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A Monolithic Integrated CMOS Thermal Vacuum Sensor*

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Abstract: The monolithic integrated micro sensor is an important direction in the fields of integrated circuits and micro sensors. In this paper, a monolithic themral vacuum sensor based on a micro-hotplate (MHP) and operating under constant bias voltage conditions was designed. A new monolithic integrating mode was proposed, in which the dielectric and passivation layers in standard CMOS processes were used as sensor structure layers, gate polysilicon as the sacrificial layer, and the second polysilicon layer as the sensor heating resistor. Then, the fabricating processes were designed and the monolithic thermal vacuum sensor was fabricated with a 0.6μm mixed signal CMOS process followed by sacrificial layer etching technology. The measurement results show that the fabricated monolithic vacuum sensor can measure the pressure range of 2～10^5 Pa and the output voltage is adjustable.

Key words: thermal vacuum sensor; monolithic integration; CMOS; micro hotplate
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1 Introduction

Compared with traditional sensor systems composed of discrete components, monolithic integrated micro sensors have many advantages such as small size, quick response, low power, low price, good resistance to interference, and are suitable for long distance transmission[1]. Some companies have engaged and developed many monolithic micro sensor products such as the SHT11/15 humidity and temperature sensor of Sersirion in Switzerland, the ADXRS300 gyroscope and ADXL05 accelerometer and linear output magnetic sensor of ADI, the MMA1220D accelerometer of Motorola, the ST3000 series pressure sensor of Honeywell, and the FCD4B14 fingerprint sensor of Atmel[2].

Thermal conductivity vacuum sensors work on the principle that gas thermal conductivity varies with gas pressure. They have simple structures and no deformation components, and are easier to fabricated with IC process technology to realize monolithic integration with processing circuits than other types of vacuum sensors. Monolithic integration not only reduces the peripheral components of the vacuum sensor and connection interference, but also makes it more convenient to apply in leak detection of microelectronic packages and compound vacuum gauges. Therefore, much research work on monolithic thermal conductivity vacuum sensors has been done. For example, University of California-Berkeley developed a MHP-based thermal conductivity vacuum sensor with a polysilicon heater fabricated by a front-side bulk micromachining process, which monolithically integrated a constant temperature bias circuit and an 8bit AD convertor[3～5]; Paul *et al*. in Switzerland used the first metal layer in the IC process as a sacrificial layer and the second metal layer as a sensitive resistor, and realized the monolithic integration of an MHP-based vacuum sensor, a constant temperature bias circuit, a bandgap voltage reference, and a 10bit AD[6～9]; The monolithic thermal conductivity vacuum sensor developed by Standford University used MOS transistor as heaters, a diode as a temperature sensitive component, and integrated a constant temperature bias circuit and a 6bit DA converter[10].

In this paper, a new monolithic integrating technique that uses gate polysilicon in the IC process as a sacrificial layer and the second polysilicon as a sensitive resistor is proposed. To test its feasibility, a monolithic CMOS thermal conductivity vacuum sensor is designed, and the monolithic integrating processes are made. In the last section, the fabricating and measurement results will be shown.

2 Sensor chip design

Figure 1 shows the architecture of the designed monolithic thermal conductivity vacuum sensor in constant voltage mode, in which the voltage output is

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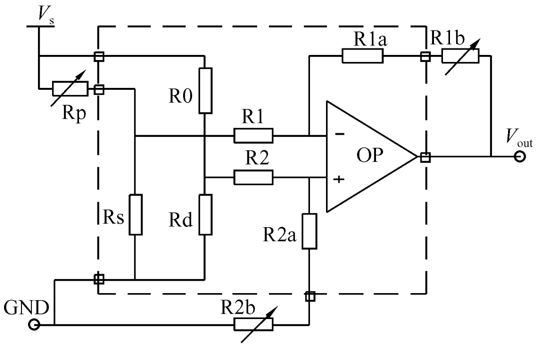

