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Performance of Differential Field Effect Transistors with Porous Gate Metal for Humidity Sensors

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Abstract

Differential field effect transistors with double gate metal for integrated humidity sensors have been fabricated and the drain current drift characteristics to relative humidity have been investigated. The aspect ratio was 250/50 for both transistors to get the current difference between the sensing device and non-sensing one. The normalized drain current of the fabricated humidity sensitive field effect transistors increases from 0.12 to 0.3, as relative humidity increases from 30 % to 90 %.

요 약

집적형 습도센서를 위해 이중게이트 금속을 증착한 차동형 전계효과 트랜지스터를 제조하고 상대습도에 따른 드레인전류 드리프트특성을 조사하였다. 감지소자와 비감지소자의 전류차를 얻기 위해 두 트랜지스터의 종횡비는 250/50으로 같게 하였다. 제조된 습도감지 전계효과 트랜지스터의 표준화된 드레인전류는 상대습도가 30 %에서 90 %로 증가함에 따라 0.12에서 0.3으로 증가하였다.

I. INTRODUCTION

Semiconductor microsensors, which are basic transducers using an active device, have been studied continuously by development of semiconductor fabrication technology since the 1970s[1-3]. When substrate semiconductors are not the optimum materials for a particular sensor, suitable materials can be deposited on the top of the semiconductor substrate to form the sensor. Semiconductor microsensors have many advantages such as miniaturization, intellectualization, systematization etc. However, all the forms of semiconductor chemical sensors have a major problem. In order to detect the chemical species of interest, the sensors must be exposed and unprotected to the ambient solutions or gases. It is difficult to make them reversibly reactive to the gases of interest and non-reactive with respect to all other possible chemical species that may appear in the atmosphere or liquid. Lundstrom and his coworkers[1] suggested the Pd-gate H_2 sensor, which is the principal example of a ChemFET for gas sensing. Also, CO-sensitive MOSFETs with a Pd/PdO gate, where pores are available for CO penetration to the interface, have been reported by Dobos and Zimmer[2].

Humidity sensitive materials absorb and desorb water vapour as the ambient humidity increases or decreases. This phenomenon usually leads to a change in electrical resistance or dielectric constant. Thus most humidity sensors utilize a conversion from the chemical to the electrical signal domain, that the sensor sensitivity depends

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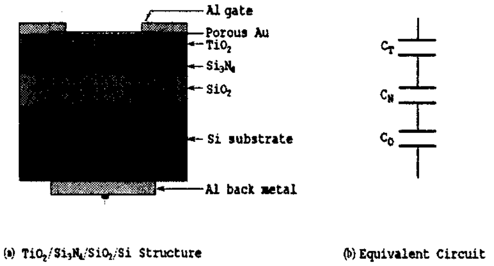
on the variation of resistance or capacitance to humidity. Titanium oxide has been studied as the major material for humidity sensors. Because it has a high ability to adsorb O-H radicals, the intermediate phases of stoichiometric lower titanium oxide have been identified, and it transforms anatase into rutile structure following the heat-treatment temperature[4].

In this paper, we have investigated the hygroscopic properties of metal insulator semiconductor(MIS) capacitor as humidity sensors to investigate the possibility of humidity sensitive field effect transistors(HUSFET) with double gate metal and focused on the design and fabrication of differential HUSFET in order to study and compare the current drift characteristics between sensing device and non-sensing one to relative humidity.

II. Experimental

A cross-sectional view of metal insulator semiconductor(MIS) capacitor for humidity sensor is shown in Fig. 1. Silicon dioxide was grown using TCA and dry oxidation technique and 500 Å silicon nitride was deposited onto SiO_2 using LPCVD. RF magnetron sputtering technigues have been used for deposition of 1,000 Å TiO_2 films onto the silicon nitride layer. The heat treatment was carried out in the temperature range of 400 ℃ and 800 ℃ for 1hr. Porous gold film of 100Å thickness, was formed onto the TiO_2 film as water molecular permeable metal layer[5]. For metal contact, Al was overlapped on Au film and deposited on the bottom of the substrate after removing the residual oxide.

