the membrane. One temperature sensor is located on the membrane and a reference sensor is located off the membrane; hence, the instrumentation amplifier amplifies the difference between the signals from the two temperature sensors (see Fig. 7).

The output voltage of the IA is linearly proportional to the voltage difference at the input; hence, it is proportional to temperature of the membrane. An offset voltage source is fed into the second stage of the IA to remove offset of the characteristics (see Fig. 8). The resistance at the input stage of IA can be accessed from outside to control the gain.

The main building block of the IA is the operational amplifier (OPAMP). The OPAMP was designed with a p-channel input differential MOSFET as shown in Fig. 9. This is a single supply (0 to 5 V) two stage OPAMP with an output buffer stage so that it can drive a low resistance load (about 4 kΩ). The OPAMP characteristics are shown in Fig. 10. It has a gain of 60 dB, bandwidth of 4 MHz and phase margin of 100 degrees.

4. Clock

A 555 timer clock has been designed for the clock signal. There is a provision to connect a capacitor from outside if we need to change the frequency of the clock.

5. A/D Converter

An 8-bit SAR has been designed to convert the analog signals into digital bits. The main building blocks of the SAR A/D converter are a sample and hold circuit (S/H), comparator,

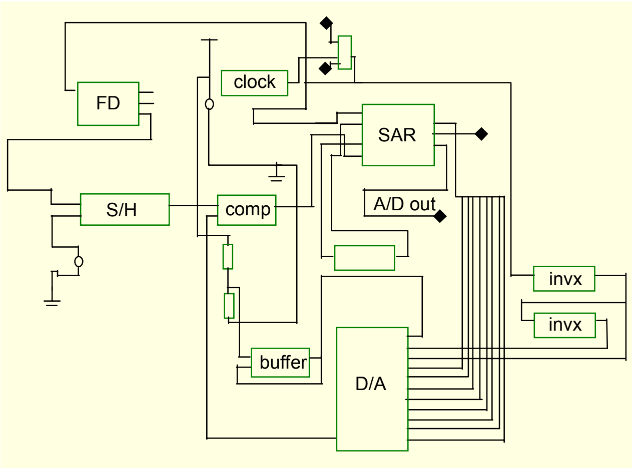

Fig. 11. SAR A/D converter.

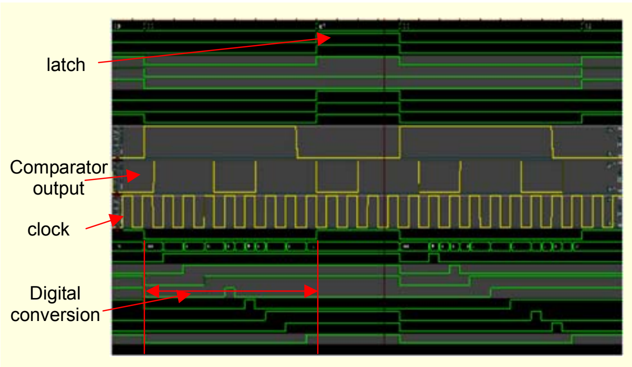

Fig. 12. SAR A/D converter characteristics.

SAR block, and D/A charge scaling converter (see Fig. 11). Figure 12 shows the SAR A/D converter characteristics. The resolution of the A/D converter is approximately 3.3/256 at 12.8 mV.

All the circuits described here have been successfully designed and simulated. In our forthcoming work, we are planning to integrate the A/D converter with the micro-hotplate. The A/D converter signal will then be processed by a microcontroller which will be connected outside the chip.

IV. Micro-Hotplate Design and Fabrication

Circular micro-hotplates with a heater radius of 75 μm and a membrane radius of 280 μm have been designed. The micro-hotplate schematic cross-section is shown in Fig. 13. The hotplate has been fabricated at the XFAB (Germany) SOI CMOS fabrication facility using a tungsten metallization process and back etched to the buried oxide at Silex (Sweden) by a low frequency deep reactive ion etching (DRIE) technique. All the layers used for the micro-hotplate, as well as the tungsten sensing electrodes, are formed during the CMOS

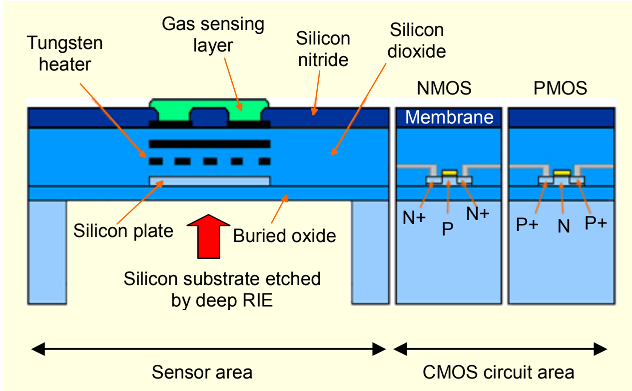

Fig. 13. Schematic diagram of micro-hotplate with integrated SOI CMOS electronics.

