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Body effect minimization using single layer structure for pH-ISFET applications

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ABSTRACT

In this study, the hafnium oxide (HfO_2) thin film deposited by using radio frequency (r.f.) sputter was used as the sensing membrane of ion sensitive field-effect transistor (ISFET) for pH detection. For low cost and easy fabrication, the single HfO_2 gate ISFET without SiO_2 as buffer layer have been developed to compare with the conventional ISFETs with HfO_2 or Si_3N_4 on SiO_2 buffer layer in same process. Electrical characteristics including off current, transconductance, subthreshold swing and body effect of metal–insulator–semiconductor field-effect transistor (MISFET) devices and pH sensing properties including sensitivity, linearity, drift coefficient and body effect of ISFET devices were investigated in detail. The single HfO_2 gate MISFET exhibits better electrical performance like higher transconductance, smaller subthreshold swing and lower body effect than the stack HfO_2/SiO_2 gate MISFET and Si_3N_4/SiO_2 gate MISFET. In pH sensing properties, both the single HfO_2 gate ISFET and the stack HfO_2/SiO_2 gate ISFET show better sensing performance than the stack Si_3N_4/SiO_2 gate ISFET. Due to the concern of exact pH detection and high operation speed for commercial product application, the single HfO_2 gate ISFET with lower body effect on pH detection and higher transconductance is a potential candidate to integrate with an analog readout circuit.

1. Introduction

The first ion sensitive field-effect transistor (ISFET) with SiO_2 insulator as sensing membrane for bio-medical applications was invented by Bergveld [1]. The basic structure of ISFET was derived from metal–insulator–semiconductor field-effect transistor (MISFET) with the gate contact replaced by a reference electrode and an electrolyte. With binding of ions on membrane surface sites in an electrolyte, pH dependent surface potential change can be observed by the shift of threshold voltage from the drain-to-source current and gate-to-source voltage (I_{DS}–V_{GS}) characteristics. With small size, fast pH response time, low cost and rugged solid-state construction, ISFET chemical sensors exhibit number of advantages in comparison with conventional ion-selective electrodes (ISEs). Beside that, ISFET devices also show their compatibility with CMOS fabrication process and give scope for integration of the sensors and processing circuitry.

For bio-medical and chemical applications, the sensing material plays a significant role on the high quality pH ISFET sensor. To get higher pH sensitivity and better stability, many kinds of insulators with high dielectric constant have been studied for pH sensitive gate insulator materials in past years, such as silicon nitride (Si_3N_4) [2], aluminum oxide (Al_2O_3) [3], tantalum pentoxide (Ta_2O_5) [4], tin oxide (SnO_2) [5], titanium oxide (TiO_2) [6], ruthenium dioxide (RuO_2) [7], amorphous tungsten oxide (a-WO_3) [8] and zirconium oxide (ZrO_2) [9]. In recent years, hafnium oxide (HfO_2) which owns higher dielectric constant, better thermal stability and compatible process with CMOS technology was proposed as the promising gate dielectric for future shrinking generation [10–13]. Therefore, choosing HfO_2 as the material of sensing membrane on ISFET device could be compatible with CMOS technology for further miniature applications. So far, the stack HfO_2/SiO_2 gate ISFET with high pH sensitivity have been reported by van der Wal et al. [14], which only focused on the pH sensing properties of stack HfO_2/SiO_2 insulator. In our previous study, the pH sensing properties, such as pH response, drift coefficient and hysteresis effect of single HfO_2 and stack HfO_2/SiO_2 insulator as sensing membrane based on electrolyte-insulator-silicon (EIS) structure were presented [15,16]. With proper rapid thermal annealing treatment, the pH sensing performance of single HfO_2 membrane could be improved greatly.

In this work, the single HfO_2 layer of ISFET as sensing membrane was first proposed to compare with stack HfO_2/SiO_2 and Si_3N_4/SiO_2 gate ISFETs. These three gate insulator structures were all fabricated for ISFET and MISFET devices. Electrical characteristics including transconductance (G_m), off current (I_{off}), subthreshold swing (S_t)

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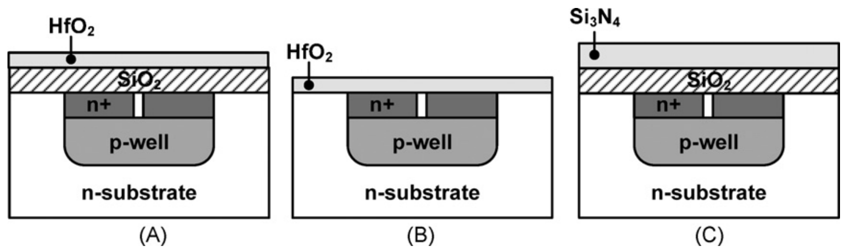

Fig. 1. Schematic of the structures of (A) the stack HfO_2/SiO_2 gate ISFET, (B) the single HfO_2 gate ISFET and (C) the stack Si_3N_4/SiO_2 gate ISFET. The sensing area is 16 μm × 600 μm.

and body effect of MISFET devices and pH sensing performance including sensitivity, drift coefficient, linearity and body effect of ISFET devices were discussed in detail.