A differential humidity sensitive field effect transistor(HUSFET) is consisted of a pair of transistors, i.e., humid-sensing transistor and non-sensing one(reference transistor) as shown in Fig. 2. The aspect ratio is 250/50 for both transistors to compare the difference of drain current for changes in humidity. The diffusion heater is embedded around the transistors and a diode is prepared for the sensing temperatures.



(a) $TiO_2/Si_3N_4/SiO_2/Si$ Structure (b) Equivalent Circuit

Fig. 1. Cross-sectional view of metal insulator semiconductor(MIS) capacitor for humidity sensors.

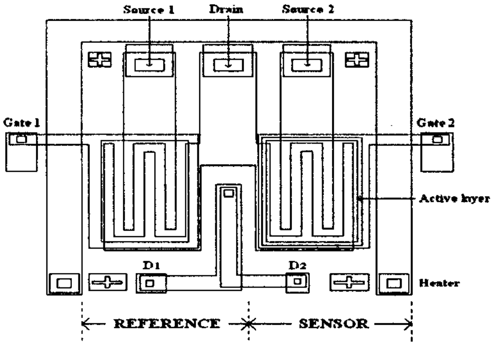


Fig. 2. A superimposed layout of differential humidity sensitive field effect transistor.

Fig. 3 shows the cross-sectional view of differential HUSFET. Resistivity of p-Si substrate is 1-5 $\Omega \cdot cm$. The conventional N^+ diffusion process is used for source and drain formation of MISFET, and P^+ diffusion layer forms to isolate the transistors. To fulfill the requirement that the transistors are operational on reference FET and sensing one, the sensing device should have the water molecule permeable gold layer deposited onto titanium oxide, which is MIS capacitor gate region. On the other hand the reference FET has only a thick Al layer not to permit the penetration of the water molecules.

To find the reationship between the humidity changes and the capacitance changes of MIS capacitors or drain current drifts of HUSFET, measurements were carried out using the fast response chamber with feedback path connected to capacitance-voltage plotter and semiconductor parameter analyzer. Fig. 4 shows the measurement system of humidity sensors.

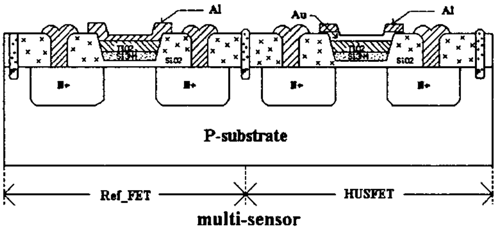


Fig. 3. Cross-sectional view of differential HUSFETs.

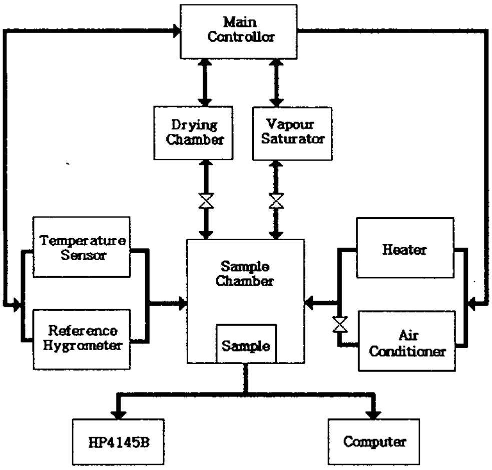


Fig. 4. Schematic diagram of measurement system.

