A MONOLITHIC IMPLEMENTATION OF INTERFACE CIRCUITRY FOR CMOS COMPATIBLE GAS-SENSOR SYSTEM

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ABSTRACT

A monolithic micro-gas-sensor system, designed and fabricated in a standard CMOS process, is described. The gas-sensor system incorporates an array of four microhotplate-based gas-sensing structures. The system utilizes a thin film of tin oxide (SnO_2) as a sensing material. The interface circuitry on the chip has digital decoders to select each element of the sensing array and an operational amplifier to monitor the change in conductance of the film. The chip is post-processed to create microhotplates using bulk micro-machining techniques. Measurements are presented for various portions of the interface circuitry used for the gas-sensor system.

1. INTRODUCTION

Microhotplate-based devices have been fabricated in silicon for some years now. One important application for such devices is the integrated gas sensor. Early examples of such devices were fabricated as discrete structures [1]. Later microhotplate fabrication was demonstrated by commercial CMOS processing with post-processing techniques to form suspended membranes [2]. The CMOS-compatible process realizes a class of devices that are based on thermo-electro-mechanical effects and are compatible with existing VLSI circuit design techniques [3 – 5]. In reference [6], we showed gas-sensor responses to various gases and their concentrations and described a scheme for combining the microhotplate structure with the integration of a fully functional CMOS interface circuit. In this paper, we present measurement results of the interface circuitry for that system.

2. CMOS GAS-SENSOR STRUCTURE

The microhotplates studied in this work are fabricated using CMOS microfabrication technology normally used for manufacturing integrated circuits. Post-processing steps are then used to remove silicon beneath fabricated layers forming a suspended membrane. Tetramethyl ammonium hydroxide (TMAH) is used for the silicon etch [7]. Additional post-processing steps can be used to deposit films on top of the membrane to form the gas-sensing element [8]. The conductivity of the sensing film (e.g., SnO_2) at high temperatures (100 °C to 450 °C) is sensitive to the presence of specific gases. Suspended structures are required to achieve high thermal efficiency in this temperature range.

The CMOS foundry microfabrication processes provide multiple layers of different materials needed to form semiconductor devices and interconnections for integrated circuits. The design layout file defines the material layers present in each region of the integrated circuit. Using the layout design files, both microhotplates and accompanying electronic circuits can be implemented on the same substrate [9].

Figure 1(a) shows the layer components of the membrane that is suspended after the post processing silicon etch, and fig. 1(b) shows an SEM micrograph of the suspended membrane microhotplate gas sensor. The SiO_2 layers are used by the CMOS process to provide isolation between interconnect layers and to form gate isolation for the MOSFET devices. For the microhotplate devices, the SiO_2 layers are used to provide isolation between the heating, sensing, and heat spreading layers, and to provide strength to the suspended membrane. The polysilicon layer used to form the MOSFET transistor gates and resistors for integrated circuits is used as the heating element in the

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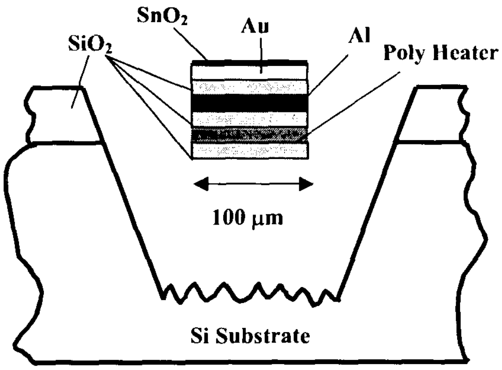
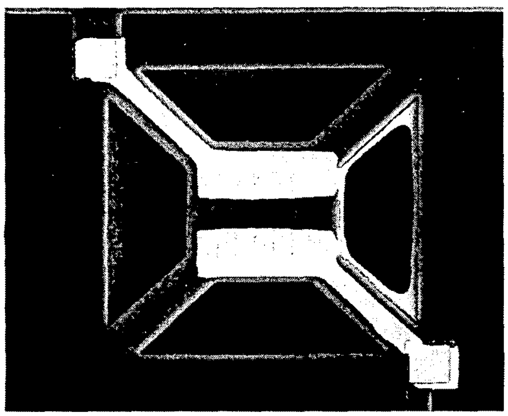
microhotplate. The aluminum layer used for interconnects in integrated circuits is used as a heat spreader in the microhotplate. The gold and the tin-oxide layers are post-processed application-specific layers used for the gas-sensing application.



(a)



(b)

Fig. 1 Microhotplate (a) cross section of layer structure and (b) SEM micrograph of the suspended structure.

3. CIRCUIT REQUIREMENTS FOR GAS ARRAY SENSING

In general, the output from a gas sensor is too weak to drive a data acquisition or other system directly, and some signal amplification and on-chip signal processing is desirable. Furthermore, it is generally desirable to have an array of microsensors for a gas sensor system, where each element of the array is independently selectable for sensing and heating. An array of gas-sensing elements is used in order to produce a signature pattern that enables the unique recognition of a specific gas species. When these arrays are made, each element of the array can be made different by controlling the material properties of the sensing film. The sensing material (SnO_2 being the most common) is deposited over the microhotplate structure using a mask-less low-pressure chemical vapor deposition (CVD) technique. During growth of the thin film, granularity depends, in part, on the microhotplate temperature; this requires the heater of each element of the array to be individually addressable [10].

