A nanowire WO₃ humidity sensor integrated with micro-heater and inverting amplifier circuit on chip manufactured using CMOS-MEMS technique

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Received 4 August 2006; received in revised form 25 October 2006; accepted 26 October 2006

Available online 29 November 2006

Abstract

The fabrication of a nanowire WO₃ humidity sensor integrated with an inverting amplifier circuit and a micro-heater on a chip using the commercial 0.35 μm complementary metal oxide semiconductor (CMOS) process and a post-process have been implemented. The humidity sensor is composed of a sensing resistor and a humidity sensing film. Tungsten trioxide prepared by a sol–gel method is adopted as the humidity sensing film. The fabrication of the humidity sensor requires a post-process to etch the sacrificial layers and to expose the sensing resistor, and then the humidity sensing film is coated over the sensing resistor. The humidity sensor, which is a resistive type, changes the resistance when the sensing film adsorbs or desorbs water vapor. An inverting amplifier circuit is utilized to convert the resistance of the humidity sensor into the voltage output. The micro-heater is utilized to provide a super-ambient working temperature to the humidity sensor, which can avoid the humidity sensor to generate the signal drift. Experimental results show that the sensitivity of the humidity sensor is about 4.5 mV/% RH at 60 °C.

Keywords: Humidity sensor; CMOS; Micro-heater; Inverting amplifier circuit

1. Introduction

Humidity sensors that are utilized to detect humidity and moisture are important devices in many industrial and biomedical applications. For instance, Tetelin et al. [1] developed a capacitive humidity sensor to equip a medical microsystem for diagnosis of pulmonary diseases. Boisen et al. [2] proposed a humidity sensor for monitoring environment. Dokmei and Najafi [3] reported a high sensitivity humidity sensor for monitoring hermetic micropackages. Bokmann et al. [4] presented a humidity sensor for industrial humidity measurement.

Various microsensors have been manufactured using micro-electromechanical systems (MEMS) technology [5]. Humidity sensors fabricated by MEMS technology have the advantage of small size, low weight, high performance, easy mass-production and low cost [6]. Several studies have recently used MEMS technology to fabricate micro-humidity sensors. For instance, O’Halloran et al. [7] employed bulk micromachining technique to fabricate a capacitive porous silicon humidity sensor. Rittersma et al. [8] fabricated a capacitive porous silicon humidity sensor using a surface micromachining technique. Park et al. [9] presented a thin-film surface micromachining technique to make humidity sensors. Boltshauser et al. [10] utilized an industrial CMOS process to make a resonant humidity sensor, which was based on silicon-oxide resonators coated with vapor-absorbent polyimide thin films achieving a sensitivity of 270 Hz/% RH. A capacitive humidity sensor with an anodized aluminum oxide (Al₂O₃) thin film, proposed by Nahar [11], had a sensitivity of 100 pF/% RH. Story et al. [12] developed a polymeric humidity sensor, and its sensitivity was 10 kΩ/% RH. A surface and bulk micromachining process, reported by Lee et al. [13], was employed to fabricate a capacitive humidity sensor with suspending structures, which had a sensitivity of 2 nF/% RH.
The CMOS-MEMS technique [14] uses the commercial CMOS process, usually employed to produce integrated circuits (IC), to fabricate MEMS devices. Many microdevices such as tunable resonators [15], micromirror arrays [16] and microwave switches [17] fabricated by the CMOS-MEMS technique require a post-process to release the suspended structures or coat the functional films. The advantage of micromachined devices fabricated by the CMOS-MEMS technique is its ability to integrate with circuits as a system on a chip (SOC) due to their compatibility with the CMOS process.

In this study, we employ the CMOS-MEMS technique to fabricate a nanowire WO$_3$ humidity sensor integrated with a micro-heater and an inverting amplifier circuit on a chip, which can enhance the performance and reduce the volume and cost. The area of the integrated humidity sensor chip is about 1 mm$^2$.

### 2. Structure of the integrated humidity sensor

Fig. 1 illustrates the humidity sensor integrated with a micro-heater and an inverting amplifier circuit. The humidity sensor, which is composed of a humidity sensing film and a sensing resistor, is a resistive type. The sensing resistor is a polysilicon winding line. The humidity sensing film is tungsten trioxide which is prepared by a sol–gel method and coated on the sensing resistor. The micro-heater is used to provide a super-ambient working temperature, which can avoid the humidity sensor to generate the signal drift. The material of the micro-heater is the polysilicon layer of the CMOS process. The sensing resistor, which is connected to the inverting amplifier circuit, changes its resistance as the sensing film adsorbs or desorbs water vapor. The inverting amplifier circuit that contains an operational amplifier and resistances is employed to convert the resistance of the humidity sensor into the voltage output. The cross-sectional view of the integrated humidity sensor is shown in Fig. 2. The tungsten trioxide film is located at the surface layer of the humidity sensor. A silicon dioxide layer is located between the tungsten trioxide film and the sensing resistor. The sensing resistor is 2 µm wide, 0.4 µm thick and 4000 µm long.