III. Results and Discussion

The presence of the fixed positive charge density located at the insulator-silicon interface and the work function difference between the gate electrode and the silicon substrate will have an effect on the surface space charge region of a MIS capacitor. The amount of gate voltage required to compensate the work function difference between gold and Si substrate in the absence of any interface charge density brings the silicon surface to a flat-band. The barrier height of gold on the silicon surfaces is 0.8 eV, which is higher than the barrier height of aluminum(0.5-0.75 eV according to substrate doping concentration), because the electronic work function of gold is 5.1 eV, whereas that of aluminum is 4.19 eV[6]. Fig. 5 shows the flat-band voltage shift of $TiO_2/Si_3N_4/SiO_2$ structured MIS capacitors at different heat treatment temperatures and 30 % relative humidity. As the heat treatment temperature increases, the flat-band voltage shifts 1.2 V toward right. It means that the devices heat-treated at 500 ℃ indicate the depletion mode but the devices heat-treated above 600 ℃ move to the enhancement mode, that is, normally off state. In case of the heat treatment below 500 ℃, the grains were small as observed by SEM photographs[7] and the pores seem to have inkbottle shape[8]. Thus, the adsorbed water molecule can not desorb easily from the adsorption site when the ambient humidity decreases. These adsorbed water molecules can create dipoles and induce the charges to Si/SiO_2 interface from the substrate, and the MIS capacitor remains normally on state.

The variation of capacitance due to relative humidity change for $TiO_2/Si_3N_4/SiO_2$ MIS capacitor humidity sensor at 1 kHz is shown in Fig. 6. As the relative humidity increases from 30 % to 90 % at positive gate voltage, the capacitance increases from 554 pF to 654 pF at the inversion state.

At the solid gas interface, the surface atoms of the solid are incompletely coordinated; one or two nearest neighbors are missing, and there are dangling bonds that are unshared with neighbors. The most important case is the metal oxide ionic crystal, such as TiO_2, in which both the cations and anions have poor coordination. The positively-charged Ti ions at the surface have an incomplete shell of negative oxide ions around them. With too few negative ion neighbors, the positively-charged ions are more attractive to electrons. Therefore, their conduction-band-like orbital can be at a lower energy than the conduction-band edge and can capture electrons from the bulk. They also can be bonded well to OH^- sharing two electrons and has an electron pair to form bonding[9,]. When water molecules present on the surface through the water permeable layer, where the cations and anions make more dipoles and lead to increasing the capacitance of sensing materials(TiO_2).

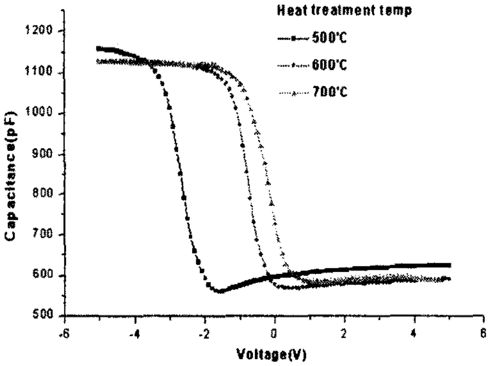


Fig. 5. C-V plot of MIS capacitors for different heat treatment temperatures at 30 % relative humidity.

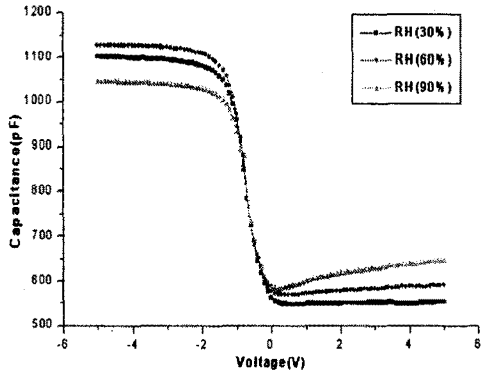


Fig. 6. Capacitance variation for $TiO_2/Si_3N_4/SiO_2$ MIS capacitor humidity sensor at 1 kHz(heat-treatment temperature: 600 ℃).

