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pH Sensing Performance and Electrical Characterization on Hafnium Oxide Gate ISFETs with Single and Dual Stack Insulator by RF Sputtering

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1. Introduction

Ion sensitive field-effect transistor (ISFET) with SiO_2 gate as sensing material for applications on bio-medical was invented by P. Bergveld in 1970. [1] To have higher sensitivity and better stability, various kinds of sensing insulators, such as Si_3N_4, Al_2O_3, Ta_2O_5 and TiO_2 have been investigated extensively in past years. Hafnium oxide (HfO_2) which owns thermal stability, low leakage current and compatible process with CMOS technology was proposed as the promising gate dielectric for future shrinking generation. [2,3] In our initial study, the pH sensing properties, such as pH response, drift coefficient and hysteresis effect of HfO_2 thin film as sensing membrane based on electrolyte-insulator-silicon (EIS) structure were presented. [4] With proper annealing treatment, the pH sensing performance of HfO_2 membrane could be improved. In this work, the pH sensing and electrical properties of HfO_2/SiO_2 ISFET and HfO_2 ISFET were systematically studied. The conventional Si_3N_4/SiO_2 ISFET with similar FET process was also used for reference. Transconductance, off current and body effect of MOSFET and sensitivity, drift coefficient and linearity of ISFET were detail discussed.

2. Experiment

To investigate pH sensing properties of HfO_2 membrane, three types of ISFET were fabricated at Institute of Electron Technology, Poland, such as HfO_2 gate ISFET, HfO_2/SiO_2 gate ISFET and Si_3N_4/SiO_2 gate ISFET. Figure 1 shows the simplified process flows of these three devices. P-well was formed to obtain the immunity on crosstalk between chips. Extended source/drain areas were designed for easy encapsulation, but with a drawback of high series resistance. Thermally grown SiO_2 layer was deposited to a thickness of 650 Å after RCA cleaning. In the sensing membrane deposition, HfO_2 layer fabricated by reactive RF sputtering and Si_3N_4 layer fabricated by standard low pressure chemical vapor deposition (LPCVD) was chosen. The thickness of HfO_2 and Si_3N_4 layers are 660 Å and 500 Å. Then the rapid thermal annealing (RTA) at 700℃ was processed on HfO_2 devices for process optimization. [5] The schematic HfO_2/SiO_2 gate ISFET profile was shown in Fig. 2.

The drain current-gate voltage (I_{DS}-V_{GS}) curves of MOSFET and ISFET devices with Ag/AgCl reference electrode were measured by Keithley 4200 semiconductor characterization system. To calculate the pH sensitivity, the I_{DS}-V_{GS} curves of ISFET were measured in standard buffer solutions from pH 2 to pH 12. In the long term stability measurement, response voltages (V_R) were extracted by constant voltage-constant current (CVCC) circuit per minute in pH 7 buffer solution. The drift coefficient was calculated by linearly fitting on V_R in the range of 3 to 8 h immersion. All measurement setup were put in dark box to keep from light interference.

3. Results and Discussions

Figure 3 shows the XRD spectra of HfO_2 layer without and with 700°C annealing. The crystalline peak of (111) was observed of 700°C annealing HfO_2. The I_{DS}-V_{DS} curves of HfO_2 gate ISFET show the normal operation as shown in Fig. 4. Figure 5(a) and (b) show the I_{DS}-V_{GS} and G_m curves of all three types MOSFET. Off current of all samples is acceptable. The G_m of HfO_2 gate MOSFET is the highest of all. I_{DS}-V_{GS} curves shift parallel due to various dielectric thickness and trapped charges. Compared to HfO_2 gate IOSFET, smaller swing and higher G_m of HfO_2 gate MOSFET was obtained as shown in Fig. 6. Various I_{DS}-V_{GS} curves were measured in various standard buffer solutions from pH 2 to pH 12. As shown in Fig. 7, V_R is the V_{GS} in linear region calculated according to a same I_{DS} level in each curve. pH sensitivity could be obtained by linearity fitting of V_R corresponding pH. pH sensitivity calculated in different I_{DS} and V_{DS} conditions were shown in Fig. 8(a) and (b), respectively. There is no obvious difference of fitting sensitivity with various extraction conditions. For the highest linearity concern, the operation point of HfO_2/SiO_2 and HfO_2 gate ISFET was chosen at I_{DS} equals to 100 and 10 μA, respectively. The pH response of these two devices was shown in Fig. 9(a) and (b). Figure 10(a), (b) and (c) show the body effect of three types MOSFET. The body effect is the effect that the threshold voltage varies with substrate bias. This substrate sensitivity was defined as equation (1) :

$$\frac{dV_t}{dV_{bs}} = \frac{\sqrt{\varepsilon_{Si} q N_a / 2(2\psi_B + V_{bs})}}{C_{ox}} \tag{1}$$