Fig. 1 Architecture of the monolithic thermal conductivity vacuum sensor chip

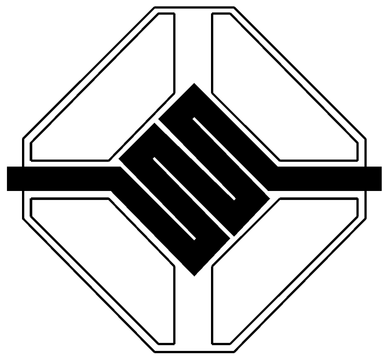

Fig. 2 MHP-based vacuum sensor in the monolithic chip

adjustable. Components in the dashed frame are integrated on the chip and those outside the dashed frame are connected discretely outside for measurement. R0, Rp, Rs, and Rd build up an electrical bridge in which Rs is the sensitive heating resistor, Rd is the ambient temperature compensation resistor, and Rp is an adjustable resistor for the electrical bridge balance. OP is a single source CMOS operational amplifier, its peripheral resistors R1 and R2 are 4kΩ. R1a and R2a are 10kΩ, which make the amplified factor 2.5 inside the sensor chip. The monolithic sensor chip should connect the electrical bridge voltage V_s, the positive voltage source, and the GND of the operational amplifier, Rp or the additional two resistors R1b, R2b to adjust the amplifying factor of the operational amplifier. All the resistors in the chip are gate polysilicon in the CMOS IC fabricating process except for Rs and Rd. Those resistors use the second polysilicon layer to obtain better sensitivity because the temperature coefficient of the second polysilicon layer is larger than that of the gate polysilicon layer in the 0.6μm mixed signal process of the CSMC Technology Corporation adopted in this paper.

Figure 2 is the designed MHP-based thermal conductivity vacuum sensor. The central square plate is 86μm×86μm in size and suspended by four supporting beams. A serpentine resistor on the plate corresponds to the sensitive heating resistor R_s in Fig. 1 and heats the micro plate. When gas pressure increases, heat dissipation through gas below the MHP will increase, which will elevate the MHP temperature and change the value of the temperature sensitive heating resistor. The positive temperature coefficient of the polysilicon heating resistor almost increases with its width and the temperature coefficient is related to the sensor sensitivity. Thus, to obtain the proper resistive value of about 900Ω, the heating resistor is designed to be 14μm wide. In the adopted 0.6μm mixed signal process, there are two metal layers for connection. The dielectric layer thickness between the second polysilicon layer and the first metal is about 500nm, and that between the first metal and the second metal is about 600nm. The passivation layers, including TEOS and SiN, are 550nm and 300nm thick, respectively. So the thickness of the MHP structure layers is about 1950nm, which guarantees the MHP strength. To avoid deformation caused by residual stress of the dielectric films, the supporting beams of the MHP are designed to be 45μm long and 22μm wide.

Figure 3 shows the schematic diagram of the designed 5V single voltage source, rail-to-rail CMOS operational amplifier, which mainly consists of a bias circuit, an input stage, a gain stage, and an output stage.

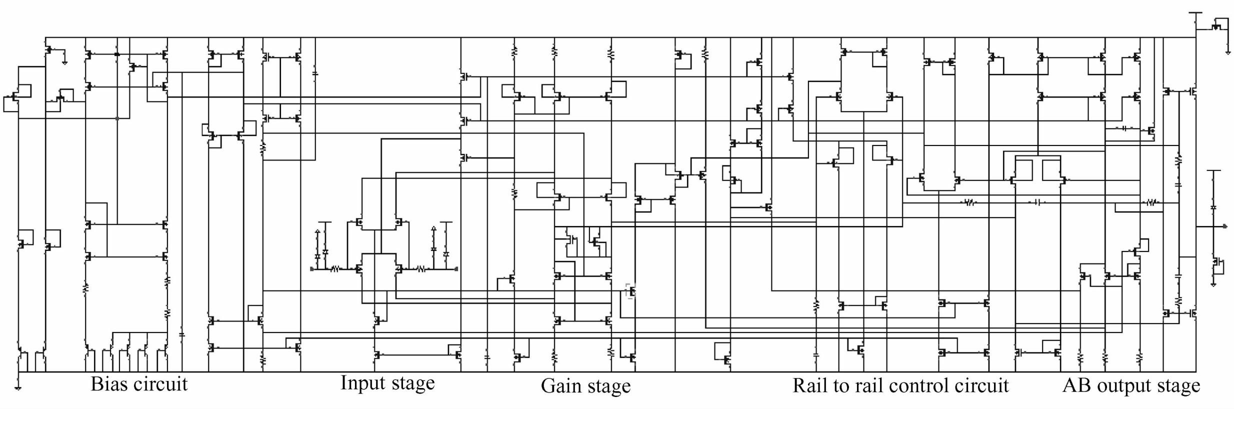

Fig. 3 Schematic of the CMOS operational amplifier

In constant voltage mode, the electric bridge is always balanced at low pressure. Thus when gas pressure changes, variations in Rs will unbalance the electric bridge and the bridge output can be amplified by the following CMOS operational amplifier.