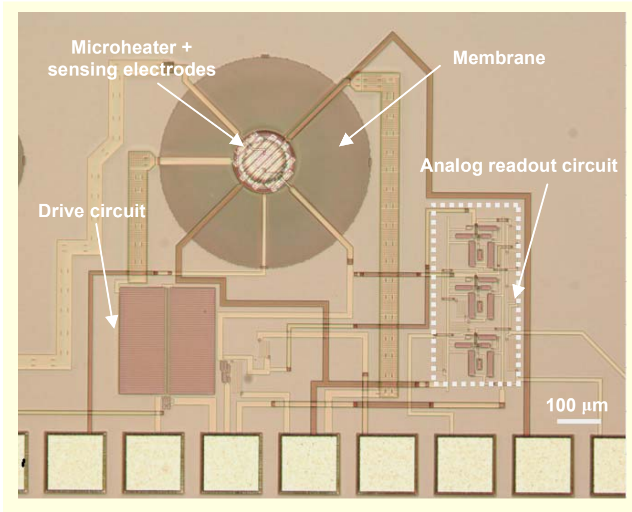

Fig. 14. Fabricated micro-hotplate integrated with drive circuit and analog readout circuit.

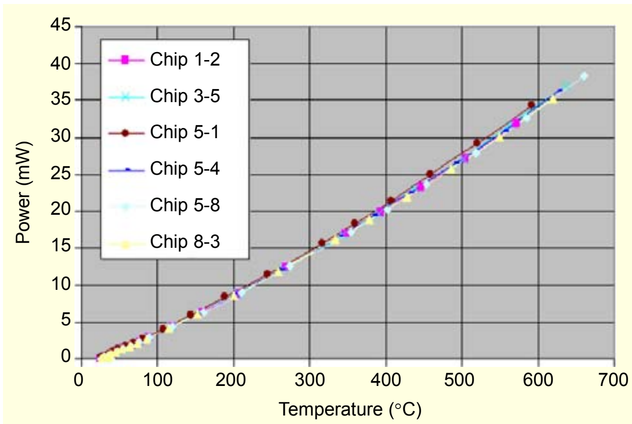

Fig. 15. Micro-heater power vs. temperature plot at various wafer positions.

sequence, with no additional post-processing steps required. A thermal sensor in the form of an SOI thermo-diode or a silicon resistive temperature detector (RTD) was integrated

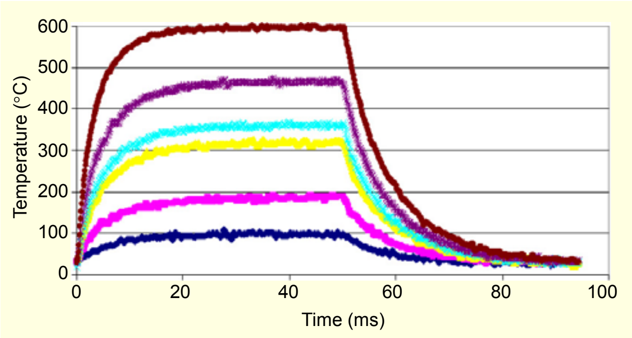

Fig. 16. Transient temperature response of micro-heater.

directly below the heater, to accurately monitor the temperature during operation. A photograph of the manufactured smart sensor platform is shown in Fig. 14.

The heaters show excellent reproducibility and very low DC power consumption (34 mW at 600°C) as shown in Fig. 15. Transient measurement was made by applying a 50 ms square voltage pulse to the heater. Figure 16 shows the rise and fall times needed for various target temperatures ranging from 100 to 600°C. The heater has a 10 to 90% rise time of about 10 ms and a fall time of about 20 ms.

V. Sensing Material Integration and Sensor Characterization

1. Overview of Sensing Material Integration with Micro-Hotplate

Commercially available semiconductor sensors which are composed of polycrystalline thick films do not satisfy the sensitivity requirement for USN applications because of the limited surface-to-volume ratio of the materials. The key factor governing the gas sensitivity of the semiconductor sensors is the amount of reactive gases (mainly oxygen) adsorbed onto the surface of the material. In the case of conventional thick film sensors, the gas species are adsorbed only near the grain boundaries or porous surface. Recently, nanostructures, such as carbon nanotubes (CNTs), SnO_2 nanowires or nanoslabs, and ZnO nanorods have attracted much attention from sensor researchers due to their extremely high surface-to-volume ratio. In particular, sensors based on a single nanostructure have been reported to show excellent sensitivity [14]-[16]. However, they are not convenient for mass production. As mass production schemes combining SOI CMOS microtechnology with nanotechnology, on-chip local growth of CNTs [17], [18] and ink-jetting of polymer/CNT composites [19] have been proposed. In the case of SnO_2, thermal evaporation at atmospheric pressure has been suggested as a potentially promising mass production scheme for SOI CMOS compatible technology [20]. Thick-film sensors based on ZnO nanowires were also reported to be fabricated by a spin coating method on a silicon-based membrane embedded with Pt interdigitating electrodes and a heater [21]. However, it is not easy to fabricate ZnO nanorods by a simple evaporation method. Furthermore, the thick layer of the nanowires considerably decreases the surface-to-volume ratio, which leads to deterioration of sensitivity. For mass production preparation of ZnO nanostructures, Wang and others hydrothermally synthesized ZnO nanorods and then mixed them with a polyvinyl alcohol (PVA) solution to form a paste [22]. An Al_2O_3 tube sensor was then coated with this paste.