The body effect could be much improved on HfO_2 MOSFET because of smaller C_{ox} value. Electrical properties and pH sensing performance of all three type devices were listed in Table I. Compared to Si_3N_4/SiO_2 ISFET, highest pH sensitivity, 58.95 mV/pH, was obtained in HfO_2/SiO_2 gate ISFET. Its corresponding drift coefficient is also very low, 0.36 mV/h. All pH sensing and electrical performance of HfO_2/SiO_2 gate ISFET are superior to the commercial product.

4. Conclusions

HfO_2/SiO_2 gate ISFET shows the excellent pH sensing performance with sensitivity 58.95 mV/pH, and drift coefficient 0.36 mV/h, which is a candidate for commercial product. Minor body effect of HfO_2 gate ISFET was observed, which is suitable for circuit compensation design. A quite promising device process and platform was built and verified for pH sensing application.

Acknowledgement

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References

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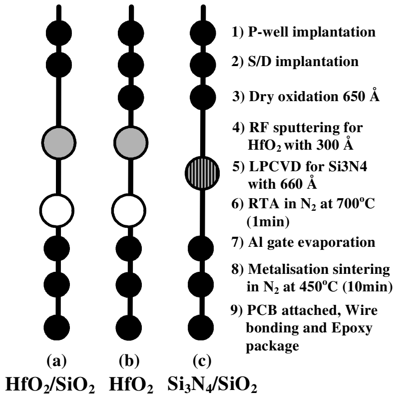

Fig. 1 The process flow of (a) HfO_2/SiO_2 gate ISFET, (b) HfO_2 gate ISFET, and (c) Si_3N_4/SiO_2 gate ISFET.

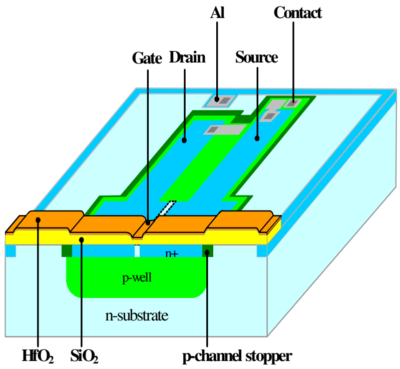

Fig. 2 The schematic of the structure of HfO_2/SiO_2 gate ISFET.

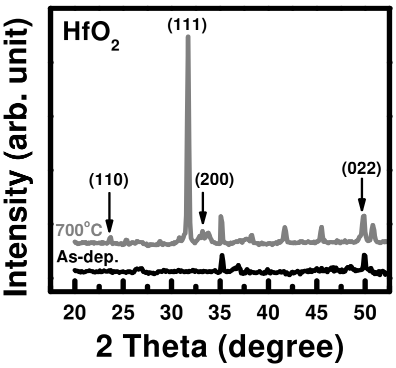

Fig. 3 XRD spectra of as-deposition HfO_2 and HfO_2 with 700°C annealing.

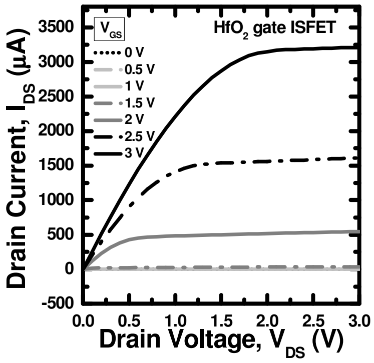

Fig. 3 The I_{DS}-V_{DS} curves of HfO_2 gate ISFET.

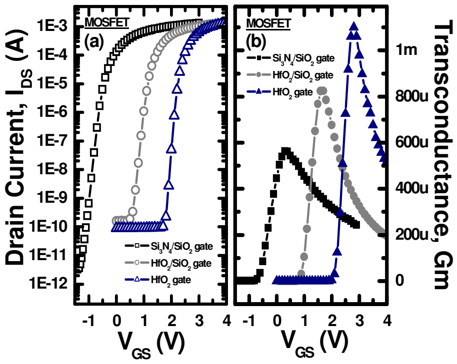

Fig. 5 The (a) I_{DS}-V_{GS} and (b) G_m curves of HfO2/SiO2 MOSFET, HfO_2 MOSFET and Si3N4/SiO2 MOSFET devices.