3 Fabrication

The great challenge of monolithic integration is the compatibility of micro sensor and integrated circuit in the fabrication process. There are three monolithic integration modes of micro sensor and integrated circuit, including fabricating the microsensor with micromachining technology before IC fabrication (Pre-IC), intermediate IC fabrication (Itermediate-IC), or after IC fabrication (Post-IC)[11]. As for Post-IC, the integrated circuit can be fabricated in any IC foundry, but excessively high temperature during sensor fabrication may influence IC performance. For example, in the micro sensor using polysilicon as a structure layer, phosphorus silicon glass should be annealed at 950℃ for densification. The annealing temperature of polysilicon for reducing residual stress is above 1000℃, which may cause the transistor junction depth to change. If the metal connections are aluminum, the temperature in microsensor fabrication cannot exceed 450℃. As for Pre-IC, the possible pollution in microsensor fabrication, step-cover ability between microsensor and circuits, and the protection of the microsensor during IC fabrication should be taken into account. For Intermediate-IC, it does not accord with the standard IC process and can only be used in some special product lines although the fabrication process of the microsensor and the IC can be adjusted freely.

According to the characteristics of the designed sensor structure, this paper proposed a Post-IC monolithic integrated technique suitable for thermal conductivity vacuum sensor, in which IC are fabricated through MPW (multiple project wafer), SiO_2 and SiN_x in the IC fabrication process are used as the sensor structure layer and gate polysilicon as the sacrificial layer, and the second polysilicon layer is used as a heating resistor. Thus, in IC fabrication, the sensor structure layer and heating resistor can be deposited and etched. Then, the chip from the standard IC foundry can be wet etched to remove the sacrificial layer to obtain the sensor chip. In the CSMC 0.6 mixed signal process, which has double polysilicon layers and double metal layers, the gate polysilicon layer is 0.32μm thick and sheet resistivity of the second polysilicon layer is 20Ω/□.

According to the characteristics of sensor structure and IC process, the fabrication processes of the

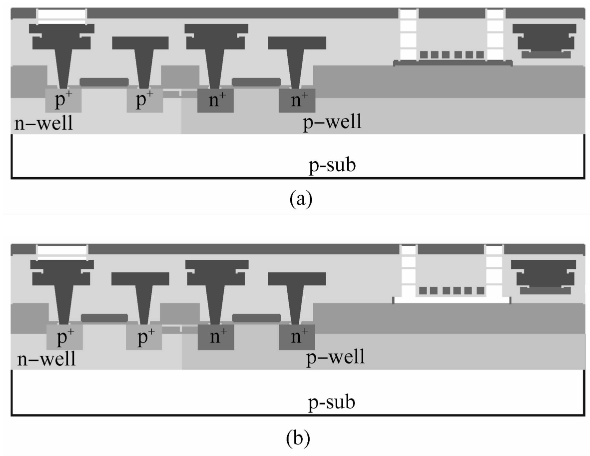

Fig.4 Cross section of the sensor chip before (a) and after (b) sacrificial layer etching

monolithic sensor chip were designed as follows: (1) Preliminary oxidation; (2) n-well pattern and ion implant; (3) p-well pattern and ion injection; (4) Well drive, oxide, and nitride deposition; (5) Oxide and nitride etch, and ion implantation in the field oxide area; (6) Oxidation and threshold voltage adjust; (7) Gate oxidation, gate polysilicon, and sacrificial layer deposition; (8) p^+ pattern and ion implant; (9) n^+ pattern and ion implant; (10) Isolation layer deposition and polysilicon heater etch; (11) Contact holes etch and sensor etching windows open partly; (12) Deposition and etch of the first metal layer; (13) Isolation layer deposition; (14) Vias open; (15) The second metal layer deposition; (16) Oxide and nitride passivation layer deposition; (17) Pad holes and etching windows etch; and (18) Polysilicon sacrificial layer etch. Figures 4(a) and (b) show the cross sections of the sensor chip before and after sacrificial layer etching, respectively.

From above, the thermal conductivity microsensor fabricated on the field oxide area can be seen. Except for sacrificial layer etching, all the fabrication processes are standard CMOS IC processes. The sensor structure layer consists of the isolation layer between polysilicon and a metal layer or between metals. The sacrificial layer etching windows are opened gradually when etching contact holes, vias, and pad holes.

Figure 5 shows the sensor chip photo before polysilicon sacrificial layer etching. There is an operational amplifier unit on the right and an additional MHP-base vacuum sensor on the left solely for testing their performance. The whole chip size is 2.5mm×1.6mm. Because the chip is thinned from 650μm to about 400μm, the dielectric layers on the chip backside have been removed and silicon is exposed directly. Thus, backside silicon will be inevitably etched at the same time when etching the polysilicon sacrificial layer.

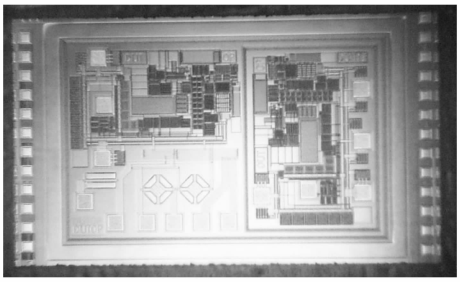

Fig. 5 Chip photo before polysilicon sacrificial layer etching

Although the sacrificial layer is only 43μm wide, an additional aluminum layer about 1μm thick is deposited on the chip backside to protect the backside silicon. Then the chip is immersed in a special TMAH solution that does not etch aluminum film to remove the sacrificial layer. Finally, the monolithic thermal vacuum sensor with suspended MHP is obtained.