Fig. 3 shows the energy band diagram of the humidity sensor. The tungsten trioxide is an n-type semiconductor, and the
Polysilicon is p-type. When the surface of WO₃ is exposed to water vapor, electrons are produced at the surface of WO₃ due to the electron-donating adsorption [18]. As shown in Fig. 3(a), an accumulation of electrons is formed at the surface of WO₃ when H₂O(gas) interacts with WO₃, so that the conduction and valence band edges of WO₃ bend downward, leading to generate a negative surface potential, \( \phi_s \) [19]. An accumulation of holes at the oxide-polysilicon interface is formed by the negative surface potential \( \phi_s \), which causes the conduction and valence band edges of polysilicon to bend upward as shown in Fig. 3(a) and results in the production of the potential barrier, \( V_s \). The conductance of polysilicon, \( G \), is determined by the potential barrier, \( V_s \), as described by the following relationship [20]:

\[
G = gq\mu_s N_d \exp\left(-\frac{qV_s}{kT}\right)
\]  

(1)

where \( q \) represents the electronic charge, \( g \) is a constant determined by the semiconductor geometry, \( \mu_s \) is the mobility of electrons, \( N_d \) is the density of donors, \( k \) is the Boltzmann constant, and \( T \) is the absolute temperature. According to Eq. (1), the conductance of the polysilicon reduces as the potential barrier \( V_s \) increases, which leads to an increase in resistance of the polysilicon. Fig. 3(b) illustrates the energy band diagram of the humidity sensor in a highly humid environment. The surface potential \( \phi_s \) increases when the WO₃ film of the humidity sensor interacts with more water vapor, resulting in an increment of the potential barrier \( V_s \) and a decrement of the polysilicon conductance \( G \). Therefore, the resistance of polysilicon increases as the humidity sensed by the WO₃ increases.

The inverting amplifier circuit shown in Fig. 1 is employed to convert the resistance variation of the humidity sensor into a voltage output. If the operational amplifier is ideal, then the output voltage of the circuit can be expressed as

\[
V_o = -\frac{R_s}{R_1} V_{in}
\]  

(2)

where \( R_s \) represents the resistance of the sensing resistor in the humidity sensor, \( R_1 \) is a constant resistance (10 kΩ in the design) and \( V_{in} \) is the input voltage. Fig. 4 shows the design of the operational amplifier circuit, where VDD represents a voltage power supply and VSS is the ground. Professional circuit simulation software, HSPICE, is used to analyze the operational amplifier and inverting amplifier circuit. Fig. 5 depicts the simulated results of the frequency response for the operational amplifier. The dc open loop gain of the operational amplifier is approximately 82 dB, and the phase margin of the operational amplifier is about 53°. Fig. 6 reveals the simulated results of the inverting amplifier circuit. In this simulation, the input voltage \( V_{in} \) is 1 V, the resistance \( R_1 \) is given with 10 kΩ and the resistance of the humidity sensor \( R_s \) varies from 12 to 45 kΩ. The output voltage of the inverting amplifier circuit changes from 1.07 to 1.67 V as the resistance of the humidity sensor varies from 12 to 45 kΩ.

3. Fabrication of the integrated humidity sensor

The integrated humidity sensor chip is manufactured by the commercial 0.35 μm CMOS process of Taiwan Semiconductor Manufacturing Company (TSMC). The chip requires a post-process to etch the sacrificial layers and to coat the humidity sensing film after completion of the CMOS process. The process flow of the integrated chip is illustrated in Fig. 7. The cross-section of the integrated chip after completion of the CMOS process is shown in Fig. 7(a). The chip consists of the humidity sensor, micro-heater and circuit. In the humidity sensor, the metal and via layers are adopted as the sacrificial layers, and the polysilicon layer is used as the sensing resistor and micro-heater. The materials of the metal and via layers are aluminum.
Fig. 7. Process flow of the humidity sensor: (a) after the CMOS process, (b) etching sacrificial layers, and (c) coating the sensing film.

Fig. 8. A photograph of the integrated humidity sensor chip after the wet etching process.

