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An accurate and stable humidity sensing characteristic of Si FET-type humidity sensor with MoS_2 as a sensing layer by pulse measurement

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ABSTRACT

In this work, we demonstrate the pulse scheme to obtain stable humidity sensing characteristics in Si FET-type humidity sensor using MoS_2 film as a sensing layer. To investigate the reaction between H_2O molecules and MoS_2 film, the transfer characteristics (I_D-V_{CG}) and transient drain current behaviors (I_D-t) are measured in both *p*MOSFET and *n*MOSFET sensors by DC measurement. To verify the effect of the pulse scheme, the pulsed *I*–*V* (PIV) and the I_D-t are measured as a parameter of relative humidity. The I_D drift of the FET-type sensor is effectively eliminated by applying the pulse to the control-gate (CG) of the FET-type humidity sensor.

1. Introduction

Humidity sensor has been widely employed today in environmental monitoring, automotive, healthcare, agriculture, home appliances and indoor air quality control. Various types of humidity sensor such as resistive [1,2], capacitive [3], optical fiber [4], field effect transistors (FET) [5,6] have been reported so far. Among them, most of studies have been focused on the resistor- and capacitor-type humidity sensors. Even though the resistor-type sensor is cheap and easy to fabricate, it has demerit in size, yield, current drift and integration with CMOS circuit [7]. In addition, although the capacitive-type sensor typically based on polymer is small and has a fabrication process compatibility with sensor readout integrated circuits (ROIC) for sensing signal processing, hysteresis coming from the cluster of the water adsorbed in the polymer is major drawback [8]. To fulfill the demands for low cost, scalable, stable, and CMOS compatibility for the humidity sensor, FET-type sensors have been widely studied. However, a number of studies for FET-type humidity sensor have been reported as a forms of thin film transistors (TFTs) which have a large hysteresis gap, low yield, poor stability, and etc [9]. The researches on TFT-type sensor are still focused on the sensing materials [8]. However, there are few studies on a Si MOSFET with high stability, reliability, and maturity in humidity sensor [10]. Also, even though FET-type sensors have a higher degree of freedom due to four terminals, there is little research on the electrical control techniques to improve the sensing performance and the stability of the sensor [11]. Thus, a Si MOSFET humidity sensor can be a good candidate for the stable humidity sensing.

Recently, various sensing material such as carbon material [1–3], polymers [8], 2D material [12], metal oxides [8,13,14], light rare earth elements [15], and ferrite [16] have been widely reported. Among them, the MoS_2 is widely studied for humidity sensor in these days owing to its high sensitivity and semiconducting property [17,18]. Since the sensing material of the FET-type gas sensor, in this work, should be mainly formed between the Control-Gate (CG) and Floating-Gate (FG) implemented with interdigitated structure, the exfoliated MoS_2 film as a sensing material is difficult to apply to our sensor structure due to the unevenness of this structure. Since the sensing material is formed in the last process step to avoid contamination, it is deposited after forming the CG. To form the ohmic contact with MoS_2 film, the gold is used as a CG electrode [19]. For this reason, MoS_2 film which is formed by CVD at a high temperature is hard to be used as the sensing layer of the FET-type gas sensor due to the morphological transformation of the gold film at high temperature [20]. To uniformly form the sensing material at

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low temperature, the MoS_2 film is formed by RF sputtering method at room temperature. In addition, the sensing performance of the FET-type sensor can be improved by applying pre-bias to the CG [11]. Thus, MoS_2 film prepared by sputtering at low temperature is adopted as a sensing material in Si FET-type humidity sensor.

In this work, we propose a pulse scheme to suppress the drain current (I_D) drift and investigate humidity sensing characteristics using DC and pulse biasing in the Si *p*MOSFET humidity sensor with MoS_2 as a sensing layer. The DC I_D-V_{CG} and transient I_D behaviors are investigated for verifying the reaction between H_2O molecules and MoS_2 film, and then the characteristics of the humidity sensor by pulse biasing are firstly investigated. A base (V_{base}) of 0 V and a read-bias (V_{rCG}) are alternatively applied to the CG of the FET-type sensor to suppress the drift in I_D. The transient I_D behaviors and pulsed *I–V* (PIV) of the FET-type sensor are measured by the proposed pulse scheme as a parameter of relative humidity. Finally, the humidity response characteristics with respect to the operating region of the *p*MOSFET sensor are investigated.