2. Experiment

2.1. Device fabrication

In order to investigate the pH sensing properties and electrical characteristics, both ISFET and MISFET were fabricated at Institute of Electron Technology (IET), Poland. To study the pH sensing properties including sensitivity, drift coefficient, linearity and body effect of hafnium oxide membrane, three types of ISFET devices were fabricated such as the stack HfO_2/SiO_2 gate ISFET (A_I), the single HfO_2 gate ISFET (B_I) and the stack Si_3N_4/SiO_2 gate ISFET (C_I). And the electrical characteristics including transconductance, off current, subthreshold swing and body effect on the MISFET with aluminum metal gate in the same wafer were also investigated. N-type ⟨1 0 0⟩ silicon wafer was used as substrate material. P-well area for active area was firstly formed to obtain the immunity on crosstalk between chips. For easy encapsulation by hand-made epoxy, the extended source/drain areas were designed with sufficient distance between contact holes to metal line and the sensing area. The drawback is the high source/drain series resistance which may lead lower drain-to-source current (I_{DS}). Then a 65 nm thick silicon oxide was thermally grown in dry oxygen after initial cleaning (RCA). After that, 65 nm thick Si_3N_4 layer for the stack Si_3N_4/SiO_2 gate ISFET was fabricated by standard low pressure chemical vapor deposition (LPCVD) method, and 30 nm thick HfO_2 layer for the stack HfO_2/SiO_2 gate ISFET and 15 nm thick HfO_2 layer for the single HfO_2 gate ISFET were fabricated by reactive r.f. sputter, respectively. The r.f. sputter system was initially pumped down to 5×10^{-6} Torr and the pressure during processing was maintained at 2×10^{-2} Torr with the gas flow rate of O_2/Ar gas mixture as 5/20 sccm. The RF power was controlled at 150 W and the sputter target was the hafnium metal with purity of 99.95%.

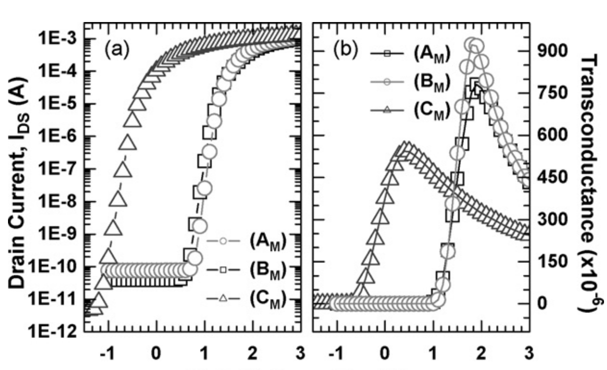

Fig. 2. (a) I_{DS}–V_{GS} and (b) G_M–V_{GS} characteristics of the stack HfO_2/SiO_2 gate MISFET (A_M), the single HfO_2 gate MISFET (B_M) and the stack Si_3N_4/SiO_2 gate MISFET (C_M).

Then the rapid thermal annealing (RTA) was performed on HfO_2 gate type devices in N_2 gas at 700 °C for 1 min for the process optimization [15,16]. After evaporating aluminum film, the front-side aluminum contact holes were opened on the extend source/drain areas which are far from sensing area. To densify the aluminum layer for high quality contact, the sintering process was performed. The condition of sintering is in nitrogen at 450 °C for 10 min. The schematic of the stack HfO_2/SiO_2 gate ISFET, the single HfO_2 gate ISFET and the stack Si_3N_4/SiO_2 gate ISFET profiles are shown in Fig. 1. The dimension of ISFET chip is 4.9 mm × 4.9 mm and the gate dimensions were 16 μm in length and 600 μm in width. Wire bonding was used as a connection between aluminum pads of ISFET device and Cu line of print circuit board (PCB). Finally, a hand-made epoxy was used to encapsulate the ISFET samples and Cu line of print circuit board.

2.2. Measurements setup

In order to study the sensing properties and electrical characteristics, the I_{DS}–V_{GS} curves of MISFETs and ISFETs were all measured by Keithley 4200 semiconductor characterization system. The gate voltages were applied to aluminum metal gate of MISFETs and silver/silver chloride reference electrode for ISFETs. For steady pH response, all ISFET samples were immersed in the reversed osmosis (RO) water for 12 h before measurement. To calculate the pH sensitivity, the I_{DS}–V_{GS} curves of ISFET were measured in standard buffer solutions (Merck Inc.) from pH 2 to pH 12. The actual pH values of standard buffer solutions were measured by pH meter before and after measurement for pH sensitivity calculation. In the long-term stability measurement, responsive voltage (V_R) was obtained by constant voltage–constant current (CVCC) circuit [17] per minute in pH 7 buffer solution for 12 h. The drift coefficient was calculated by linearly fitting on V_R in the range from 5 to 12 h [18]. All measurement setup was carried out in a Faraday cage at room temperature to keep from light and r.f. signal interference.

3. Results and discussion

3.1. Electrical characteristics of MISFETs and ISFETs

Electrical characteristics including G_m, I_{off} and S_t were all calculated through I_{DS}–V_{GS} curves. Fig. 2(a) and (b) shows the I_{DS}–V_{GS} and transconductance curves of the stack HfO_2/SiO_2 gate MISFET (A_M), the single HfO_2 gate MISFET (B_M) and the stack Si_3N_4/SiO_2 gate MISFET (C_M), respectively. In Fig. 2(a), the I_{off} extracted at $V_{GS} = V_T - 0.5$ V were 3.9×10^{-11}, 7.6×10^{-11} and 5.1×10^{-12} A for A_M, B_M and C_M MISFET. I_{off} of all devices are acceptable for FET operation. The smaller I_{off} in the stack Si_3N_4/SiO_2 gate MISFET could be from no plasma induced damage in gate insulator process. The simple model of I_{DS}–V_{GS} characteristic in MISFET biased in linear region is given by Eq. (1):

$$I_{DS} = \mu_n C_I \frac{W}{L}\left[(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}\right] \tag{1}$$