A 3.5x3.5mm^2 1.47mW/Ch 16-Channel MSS-CMOS Heterogeneous Multi-Modal Gas Sensor Chip Stack

Miniaturizing and reducing the power consumption of multi-modal gas sensors with multiple channels can enable a wide array of applications, including integrating with wearable devices for daily breath analysis, encapsulation into ingestible pills for internal body measurements, and embedding into smart tags for food freshness management (Fig.1). Traditional gas sensors typically have the transducer and CMOS chip connected via wiring on a substrate, leading to a large-form factor that requires complicated and expensive packaging and cannot readily scale to many-sensor array [1]. Recent studies have proposed gas sensors utilizing a MEMS-CMOS stack; however, these have yet to demonstrate responses to different gas types, and there are also challenges regarding increasing the number of channels and reducing the power consumption [2]. In this paper, we propose a heterogeneous multi-modal gas sensor that employs a Membrane-type Surface-stress Sensor (MSS) as the transducer stacked on top of CMOS for analog frontend and digital readout.

MSS is an ideal gas-sensing element since it combines compact size, low power consumption, and high sensitivity, while being able to detect and differentiate many different gases by the choice of receptor materials coated on top of the MSS membrane surface. Figure 1 details the implementation of the proposed multi-modal gas sensor. Each channel of the MSS is constructed by using piezoresistors embedded in each of four narrow bridges supporting a silicon thin-film on an SOI substrate, forming Wheatstone bridge through their interconnections. On the reverse side, there is an opening cavity for gas flow, through which a gas sensitive receptor polymer is coated onto the silicon thin-film to adsorb gas and provide selectivity. The sensitive polymer expands when it adsorbs gas molecules, causing the silicon thin-film to bend upwards. The stress caused by the bending is transmitted to the piezoresistors, resulting in a change in resistance. Since the stress is efficiently transmitted to the four piezoresistors Wheatstone bridge in differential manner, the sensitivity of the MSS is over 100 times higher than that of conventional cantilever-type elements with one end fixed [3]. The type of sensitive polymer applied to the MSS can be varied for each channel, allowing each channel to respond uniquely to different gases. It has been demonstrated that an MSS array with multiple types of sensitive membranes can distinguish between cancer patients and healthy individuals from breath samples [4].

In this paper, a readout circuit specialized for the differential voltage output of the MSS is proposed. Figure 2 illustrates the circuit diagram of the proposed multi-modal gas sensor readout. Each channel consists of an MSS, a differential voltage to current (DV/I) conversion circuit, two relaxation oscillators, and two counters. The current copy from a constant current generator and the reference voltage from the Subthreshold BGR (SBGR) circuit [5] to the oscillators are shared across all 16 channels. The MSS and the CMOS readout circuit are connected through four terminals: V_I, V_O, V_P, and V_N. Current is supplied to the MSS Wheatstone bridge through V_I from the CMOS readout circuit, and V_O is connected to the ground of the readout circuit. When the sensitive polymer coated on the MSS adsorbs gas, the change in the resistance balance of the bridge alters the differential voltage. This change in differential voltage appears as a variation in current I_{SENS} through the DV/I converter, where V_P and V_N serve as differential inputs. I_{SENS} acts as the reference current for one of the two relaxation oscillators, and its oscillation frequency is proportional to I_{SENS}. A constant current I_{REF} flows through the other oscillator. These two relaxation oscillators operate simultaneously, incrementing the counter. Finally, by taking the ratio R_f of the respective oscillation frequencies f_{SENS} and f_{REF}, a common-mode disturbance such as supply noise can be greatly suppressed and a stable digital output linear to gas concentration is obtained.

By stacking the MSS on top of a CMOS chip, the length of the wiring between the MSS and CMOS is minimized, enabling not only a reduction in implementation size and significant simplification of packaging complexity, but also a stable, low-noise readout of the potential difference output from the MSS. This paper implements a 4x4 channel MSS-CMOS prototype multi-modal gas sensor array (Fig.3). The sensor surface has openings with a diameter of 0.3 mm for gas flow corresponding to the number of channels, and located on top of the MSS transducer array, which are stacked facing the underlying CMOS chip. The piezoresistors of the MSS are fabricated via ion implantation, and the wiring of the MSS chip is deposited using an aluminum pattern. The four terminals of the MSS Wheatstone bridge are vertically connected to the CMOS chip using electrodes with microbumps. The CMOS chip is manufactured using a standard 180nm process. Since the readout circuit for each channel is designed to match the size of the MSS above it, array can readily be scaled up to any desirable number of channels.