The interface circuit described in this work allows the independent selection of both heaters and sensing elements of a gas-sensor array. The independent selection of the heaters is required for both thin-film deposition during post processing and normal operation of the completed gas sensor. The interface circuit must be able to supply up to 15 V at 5 mA, and an appropriate driver circuit is described in section 4. The sensing circuit must be able to measure sensing film resistance between 10 kΩ and 1 MΩ, and an appropriate circuit is described in section 4.

4. INTERFACE DESIGN

In this section, an interface circuit for automatic sensor selection and conductance measurement is described. To measure the conductance of the SnO_2 sensing film, an inverting operational amplifier configuration is used, where the sensing film is in the feedback loop of the amplifier.

Figure 2 shows the interface circuit, which contains both a selectable sensor array (S1, S2, ..., S4) and a selectable heater array (H1, H2, ..., H4). A 2-bit decoder activates a given sensor along with a corresponding heater for that sensor.

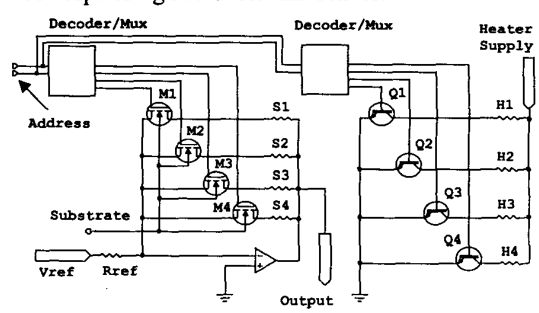


Fig. 2 Interface circuit

The bipolar junction transistor (BJT) pass-switches (Q1, Q2, ..., Q4), indicated in fig. 2, implement heater switching, and the MOS pass switches (M1, M2, ..., M4) implement sensor array switching. BJTs were used for heater switching because of the higher voltage and current requirements. MOS pass-switches were used for sensor array switching because of their small dc offset. Only one heater-sensor pair is activated at one time. Figure 3 shows a micrograph of the gas-sensor system.

An on-chip operational amplifier is designed and configured to measure the conductance of a selected sensing element of the gas-sensor array. A circuit schematic of the operational amplifier is shown in fig. 4, and the layout is given in fig. 5. This operational amplifier will be described in detail below.

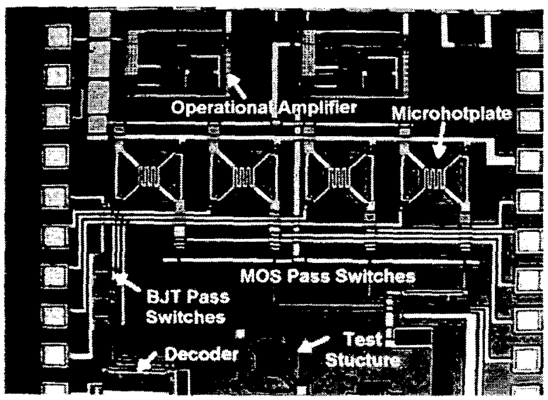


Fig. 3 Micrograph of gas-sensor system

Due to the very large open loop gain and high input resistance, the closed loop gain of the inverting amplifier depends on Rref (fig.2) and the sensor's resistance, and is independent of the open-loop gain. The output of the amplifier thus reflects the conductance of the selected sensor element. The resistances of the MOSFET pass switches are known, and the output can be calibrated to compensate for this effect.

The advantage of this scheme is that only one operational amplifier and two decoders are needed to measure the change in conductance of the entire gas array. Furthermore, variations in Vref, Rref, and amplifier offset and gain will track for all sensing elements.

The digital portion of the micro-gas-sensor system, comprised of the 2-bit decoder, was designed and implemented using a standard CMOS gate cell library. The layout-program automatically generated the layout for the 2-bit decoder. Pass transistor layout was done manually to insure low on-resistance.

The analog part of the circuit, which includes the operational amplifier, was designed using a standard three-stage configuration scheme [11]. This scheme includes the input differential stage, a gain stage and the output buffer stage. The layout for the operational amplifier was also done manually to optimize device matching and performance. The operational amplifier is designed to operate with supply voltage of plus and minus 3 V. In the operational amplifier, transistors T1 and T2 (fig. 4) are the input transistors of the differential stage. T10 provides most of the gain of the amplifier. T7 and T12 serve as the output buffer stage. All other transistors act as current source loads or current references.