The computer simulation for n-channel HUSFET was performed using the current-voltage relation of HUSFET[6]. Performing the integration from drain to source, we can obtain

$$I_D = \frac{C_oC_n}{(C_o+C_n)+(C_oC_nd_t)/\varepsilon_o\varepsilon_t}\mu\frac{W}{2L}\left[\left(V_G-2\phi_F-\frac{1}{2}V_D\right)V_D - \frac{2}{3}\frac{(2\varepsilon_s qN_A)^{1/2}\left[(C_o+C_n)+(C_oC_nd_t)/\varepsilon_o\varepsilon_t\right]}{C_oC_n}\left[(V_D+2\phi_F)^{3/2}-(2\phi_F)^{3/2}\right]\right] \quad (1)$$

where C_o and C_n are the capacitance per unit area, respectively, in SiO_2 and Si_3N_4, d_t is the thickness of TiO_2, ε_t is the relative permittivity of titanium oxide, W is the channel width, L is the channel length and μ is the electron mobility.

The behavior of I_D-V_D as a function of V_G for a n-channel HUSFET in the humidity range from 30 %RH to 90 %RH is illustrated in Fig. 7. The family of curves presents the typical enhancement mode characteristics. The simulation was carried out for a series of relative permittivity(ε_t), which was varied between 123 and 223.

Fig. 8 shows the drain output of the fabricated HUSFET to the humidity changes by HP 4145B semiconductor parameter analyzer. Source was grounded, gate voltage was varied from 1.5 V to 4.5 V with a step of 1.5 V and drain voltage was varied from 0 V to 6.0 V with a step of 0.5 V, respectively. It indicates that the drain current of humidity sensing device which is at the right side in Fig. 3, increases from 1.84 mA to 2.13 mA at V_G = 3.0 V and V_{DS} = 4.0 V with increase in relative humidity from 30 % to 90 %. As mentioned above, the physisorbed water molecules easily dissociated to form H_3O^+ are only singly bonded and form a liquid-link network. These singly bonded water molecules are able to form dipole and reorient freely under an externally applied gate field, resulting in an increase of the dielectric constant. Therefore, the steady state value of the drain current depends on the water molecule concentration. When the ambient humidity increases, the behavior of drain current drift is existent in non-sensing device, although the value is small. It shows that some water molecules penetrate through Al electrode layer.

$$I_x - I_o / I_o = \frac{C_o C_n d_t}{\varepsilon_o} \frac{2}{3}(2\varepsilon_s q N_A)^{1/2} [(2\phi_F)^{3/2} - (V_D + 2\phi_F)^{3/2}](\frac{1}{\varepsilon_t} - \frac{1}{\varepsilon_x}) /([C_o C_n (V_G - 2\phi_F - \frac{1}{2} V_D) V_D - \frac{2}{3}(2\varepsilon_s q N_A)^{1/2}] [(V_D + 2\phi_F)^{3/2} - (2\phi_F)^{3/2}][C_o + C_n + \frac{C_o C_n d_t}{\varepsilon_o \varepsilon_t}]) \tag{2}$$

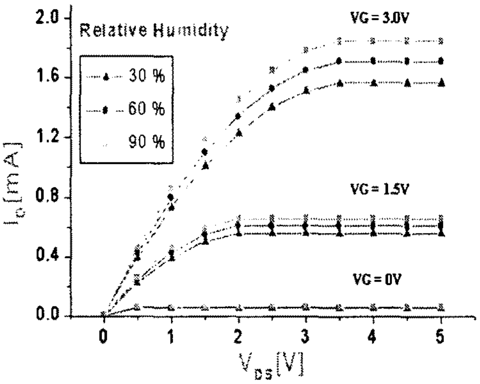


Fig. 7. Simulated drain current characteristics of n-channel HUSFET for relative humidity.