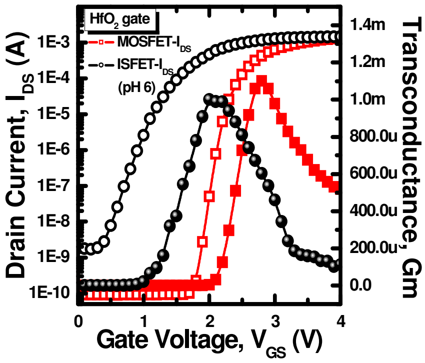

Fig. 6 The I_{DS}-V_{GS} and G_m curves of HfO2 MOSFET and HfO_2 gate ISFET.

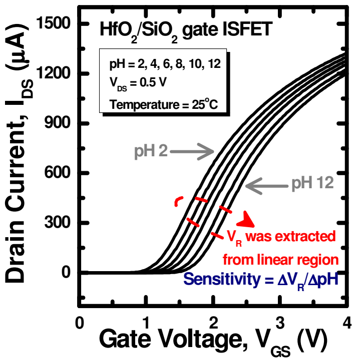

Fig. 7 The typical I_{DS}-V_{GS} curves of HfO_2/SiO_2 gate ISFET device in different pH buffer solution.

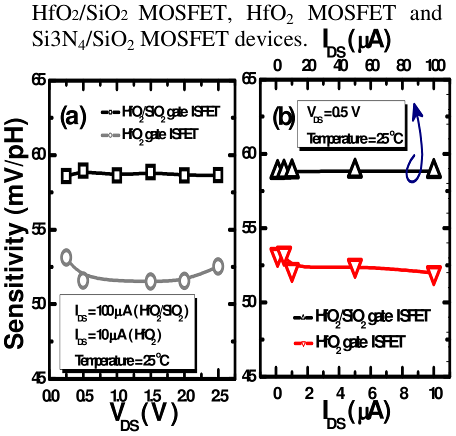

Fig. 8 The sensitivity distribution with different (a) V_{DS} working point and (b) extracted I_{DS} current of HfO_2/SiO_2 gate ISFET and HfO_2 gate ISFET. The sensitivity was similar in all conditions.

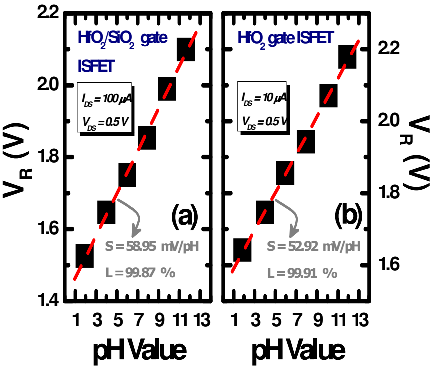

Fig. 9 The pH response and linearity of (a) HfO_2/SiO_2 gate ISFET and (b) HfO_2 gate ISFET at V_{DS}=0.5 V.

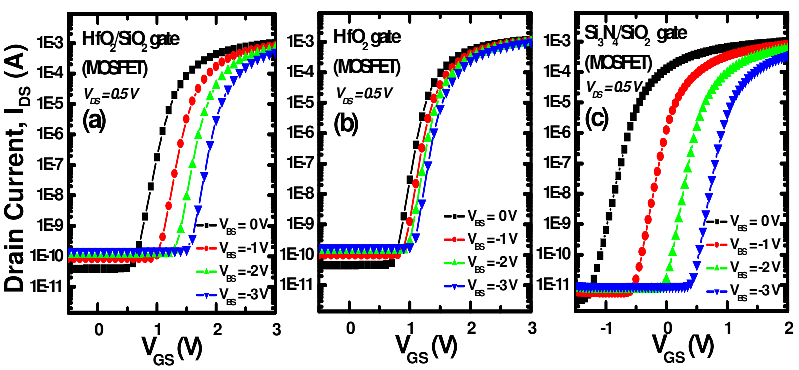

Fig. 10 The body effect of (a) HfO_2/SiO_2 gate MOSFET, (b) HfO_2 gate MOSFET and (c) Si_3N_4/SiO_2 gate MOSFET..

Table I Electrical properties and pH sensing performance of HfO_2/SiO_2 gate ISFET, HfO_2 gate ISFET and Si_3N_4/SiO_2 gate ISFET.

Properties \ Devices	HfO_2/SiO_2	HfO_2	Si_3N_4/SiO_2
Sensitivity (mV/pH)	58.95	52.92	42.7
Linearity (%)	99.87	99.91	99.53
Drift (mV/hr)	0.362	0.578	0.65
I_{off} current (A)	1.6×10^{-10}	9.0×10^{-11}	3.6×10^{-12}
G_m	8.2×10^{-4}	1.1×10^{-3}	5.6×10^{-4}
Body effect	Large	Small	Large