On-chip CO_2 Sensor Integrated with MEMS Emitter and Pyroelectric Detector

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ABSTRACT

A demonstration of an on-chip CO_2 gas sensor is reported. It is constructed by the integration of a MEMS-based thermal emitter, a scandium-doped aluminum nitride (ScAlN) based pyroelectric detector, and a sensing channel built on Si substrate. The integrated sensor has a small footprint of 13mm × 3mm (L×W), achieved by the replacement of bulky bench-top mid-IR source and detectors with MEMS-based thermal emitter and ScAlN-based pyroelectric detector, with their footprints occupying 3.15 mm × 3 mm and 3.45 mm × 3 mm, respectively. In addition, the performance of the integrated sensor in detecting CO_2 of various concentrations in N_2 ambient is also studied. The results indicate that the pyroelectric detector responds linearly to the CO_2 concentration. The integration of MEMS emitter, thermal pathway substrate, and pyroelectric detector, realized through CMOS compatible process, shows the potential for mass-deployment of gas sensors in environmental sensing networks.

Keywords: Gas sensor, Pyroelectric detector, MEMS emitter, Carbon dioxide,

1. INTRODUCTION

Detection and monitoring of carbon dioxide (CO_2) concentration levels have been attracting considerable attention due to their impacts on diverse areas, including climate change[1], biology, chemical industry[2], agriculture, food[3] and healthcare[4-5]. For example, with the rising concern about climate change and serious air pollution due to rapid industrialization and urbanization, huge efforts have been made to develop technologies for the evaluation of environmental air quality by monitoring CO_2 concentration levels. Meanwhile, with the technological evolution in the agricultural and food industry, CO_2 concentration control becomes more important including process control and safety assessment. Moreover, research studies have identified that CO_2 concentrations are related to many health issues and could help doctors to diagnose respiratory system problems as well as cardiopulmonary diseases.

Various CO_2 detection techniques and gas sensing applications have been demonstrated[7-10]. However, some of those are costly, lack portability, and demand high operating power, even though they are with high accuracy and precision. For widespread CO_2 gas sensing applications, cost-effective sensing devices with a small footprint and the ability of real-time detection are preferred. On the other hand, advances in modern micro-/nano-fabrication technologies and miniaturizations have enabled sensing technologies to turn to systems on a chip (SOC) scheme. In particular, microelectromechanical system (MEMS) devices have been proven as a promising candidate for the development of SOC technology, due to the maturity of processes and its compatibility with standard complementary metal-oxide-semiconductor (CMOS) technology.

This work demonstrates an on-chip integrated CO_2 sensor, which consists of a MEMS emitter and a pyroelectric detector. Both the emitter and detector are bonded on a thermal pathway substrate. The MEMS thermal emitter acts as a radiation source, while the pyroelectric detector converts the changes in temperature due to CO_2 gas concentration into a current signal. All key components use CMOS compatible fabrication method. The performance of the sensor is tested and discussed. Results indicate that the sensor responds linearly to variations in the CO_2 concentration.

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2. SENSOR DESIGN AND INTEGRATION

2.1 Pyroelectric effect and thermal conductivity

Gas concentration can be measured based on the thermal conductivity of different gases. In principle, when there is a change in the concentration of the gas components under measurement, the thermal conductivity of the gas mixture changes. The rate of change of the temperature can be detected by a pyroelectric detector[11], which generates a pyroelectric current proportional to the rate of the temperature change. Therefore, we propose an on-chip CO_2 gas sensor configuration, which consists of a MEMS emitter and a pyroelectric detector, integrated with a thermal pathway substrate, as shown in Fig. 1. Upon detection of the modulated radiation from the emitter, the pyroelectric detector responses to various temperature differences and exhibits different current peak level according to the CO_2 concentration in the sensor.

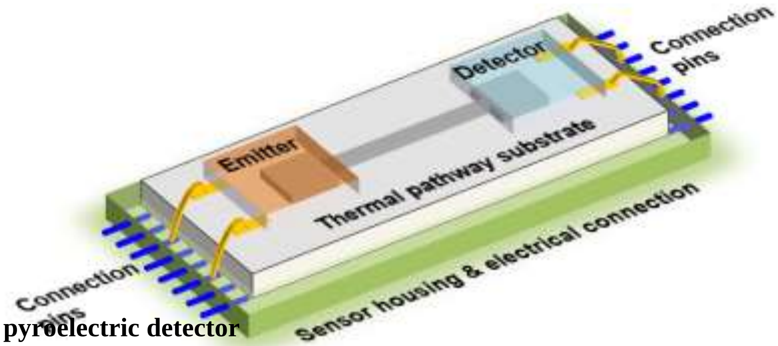

Figure 1. Schematic drawing of the integrated CO_2 gas sensor. The emitter and detector are aligned and bonded on the thermal pathway substrate.