2. Experimental details

2.1. Device fabrication

The structure of the Si FET-type humidity sensor is shown in Fig. 1. The top optical image of the fabricated humidity sensor is shown in Fig. 1 (a). The cross sectional view of the humidity sensor cut along the white dashed line A–A' in Fig. 1 (a) is shown in Fig. 1 (b). Detailed process steps to fabricate the Si MOSFET sensor platform have been reported in our previous work [21]. The fabrication process of Si FET-type humidity sensor is nearly the same as conventional MOSFET fabrication except forming a sensing layer. The active regions are isolated by Local Oxidation of Silicon (LOCOS) process. After growing 10 nm-thick gate oxide, a 350 nm-thick in-situ doped n^+ Poly-Si layer is deposited and patterned to form the FG for the FET-type sensor. Then, an insulating stack (O/N/O) composed of SiO_2 (10 nm)/Si_3N_4 (20 nm)/SiO_2 (10 nm) is formed on the wafer. After defining the contact holes, 30 nm-thick Cr and 50 nm-thick Au layers are consecutively deposited by sputtering process to be used as electrodes for CG, source, and drain. In this work, the MoS_2 film, as a sensing material, is deposited by RF magnetron sputtering from MoS_2 target with a purity of 99.9% and patterned by lift off process. The MoS_2 film covers some areas of the interdigitated CG and FG and the area between them. It is noted that the MoS_2 film directly contacted to the CG acts as a semiconducting CG, but is electrically isolated from the FG passivated by the insulating stack. The sputtering conditions are an RF power of 50 W, an argon flow rate of 5 sccm, and a pressure of 5 mTorr at room temperature [22]. The deposition rate is ~3 nm/min. The atomic concentration of Mo:S is about 1:1.81 from the energy dispersive spectroscopy (EDS) result. The height profile of MoS_2 film is obtained by scanning along the red line A to B in the inset using atomic force microscopy (AFM) as shown in Fig. 1 (c). The inset in Fig. 1 (c) shows a patterned sensing layer (MoS_2) to see the profile. To obtain a stable humidity sensing characteristic, a 60 nm thick MoS_2 film is selected. We think that further research needs to be done to optimize the thickness of the sensing material. Finally, 1.4 μm thick PR (SU-8 2002) is patterned to expose only the sensing and pad open area to eliminate any problem caused by moisture.

2.2. Humidity measurement system

A schematic diagram of the humidity-sensing measurement system in our group is displayed in Fig. 2. Humidity-sensing characteristics of the sensors are obtained and analyzed by using a semiconductor parameter analyzer (B1500A, Agilent) and a probe station. The probe station is equipped with a test chamber, chuck, gas inlet and outlet. We use humid air as a target gas and air flow is controlled by a mass flow controller (MFC). Humid air flows into

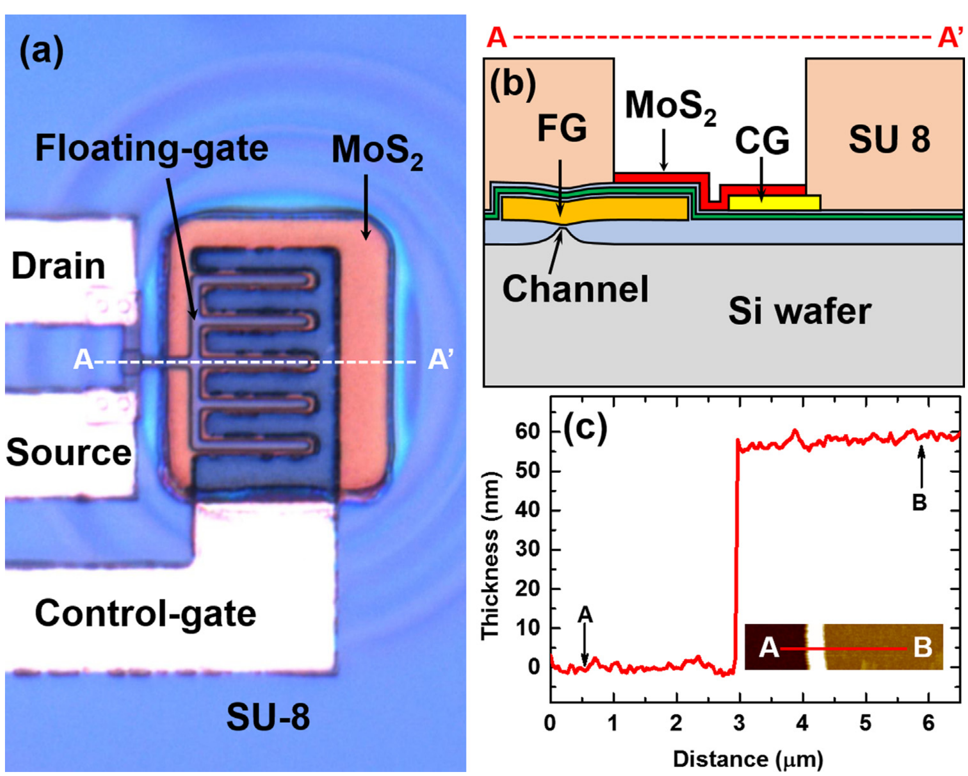

Fig. 1. (a) Top optical image of the fabricated humidity sensor. (b) Cross sectional view of the humidity sensor cut along the white dashed line A–A' in (a). MoS_2 sputtered as a sensing material is formed on the ONO covering the FG and the CG formed on the ONO. 1.4 μm thick PR (SU-8 2002) is pattered to isolate the metal electrodes and open the sensing area. (c) AFM image obtained across areas with and without MoS_2 sensing layers. The thickness of MoS_2 film is ~ 60 nm.