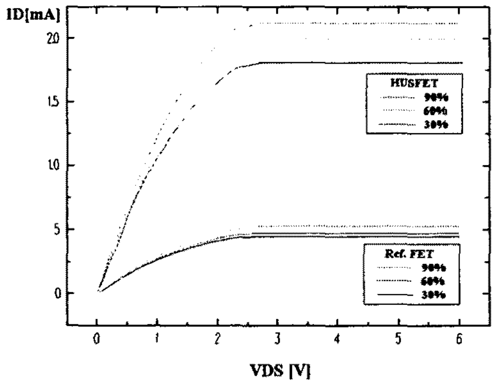


Fig. 8. I_D-V_D characteristics of differential type HUSFET for relative humidity.

The normalized drain current called sensitivity, which indicates the difference between the humidity-sensing device and non-sensing one, is shown in Fig. 9 as a function of relative humidity. Since I_o is the drain current of non-sensing device and I_x is the drain current of sensing device. From eq.(1), the normalized drain current can be expressed as where ε_t is the relative permittivity of TiO_2 in non-sensing device and ε_x means the relative permittivity of TiO_2, which can be varied by the ambient humidity, in sensing device. This normalized values versus the relative humidity are proportional to $(1/\varepsilon_t - 1/\varepsilon_x)$ from Eq.(2).

The experimental results indicate that for the low humidity range the normalized drain current drifts exhibit a linear dependence on the humidity changes that is a good agreement of the theoretical results as shown in Fig. 9. However, for the high humidity range the increase in current drift is not rapid. Because the simulation is done under the assumption that aluminum gate of non-sensing device does not permit the penetration of the water molecules. Some differences between experiment and theory at the high humidity range can be seen.

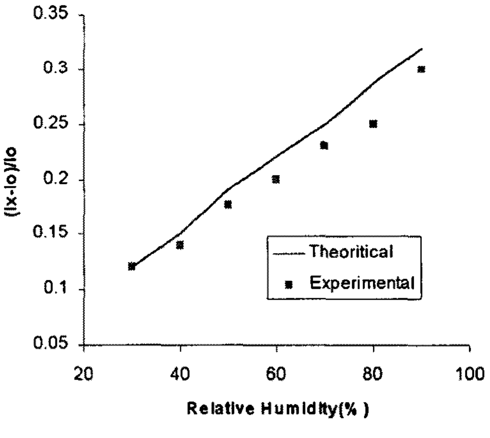


Fig. 9. Normalized drain current drifts as a function of relative humidity.

Ⅳ. CONCLUSIONS

The capacitor type humidity sensors, which have the same gate structure with humidity sensitive field effect transistors, have been fabricated by conventional silicon technology. TiO_2 film was deposited onto the silicon nitride layer and porous gold was formed as water molecular permeable metal. The flat-band voltage of $TiO_2/Si_3N_4/SiO_2$ structured MIS capacitor shifted 1.2 V toward right as heat treatment temperature increases from 500 ℃ to 600 ℃. It means that the devices heat-treated above 600 ℃ have the enhancement mode characteristics, that is, normally off state. The capacitance of the device heat-treated at 600 ℃ increased from 554 pF to 654 pF in the inversion state with increasing the relative humidity from 30 % to 90 %. The differential type humidity sensitive field effect transistors with double gate metal for integrated humidity sensors have been fabricated and the drain current drift characteristics to relative humidity have been investigated theoretically and experimentally. The aspect ratio was 250/50 for both transistors to get the current difference between the sensing device and non-sensing one. The normalized drain current of the fabricated HUSFET was compared with the theoretical results. It is found that the normalized values are proportional to $(1/\varepsilon_t - 1/\varepsilon_x)$ in the relative humidity range of 20 % to 90 %.

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Biographies

Sung Pil Lee received a Ph.D. in the field of gas sensors in 1989 from Kyungpook National University, Taegu, Korea. He is currently an Associate Professor at the department of Electrical and Electronic Engineering, Kyungnam University, Masan, Korea. He gas performed the research on semiconductor sensors and sensor modeling. His research interest includes multi-sensors, VLSI technology, nitride film and sensor modeling.

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