Fig. 9. A SEM image of tungsten trioxide film.

chip after the wet etching process. Then, the chip is put in an oven at 140 °C for 2 h, so that the polysilicon surface grows a thin silicon dioxide layer. Finally, the tungsten trioxide is coated on the sensing resistor as shown in Fig. 7(c). The tungsten trioxide, which is made by a sol–gel method [21], is prepared according to the following steps: (1) 2.02 g Na2WO4·2H2O is mixed with 100 ml deionized water and stirred until a homogenous solution is obtained; (2) the solution of 1 ml H2SO4 is added into the Na2WO4·2H2O solution with stirring until the mixing solution becomes homogenous, producing a primrose yellow slurry; (3) the product is aged at room temperature for 240 h; (4) the resulting product is filtered, dropped on the humidity sensor chip, followed by calcination in air at 150 °C for 3 h. Fig. 9 shows a scanning electron microscopy (SEM) image of the tungsten trioxide film. The sensing film, which is constructed by many nanowires of tungsten trioxide as shown in Fig. 9, is porous and has a large surface area.

4. Results and discussion

A power supply, a function generator, an oscilloscope and a test chamber (GTH-099-40-1P, Giant Force Instruments Enterprise Co.) were employed to measure the performance of the integrated humidity sensor chip. The sensor chip was set in the test chamber. The power supply and function generator provided a bias voltage of 3.3 V and an input voltage of 1 V, respectively, to the inverting amplifier circuit in the sensor chip. The oscilloscope was utilized to record the output signal of the sensor to humidity changes. The test chamber was capable of providing a temperature range of 0–100 °C and a humidity range of 25–95% RH. In the test chamber, the temperature and humidity could be tuned separately and maintained at constant levels.

The test chamber supplies different humidity levels, and the humidity sensor changes its resistance as the humidity rises or drops. The output voltage of the inverting amplifier circuit is measured by the oscilloscope. Fig. 10 shows the output voltage changes of the inverting amplifier circuit. In this investigation, the temperature was maintained constant at 75 °C, while the humidity was increased from 25% RH to 85% RH in 35 min and
then dehumidified to 25% RH at the same rate. The experiments revealed that the humidity sensor exhibited a small degree of humidity hysteresis. With the same procedure, the output voltage of the humidity sensor was measured in the humidity range from 25% RH to 85% RH at constant temperatures of 25, 30, 45 and 60 °C. Fig. 11 displays the measured results of the humidity sensor at different temperatures. The humidity sensitivity, which could be obtained by the linear fitting to the data in Fig. 11, was 4.5 mV/% RH at 60 °C and 4.8 mV/% RH at 75 °C. The results showed that the humidity sensitivity increased as the temperature rose. Therefore, the humidity sensor has the disadvantage of the variation in humidity sensitivity with ambient temperature.

The micro-heater in the chip was adopted to provide a super-ambient working temperature to the humidity sensor in order to overcome the influence of ambient temperature. A dc power supply provided different voltages of 2, 4, 6, 8 and 10 V to the micro-heater, and the test chamber was maintained at a constant temperature of 25 °C. In this experiment, the humidity sensor was heated by the micro-heater, and was not heated by the test chamber. Fig. 12 displays the measured results of the humidity sensor with the micro-heater under different voltages. The results showed that the micro-heater could be used to provide the working temperature of the humidity sensor. The humidity sensor should not produce any signal drift if the ambient temperature is lower than the working temperature from the micro-heater.

5. Conclusion

The nanowire tungsten trioxide humidity sensors integrated with an inverting amplifier circuit and a micro-heater were successfully implemented using the commercial 0.35 μm CMOS process and the post-process. The humidity sensor contained a sensing film and a sensing resistor. The sensing film, which was prepared by a sol–gel method, was the structure of nanowire tungsten trioxide. The humidity sensor, which was a resistive type, changed its resistance when the sensitive film adsorbed or desorbed water vapor. The inverting amplifier circuit was used to convert the change in resistance of the humidity sensor into a voltage output. The post-process utilized etchants to etch the sacrificial layers to expose the sensing resistor, and then tungsten trioxide was coated on the sensing resistor. Experimental results showed that the sensitivity of the humidity sensor was about 4.5 mV/% RH at 60 °C and 4.8 mV/% RH at 75 °C. The humidity sensor had a variation in humidity sensitivity with ambient temperature. In order to solve the influence of ambient temperature, the micro-heater was adopted to provide a super-ambient working temperature to the humidity sensor, which could avoid the humidity sensor to generate the signal drift.

Acknowledgements

The authors would like to thank National Center for High-performance Computing (NCHC) for chip simulation, National Chip Implementation Center (CIC) for chip fabrication and the National Science Council of the Republic of China for financially supporting this research under Contract No. NSC 95-2221-E-005-043-MY2.

References

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