2.2 MEMS emitter and pyroelectric detector

Within the CO_2 sensor, we use a MEMS thermal emitter[12] as a resistive heater. A meander design is employed to improve the thermal uniformity and temperature distribution in the active region. The MEMS emitter is fabricated on an 8-inch wafer using a CMOS-compatible fabrication facility. The device includes a metal layer acting as a resistor to generate heat when applying an electrical voltage. A top metal layer acts as the interdigitated electrode to ensure homogeneous heat distribution. To achieve thermal isolation from surrounding components, we designed a suspended membrane that is surrounded by air acting as a thermal insulator. The suspended membrane is formed using the deep reactive ion etching (DRIE) process to remove the silicon substrate from the wafer back.

The detector is another critical component in this integrated on-chip CO_2 gas sensor solution. Many studies have demonstrated uncooled thermal detectors, among which pyroelectric thermal detectors have inherent uncooled advantages over other thermal detectors technologies. In particular, aluminum nitride (AlN) based pyroelectric detectors have been reported capable of infrared detection at room temperature operation conditions. In this work, we select a MEMS pyroelectric detector[7] to be integrated into the gas sensor device. The pyroelectric detector contains multiple layers that provide different functionalities. The top SiO_2-SiN-SiO_2 stack acts as an absorber, which sits on the top electrode layer constructed by TiN layer. The bottom electrode is formed by Mo. A ScAlN pyroelectric film is sandwiched between the top- and bottom- electrodes. In this device, we use Al metal contacts to link respective electrodes. To improve thermal isolation and detection efficiency, the entire film stack membrane is released from the backside Si substrate. Meanwhile, to obtain higher material pyroelectric coefficient, we doped AlN with 12% Scandium (Sc) which has demonstrated a detectivity of up to ~6.08×10^7 $cm\sqrt{Hz}/W$. The whole fabrication process is CMOS compatible. The active region of this detector is 3.45 mm × 3 mm.

2.3 Sensor integration

Flip-chip integration has been widely used in the assembly of MEMS devices[13], especially with process optimization, low temperature, low bonding force, and short bonding time could enable high yield. In this work, as the MEMS emitter and pyroelectric detector both feature active regions at the top surface, we selected a polyimide material as the bonding adhesive layer for protection. Before the sensor integration, the polyimide is pre-patterned on the thermal pathway substrate chip, forming a cavity structure to protect the active surfaces of MEMS devices. Plasma treatment on the substrate surface is conducted to improve the adhesion between bonded surfaces. Subsequently, the separate MEMS chips are aligned and bonded to the patterned substrate, forming the integrated sensor chip, as shown in Fig. 2(a). After that, the bonded sensor device is subjected to curing at the temperature of 200ºC for 2 hours inside an oven to ensure the bonding quality. For the convenience of external electrical connections and sensor characterizations, the integrated sensor chip is placed inside a bathtub with wire bonding to different leads at two ends of the hybrid package housing, as shown in Fig. 2 (b).

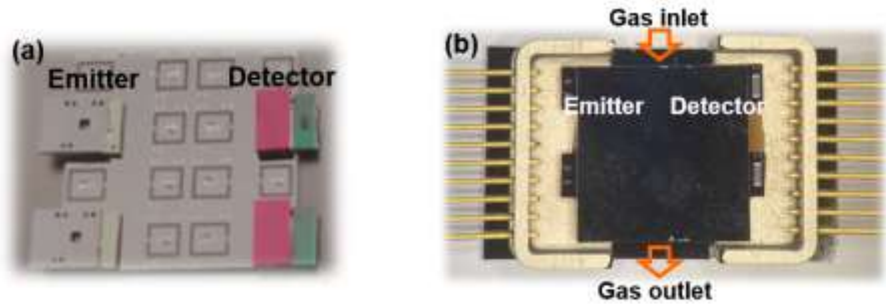

Figure 2 The images of the integrated CO_2 gas sensor. (a) The on-chip integrated CO_2 gas sensor, and (b) the hybrid packaged sensor chip wire-bonded in a bathtub housing.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

A schematic diagram of the overall gas sensor testing setup is shown in Fig. 3. The 99.8% CO_2 gas source is diluted with 99.99% purity nitrogen (N_2) gas. Varying CO_2 concentrations are obtained by a gas mixing system with computer-controlled mass flow meters for tuning the CO_2 and N_2 gas flow rates. The gas sensor is placed in an environmental control chamber throughout the measurement duration to control and monitor the humidity and temperature. Additionally, N_2 gas is also used for purging and cleaning the measurement chamber. A waveform generator is used to drive the MEMS emitter using a square wave with a modulation frequency of 17 Hz and a peak-to-peak voltage of 1.8 V. The pyroelectric response is proportional to the rate of temperature change, and the signal detected is relatively weak. Therefore, a low-noise current preamplifier with a gain of 10^9 is used to amplify the signal, which is then captured by a lock-in amplifier (Zurich Instruments HF2LI).