Even though the hydrothermal process is suitable for mass production, the lack of consistency in the sensor properties has been noted as the major problem associated with this technique. Furthermore, the integration of this technique with the SOI CMOS is impossible due to the process incompatibility [23].

In this section, we introduce a novel hydrothermal method to laterally grow ZnO nanorods directly onto the micro-heater, which is ideal for combining SOI CMOS microtechnology with nanotechnology.

2. Hydrothermal Synthesis of ZnO Nanowires

To deposit ZnO nanowires directly onto the micro-hotplate, we used a hydrothermal method. It is reported that arrayed ZnO nanorods were grown vertically by hydrothermal process [24]. However, in our sensor application, the ZnO nanorods should bridge electrodes by growing laterally. In this paper, we report the hydrothermal lateral growth of ZnO nanorods. First, we made a solution by dissolving zinc nitrate hexahydrate (HMTA, $Zn(NO_3)_2 \cdot 6H_2O$) and methenamine (HMTA, $C_6H_{12}N_4$) in DI water (MilliQ, 18.2 MΩcm) to a concentration of 0.01 M. Then, a sensor platform on which a photo resist (PR) pattern had been formed was placed in the solution, which was maintained at 95°C for 2 hours to deposit ZnO nanorods. The as-deposited nanowires were further defined on the micro-hotplate using lift-off as shown in Fig. 17(a). The lateral growth of ZnO nanorods can be confirmed by the SEM image of the nanostructured ZnO sensing materals (Fig. 17(b)).

3. Sensor Performance

To test our ZnO nanowire-based sensors, we investigated their responses to NO_2 gas, which was balanced with dry N_2 carrier gas fixed at 1000 sccm. During the test, sensing and refreshing were performed at 18 and 25 mW, respectively. The measured gas sensing property is shown in Fig. 18.

The sensitivity was found to be as high as 40% per 100 ppb NO_2, and the detection limit can be down to ppb level. The gas sensing and refreshing processes were facilitated by operation

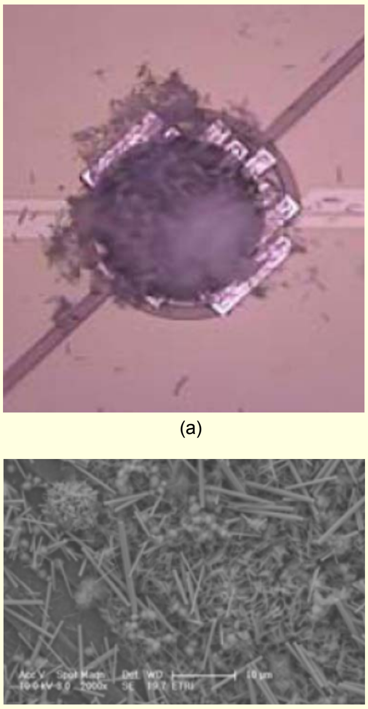

Fig. 17. (a) Optical image of ZnO nanorod sensor formed on an interdigitated electrode fabricated on a micro-heater and (b) SEM image of the deposited ZnO nanorods.

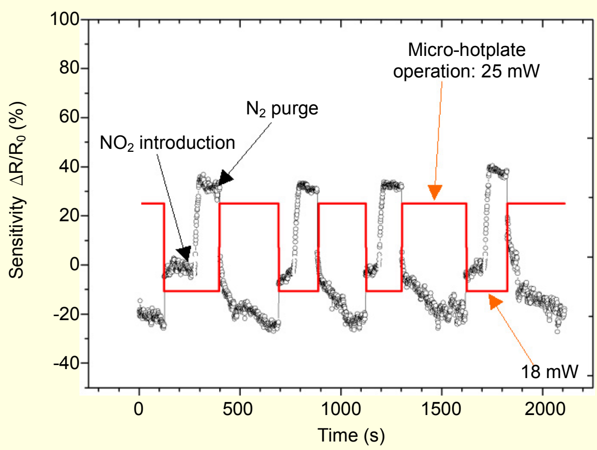

Fig. 18. Gas sensing property of ZnO nanowire-based sensor.

of the micro-hotplate, varying the temperature of the sensing element, which is the merit of our microhotplate-based sensor platform.

VI. Conclusion

In this paper, we propose a highly compact, energy-efficient gas sensor system for USN application. By employing SOI technology, the sensor part is fully integrated with CMOS circuits and the power consumption is dramatically reduced. We believe that this technology requires the lowest power consumption of any technology in the field to date and is, therefore, of enormous commercial impact. The hydrothermal growth of ZnO nanorods directly on the sensing electrodes is described for the first time and demonstrates the ability to realize highly sensitive NO_2 gas sensors from nanomaterials.

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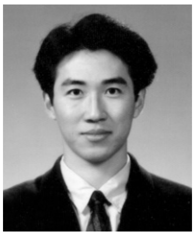

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