Specialized circuit is designed to read the differential voltage of the MSS while being robust against various measurement condition variations and nonidealities. As a preliminary performance evaluation of the readout circuit, the potential difference of the MSS was instead supplied from an external power source, and the frequency ratio shift (ΔR_f) corresponding to the potential difference change was measured (Fig.4). On a log-log plot, ΔR_f shows a very linear response to differential voltage changes, successfully reading a differential voltage change as small as 0.1 mV under temperature variations from -20 to 80°C and V_{DD} variations between 1.7 and 2V. Similarly, a linear response of ΔR_f to potential difference changes was observed under common-mode voltage V_{CM} variations of 400 to 900mV and offset voltage V_{OFFSET} variations of -50 to 50mV. The stability of the response to V_{CM} variations allows for sensitivity correction through current adjustment to the Wheatstone bridge, and the response stability to V_{OFFSET} ensures tolerance to manufacturing variations in piezoresistors.

The implemented gas sensor prototype successfully achieved stable readings of responses to actual gases with a sensor array where sensitive polymers specialized for different gases were applied to each channel. A chamber was placed on top of the gas sensor to introduce gas, and the target gas and baseline gas (N_2) were alternated using a gas flow control device. Figure 5 shows measurement data for ammonia (NH_3) and toluene.

Time-series data of the sensor response was obtained at 1-second intervals with a 10ms sampling time via digital control signal communication between the sensor circuit and an FPGA. Although noise from the power supply affects the oscillation frequency (f_{SENS}), it was significantly suppressed by taking the ratio with f_{REF}, which was similarly affected by the same noise sources. Calculated from the frequency ratio R_f measurement data during a 5-minute baseline, the 3σ value was 0.000279. Distinct responses were observed when switching from N_2 to 500ppm NH_3 and from N_2 to 500ppm toluene, with a fast response time of 12 seconds to reach 90% of the stable value for 500ppm NH_3. The baseline shift observed between the NH_3 and toluene measurements can be attributed to differences in the measurement environmental temperature. Under a temperature-controlled measurement environment set to 25°C, the NH_3 concentration was varied stepwise, and the average value during 50 seconds of gas introduction was plotted (Fig.6). On a log-log plot, ΔR_f showed a linear response to NH_3 concentration changes. Based on the 3σ baseline variation in Figure 5, the Limit of Detection (LoD) for NH_3 was determined to be 0.1ppm. This value of ΔR_f is in the range of measurements covered by the performance evaluation of the readout circuit in Fig.4.

The multi-modal gas sensor proposed in this paper also supports a wide range of temperature and humidity sensors. Due to the temperature dependence of the piezoresistors in the MSS, the baseline frequency ratio changes linearly with temperature. Since f_{REF}, which is entirely contained within the CMOS chip, also changes linearly with temperature variations from -20 to 80°C, the baseline temperature variation can also be compensated by using this f_{REF} as a temperature sensor. Additionally, ΔR_f shows a linear response to humidity changes, accommodating relative humidity variations from 20 to 100%.

Figure 7 presents a performance comparison among the-state-of-the-art gas sensors reported at recent ISSCCs. Gas sensors with heaters are excluded because the power consumption of the transducer during heating is dominant and huge although its sensitivity is very high [6]. The gas sensor proposed in this paper has the smallest chip size per channel compared to other gas sensors presented at ISSCC. Compared to the latest gas sensor [2], the active power consumption per channel is less than one-sixth. The active channel power of [7] cannot be calculated as its active rate and sampling rate were both not disclosed. The gas sensor proposed in this paper exhibits very high sensitivity with an NH_3 LoD below 1ppm, and superior performance in terms of size and power consumption, making it promising for practical applications in a wide range of important fields, including food and healthcare.