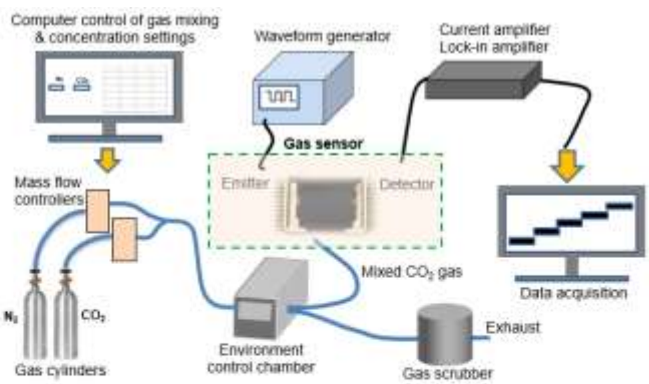

Figure 3 Schematic representation of the CO_2 gas sensor characterization set-up and integrated gas sensor.

Figure 4 plots the measured sensor response to different CO_2 gas concentrations for different ranges. In Fig. 4(a), the CO_2 concentration is varied over a range from 50% to 0% in intervals of 10%. For each concentration level, the duration cycle is 7 minutes, and it switches to the next concentration level through automatic control by the gas mixing system. Each data point in the plot is an average value of the sensor voltage readings over the 7-minute duration. The error bars (i.e., standard deviation) for most experiments are around ~ 5 µV. As shown in both plots in Fig. 4 (a) & 4(b), the sensor response is linear from 0% to 100% CO_2 concentration. We observe a slight difference in the slope for the decreasing (Fig.4(a)) and the increasing (Fig.4(b)) CO_2 concentrations, whose raw data collected are presented in Fig. 4(c) and 4(d),

[redacted]

respectively. The exact cause for such differences requires further investigation, but it could be attributed to experimental nonidealities such as thermal insulation during measurements. The dependence of the slope on the increase/decrease of concentration will be our future studies.

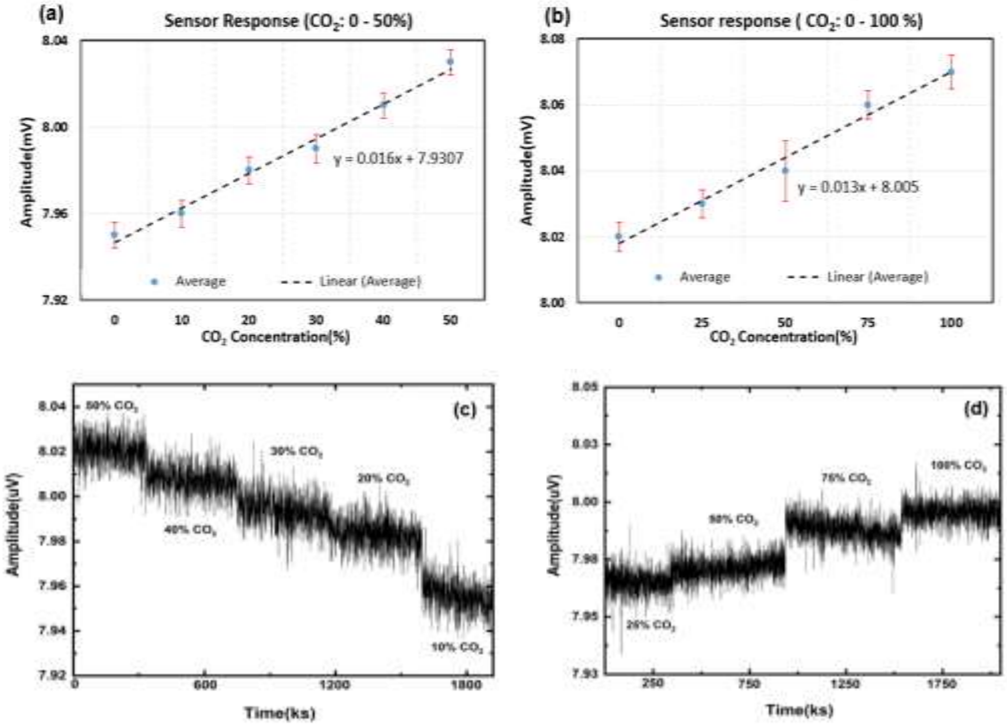

Figure 4 (a) The sensor response to the CO_2 concentration changes over 0%-50% at a step of 10%. (b) The sensor response to the CO_2 concentration changes over 0%-100% at a step of 25%. (c) and (d) are the raw plots of the experimental sensor voltage response (in the time domain) without any signal processing to CO_2 concentrations over 50%-0% and 0%-100%, respectively.

4. CONCLUSION

In summary, an on-chip integrated CO_2 gas sensor with a MEMS-based thermal emitter and a pyroelectric detector is demonstrated. Each component is fabricated using CMOS-compatible processes and the integrated sensor has a small footprint of 13mm × 3mm (L×W). Sensor characterization results show that the sensor response increases linearly with CO_2 concentration over a range from 0 to 100%. The integrated gas sensor is highly promising for other low-cost and miniature gas sensor solutions, and for mass deployment of gas sensors in environmental sensing networks.

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