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High sensitive biosensor with extended-gate ISFETs based on in-plane-gate structure a-IGZO TFTs with engineered gate oxide

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Abstract

In this study, we proposed a high-performance extended-gate ion-sensitive field-effect transistors (EG-ISFETs) for pH sensing platform. The EG-ISFETs consisted of a SnO_2, sensing region and the in-plane-gate sturcture of amorphous a-IGZO thin-film transistors (TFTs) with SiO_2/Ta_2O_5 engineered top-gate oxide, transducer region. To self-amplifiy the pH sensitivity, we maximized the capacitive coupling effect by applying high-k dielectric at the top-gate oxide layer and using in-plane gate instead of bottom gate. An engineered top-gate oxide, SiO_2/Ta_2O_5 layer of 10/35-nm-thick had a smaller equivalent oxide thickness (EOT) (~13.3 nm). In IG mode, the bottom gate oxide has an effect of doubling the thickness (~400 nm). The in-plane structure of a-IGZO EG-ISFETs with high-k engineered top-gate oxide could self-amplify the sensitivity of 2363.9 mV/pH in IG mode for sensing membranes with Nernstian pH response limit. In addition, we found that the IG mode has improved non-ideal behavior in the results of hysteresis and drift measurement.

1. Introduction

Recently, as social interest in quality of life has increased, the biosensor has become important technologies that can quickly, reliably, and accurately detect a health conditions [1]. A biosensors represent any device that detect biological signals for disease diagnosis. Typically, biosensors are consist of two parts: a sensing region and a transducer region. Among various types of transducers, FET based ISFETs have advantages such as accurate detection, low power consumption, and expectation to be applied in the healthcare. The sensing and transducer region of conventional ISFETs are integral. Their structure has disadvantages in terms of their chemical instability, and optical effects on the sensitivity. However, EG-ISFETs are suitable for disposable biosensors, because the separative trasducer region is reusable when the sensing region needs to be changed. However, the conventional EG-ISFETs are still subject to problem, their poor sensitivity. The theoretical maximum value of pH sensitivity has been confined to a Nernst limit of 59.5 mV/pH at room temperature by site binding model. The ion sensing ability depends on the surface potential [2].

$$\psi = 2.303\frac{kT}{q}\frac{\beta}{\beta+1}(pH_{pzc} - pH) \tag{1}$$

To self-amplifiy the pH sensitivity, dual gate (DG) mode has been reported. In case of the DG mode, the sensor needs to have a thicker bottom gate oxide or thinner top-gate oxide to enhance the capacitive coupling effect. The in-plane gate structure of EG-ISFETs with high-k engineered top-gate oxide can self-amplify the sensitivity more efficiently in IG mode. A capacitive coupling effect occurs between the top-gate, the bottom gate (floating layer), and the in-plane gate. Then the capacitive coupling ratio and sensitivity amplification in the IG mode can be described as:

$$\Delta V_{BG}^{Th} = -\frac{C_{top}}{C_{bottom}}\Delta\psi = \frac{(C_1 + C_3)C_1}{(C_2 \times C_3)}\Delta V_{TG}^{Th} \tag{2}$$

IG mode has more benefit than a DG mode for increasing capacitive coupling, because the C_2 and C_3 are connected in series shown in Fig 1 (b). The IG mode has the effect of doubling the thickness of the bottom gate oxide [3]. Moreover, the high-k engineered top-gate oxide has much larger capacitnace of top-gate oxide ($C_{1)}$ than capacitance of single SiO_2 oxide.

2. General Instructions

To fabricate the in-plane structure of a-IGZO TFTs, capacitive coupling effect is an important factor for high sensitivity. The thinner top-gate oxide and the thicker bottom gate oxide can increase capacitive coupling effect. For the thinner EOT of top-gate oxide, we applied a Ta_2O_5 layer. We fabricated in-plane gate a-IGZO TFTs with high-k engineered top-gate oxide and EG using glass substrates. A 300-nm-thick indium tin oxide ITO and a 200-nm-thick SiO_2 film was sequentially deposited by using sputtering as bottom gate electrode and bottom gate oxide. Then, the deposition of a 20-nm-thick a-IGZO active layer was followed by sputtering. To activate the active layer, microwave annealing is carried out at 1000 W for 2 min in air ambient. After the active region was formed by photolithography and wet etching processes, a 100-nm-thick ITO film was deposited on the source/drain regions using sputtering. Then, the engineered top-gate oxide of a single SiO_2 layer of 20-nm-thick (Device A) and SiO_2/TaO_5 layer of 10/25-nm-thick (Device B) was deposited on active layer using sputtering. After deposition of a 150-nm-thick ITO film by sputtering, top-gate and in-plane-gate electrodes were simultaneously defined by photolithography and wet etching. The dimension of the in-plane-gate is 100 μm × 20 μm, which is the same size of channel width and length. The FGA was performed at 450 °C for 30 min in H_2/N_2 (5/95 %, 50 sccm) ambient. Moreover, the EG was fabricated by depositing a 300-nm-thick ITO film and a 50-nm-thick SnO_2 for sensing membrane on a glass substrate. Then, attaching a polydimethylsiloxane (PDMS) reservoir with a diameter of 0.6 cm. Fig. 1(a) shows the schematic diagram of EG-ISFETs. To compare the capacitance of top-gate oxide, we fabricate metal-insulator-metal (MIM) capacitors. A platinum (Pt) was used as the substrate of the MIM capacitors. The SiO_2/Ta_2O_5 layers with a thickness of 20/0 nm or 10/35 nm were deposited using sputter for insulator. Then, a 150-nm-thick ITO electrode with an area of 230 × 310 μm^2 was deposited by sputtering. The forming gas annealing (FGA) was performed at 450 °C for 30 min in H_2/N_2 (5/95 %, 50 sccm) ambient. The schematic diagram of the MIM capacitors is shown in Fig. 1(b). In this paper, we measured the pH sensitivity of the in-plane structure of EG-ISFETs with high-k engineered top-gate oxide in SG, DG and IG mode. In addition, we compared with the in-plane structure of EG-ISFETs with conventional SiO_2 top-gate oxide. To evaluate the stability, the hysteresis and drift effects were evaluated. The pH characteristics of EG-ISFETs were measured by Agilent 4156B semiconductor parameter analyzer and the capacitance of the MIM capacitors were measure by using Agilent precision LCR meter 4284A. To avoid external influences such as light and electrical noise, all of the measurements were performed in a dark box.