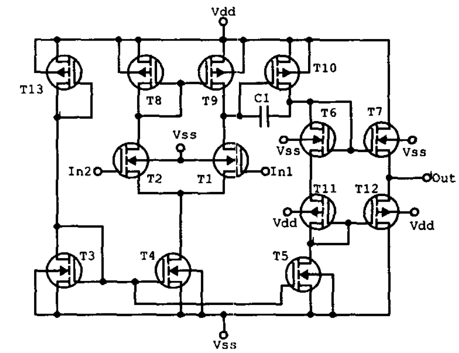


Fig. 4 Operational amplifier schematic

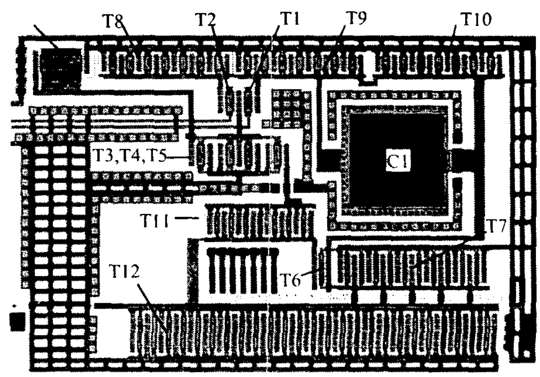


Fig. 5 Operational amplifier layout (410 μm x 275 μm)

5. MEASUREMENT RESULTS

Figure 6 shows the measured transfer characteristics of one of the BJT pass switches. The collector breakdown voltage exceeds 30 V. The current gain is 50 at a collector current of 5 mA and 1 V collector to emitter. BJTs were fabricated using the P base layer provided by the CMOS process.

The gas-sensor system shown in fig. 3 contains an operational amplifier as a test structure in addition to the one connected to the gas-sensor system. Figure 7 demonstrates the dynamic range of the test structure operational amplifier. The amplifier was configured as an inverting amplifier with a gain of five, set by external resistors for this measurement. The input is 0.5 V peak-to-peak, and the measured output is 2 V peak-to-peak with some clipping. The amplifier is overdriven to demonstrate its dynamic range. Figure 8 demonstrates the speed of the amplifier. A square wave of 100 kHz is reproduced adequately.

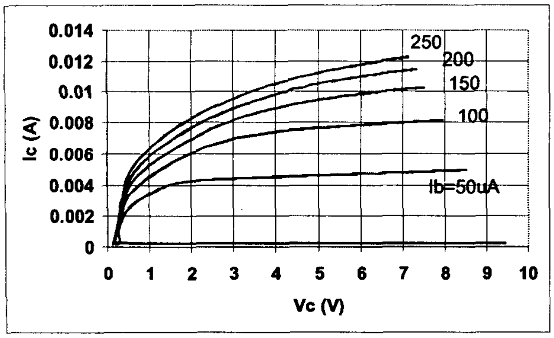


Fig. 6 BJT transfer characteristics

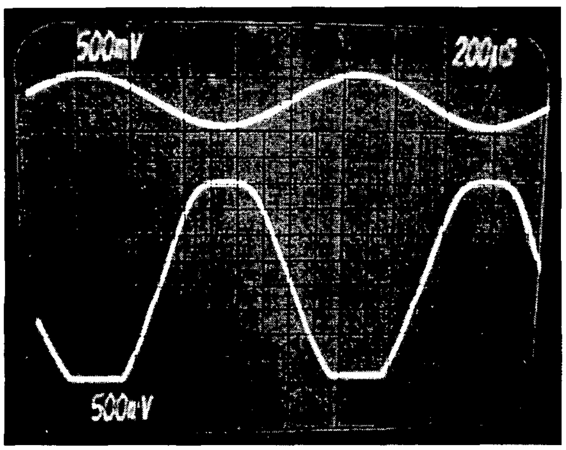


Fig. 7 Operational amplifier response

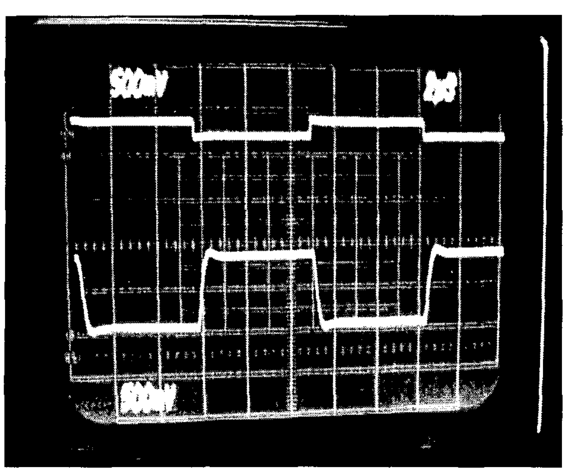


Fig. 8 Operational amplifier response

6. CONCLUSION

In this paper, we have presented an interface design for a monolithic microhotplate-based gas-sensor system. It is found that bipolar transistors are suitable for driving heater elements of the microhotplate structures and MOSFETS are suitable for addressing the desired sensing film. An on-chip operational amplifier used for measuring the sensing film conductance is described, and measurements are given.

We have demonstrated that by using CMOS compatible post processing steps to realize microhotplate structures and integrated electronics, low-cost, robust sensor systems can be implemented on a common substrate. Other issues regarding packaging and sensor reliability will need to be addressed in future work before such systems can become commercially viable.

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