4 Measurements

For measurement, the monolithic MHP-based vacuum sensor is encapsulated in a DIP-16 ceramic package. The wire connections and package photos are shown in Fig. 6.

According to the circuit architecture shown in Fig. 1, Rp, Rs, R0, and Rd are connected together to form one Wheatstone bridge, and the bridge voltage V_s is about 7V. The Wheatstone bridge is balanced at 0.1Pa. Then, the air is put in the vacuum chamber through the mass flow counter and variation of the voltage output of the operational amplifier with gas pressure is measured. Figure 7(a) shows the response curve of the monolithic MHP-based vacuum sensor without R1b and R2b to adjust the amplifying factor in which R1a and R2a are connected to output and ground, respectively. In Fig. 7(a), the voltage output of the monolithic sensor chip is actually 2.5 times the bridge output. Figure 7(b) shows the monolithic sensor response curve, in which R1b and R2b are 30kΩ, making the multiplying factor ten. The sensor voltage output can be amplified by changing the value of the

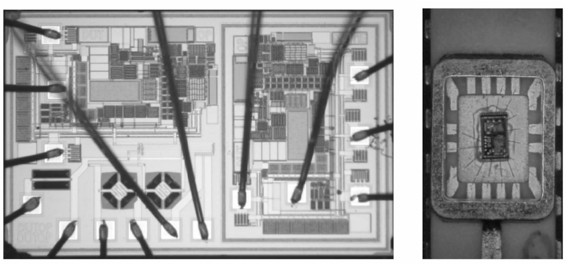

Fig. 6 Wire connection and package of the monolithic MHP-based vacuum sensor

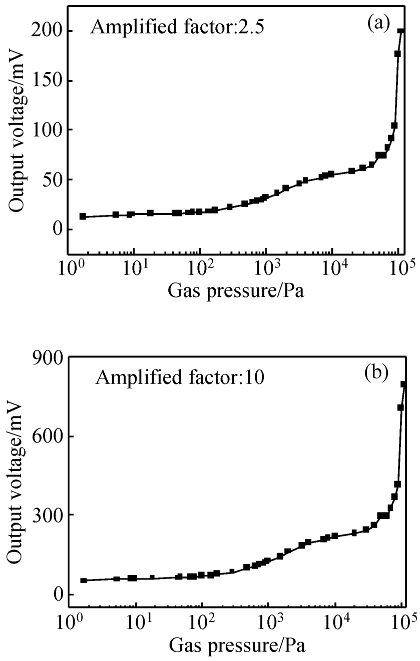

Fig. 7 Response curves of the monolithic MHP-based vacuum sensor

external resistors. Thus, the voltage output of the monolithic MHP-based vacuum sensor can be adjusted to the required value. The monolithic integration of microsensor and processing circuits is realized and the monolithic integration technique proposed in the paper is fulfilled.

5 Conclusion

The architecture of a monolithic CMOS thermal conductivity vacuum sensor at constant bias voltage mode is designed. An MHP-based vacuum sensor and a CMOS operational amplifier as the kernel circuit unit are designed based on the actual fabricating conditions. A new monolithic integration technique is proposed in which dielectric and passivation layers are used as a structure layer, gate polysilicon as a sacrificial layer, the second polysilicon layer is used as a heating resistor, and etching windows for sacrificial layer etching are opened gradually during etching of contact holes, vias, and pad holes. The fabrication processes of the monolithic MHP-based vacuum sensor are designed according to the characteristics of the 0.6μm CMOS mixed signal process and sacrificial layer etching. Measurement results of the monolithic vacuum sensor show that the sensor chip can measure gas pressure in the range of 2～10^5 Pa and voltage output can be adjusted through external resistors. The feasibility of the proposed monolithic integration method is confirmed.

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单片集成 CMOS 电阻真空传感器*

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摘要: 设计了一种工作在恒电压模式的、微热板结构的单片集成电阻真空传感器芯片.提出了一种以 CMOS 集成电路中的介质层与钝化层为结构层、栅多晶硅为牺牲层、第二层多晶硅为加热电阻的微传感器单芯片集成工艺模式,制定了相应的工艺流程.采用 0.6μm CMOS 数模混合集成电路工艺,结合牺牲层腐蚀技术实现了单片集成真空传感器的加工,测试结果显示该芯片能够测量 2～10^5 Pa 范围内的气压大小,且输出电压范围可调,验证了单片集成工艺的可行性.

关键词: 电阻真空传感器; 单片集成; CMOS; 微热板
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