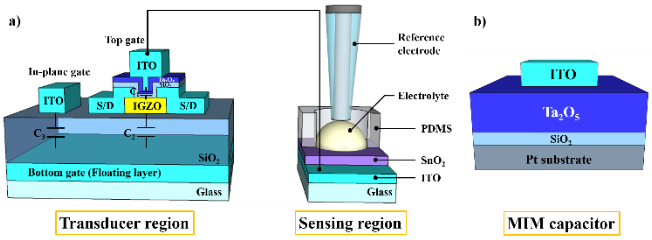

Figure 1. Schematic diagram of fabricated (a) MIM capacitor and (b) EG-ISFETs with high-k engineered oxide.

The C–V curves of the fabricated MIM capacitors were shown in Fig. 2. The MIM capacitor of device B had larger capacitance than capacitance of device A and EOT of 13.34 nm. In addition, the gate leakage current can be suppressed by stacking a thin SiO_2 layer with a large band offset and excellent interface unlike single Ta_2O_5 layer [4].

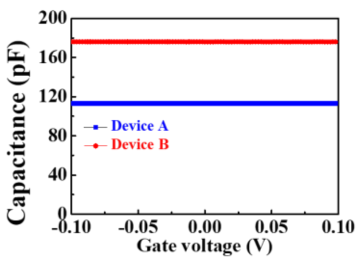

Figure 2. C–V curves of MIM capacitors with high-k engineered insulator (SiO_2/Ta_2O_5 = 20/0 and 10/35 nm).

Figure 3 shows the pH sensitivity of the EG-ISFETs for device A and B using SG, DG and IG modes. The pH sensitivity of EG-ISFETs for device B was a 55.58 mV/pH in SG mode, 1038.89 mV/pH in DG mode, and 2363.9 mV/pH in IG mode. Compared to device A, device B has a better pH sensitivity for each mode, with the highest pH sensitivity, especially in IG mode.

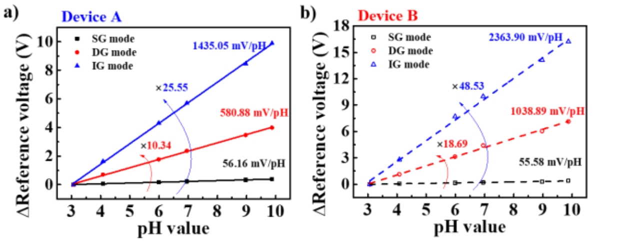

Figure 3. pH sensitivity of EG-ISFETs for (a) device A and (b) B in SG, DG and IG modes.

Moreover, the stability of EG-ISFETs for device A and B was evaluated by measuring the hysteresis and drift with respect to the amplification factor of sensitivity as shown in Fig. 4. As a result, EG-ISFETs have been found to have excellent stability.

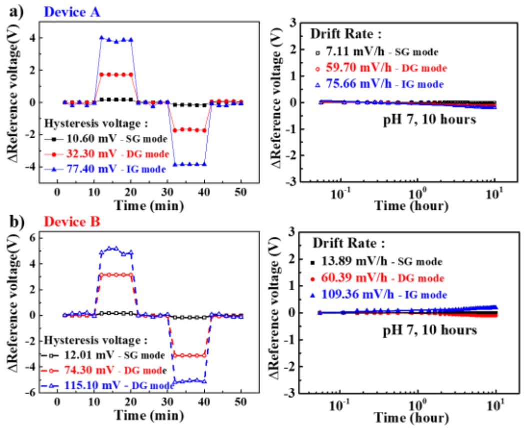

Figure 4. (a) Hysteresis and (b) drift measurement of EG-ISFETs.

3. Conclusions

In this study, we applied the the in-plane structure of EG-ISFETs with high-k engineered top-gate oxide for pH sensors. The proposed EG-ISFETs had a excellent pH sensing performance in IG mode through self-amplification using capacitive-coupling effect between top, bottom, and in-plane gate. Therefore, the proposed EG-ISFET is a promising biosenser platform to detect biological signals for disease diagnosis.

Acknowledgements

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