Realization of ion-sensitive field-effect transistor on SOI substrate with engineered sensing membrane for high stability

Hyun-June Jang¹ and Won-Ju Cho¹
Department of Electronic Materials Engineering, Kwangwoon University, Seoul 447-1, Wolgye-dong, Nowon-gu, Seoul Korea 139-701, E-mail address: chowj@kw.ac.kr

Abstract
The ion-sensitive field-effect transistor (ISFET) was successfully realized on the silicon-on insulator (SOI) substrate. We proposed a new engineered sensing membrane of ISFET by stacking SiO₂/HfO₂/Al₂O₃ (OHA) layers to improve the chemical stability and output signal. As a result, the SOI-ISFET with OHA membrane exhibited a lower drift effect, lower hysteresis phenomenon, and higher pH sensitivity.

I. INTRODUCTION
The ion-sensitive field-effect transistor (ISFET) is an electrochemical sensor that reacts to ionic activity at the electrolyte/membrane interface of exposed gate window as non-invasive and multi-site recording of electrical cell activity over long periods [1]. However, the main obstacle of cell-coupled transistor is a rather poor signal-to-noise ratio. Therefore, it is necessary to reduce noise elements of devices or increase its output signal. In order to enhance the electrical and chemical stability, we fabricated ISFETs using silicon-on insulator (SOI) substrate and proposed the SiO₂/HfO₂/Al₂O₃ (OHA) stacked gate insulator as engineered sensing membrane. Compared to SiO₂, the high dielectric constant of HfO₂ enables the ISFET to obtain a better signal-to-noise ratio. However, it has weak point in non-ideal effect such as the drift effect and the hysteresis phenomenon. Although Al₂O₃ has a smaller dielectric constant than HfO₂, it shows stronger immunity against non-ideal effects [2-3]. Consequently, each layers of the engineered sensing membrane composed of SiO₂, HfO₂ and Al₂O₃ are designed for lower interface states density, larger capacitance and stronger immunity against non-ideal effects, respectively. ISFET with a conventional single SiO₂ (O) membrane was also prepared for comparison. In order to demonstrate the feasibility of OHA membrane, the electrical characteristics of MOSFETs and the pH sensing performances of ISFETs were investigated.

II. EXPERIMENTAL
ISFETs and MOSFETs were fabricated on the SOI substrate with a top silicon thickness of 97 nm.100-nm-thick phosphorus-doped poly-Si layer was deposited for source/drain regions using low pressure chemical vapor deposition (LPCVD). In order to form the OHA sensing membrane, 5-nm-thick SiO₂ layer was grown by dry oxidation at first. Subsequently, 7.8-nm-thick HfO₂ and 13.6-nm-thick Al₂O₃ layers were deposited on SiO₂ using atomic layer deposition (ALD). Meanwhile, the single O membrane for comparison was prepared by thermal oxidation with a thickness of 28.2 nm. The TEM images of each membrane are shown in Fig. 1. Then, a rapid thermal annealing (RTA) in N₂/O₂ gas ambient was carried out at 850 °C for 30 sec. After deposition of 150-nm-thick Al layer for S/D contact, a forming gas annealing at 450 °C for 30 min in 2 % H₂/N₂ ambient also was conducted. Fig. 2 shows optical microscope images of 4×4 FETs array chip.

III. RESULTS AND DISCUSSION
Fig. 3 shows the electrical characteristics of MOSFETs with SiO₂ or OHA structure gate insulators. Measured parameters of bulk-Si MOSFET and SOI-MOSFET are summarized in table 1. Obviously, the SOI-MOSFET revealed better electrical characteristics in terms of on/off current ratio and subthreshold swing (SS) than bulk-Si MOSFET. Besides, the OHA structure gate oxide largely improves the SS and output current of MOSFET.

Fig. 4 shows I-V curves of ISFETs responded in different pH buffer solutions. It is worth noticing that the OHA membrane exhibits a higher pH sensitivity and better linearity (57.1 mV/pH, 99.94%) than the O membrane (36.7 mV/pH, 99.74%).

Then the ISFETs were subjected to pH loops of 7→10→7→4→7 over a period of 60 min to evaluate the hysteresis phenomenon for OHA and SiO₂ membranes as shown in Fig. 5. As a result, the smaller hysteresis voltage of 1.85 mV was obtained from the OHA sensing membrane.

Fig. 6 shows the drift rate for each membrane measured in pH 7 solutions for 12 hours. The ISFET with OHA membrane exhibited better long-term stability (0.80 mV/h). Consequently, the OHA sensing membrane shows higher quality characteristics in term of hysteresis phenomenon, drift effect, sensitivity, and linearity as summarized in table 2. We believe that these improvements in ISFET are attributed to engineered sensing membrane using high-k materials.
IV. CONCLUSION

We fabricated high performance ISFET using SOI substrate and engineered sensing membrane. The SOI substrate revealed better electrical characteristics in terms of leakage current and SS than bulk substrate. The OHA engineered sensing membrane was designed for lower interface states density, larger capacitance and stronger immunity against non-ideal effects. Compared with conventional O membrane, the OHA membrane has higher sensing performances such as lower drift effect, lower hysteresis phenomenon, and higher sensitivity. Therefore, the OHA sensing membrane is promising for the cell-coupled transistor application with high signal-to-noise ratio.

Acknowledgment

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Reference


Table 1 Electrical characteristics of MOSFETs.

<table>
<thead>
<tr>
<th>Gate oxide</th>
<th>V_T</th>
<th>SS</th>
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<tbody>
<tr>
<td>SiO2 (bulk)</td>
<td>0.15V</td>
<td>83 mV/dec</td>
</tr>
<tr>
<td>SiO2 (SOI)</td>
<td>-0.27V</td>
<td>70 mV/dec</td>
</tr>
<tr>
<td>OHA (SOI)</td>
<td>0.72V</td>
<td>65 mV/dec</td>
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Table 2 Summary of ISFET sensing performances.

<table>
<thead>
<tr>
<th>Gate oxide</th>
<th>Sensitivity</th>
<th>Linearity</th>
<th>V_T</th>
<th>Drift rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>36.7 mV/pH</td>
<td>99.74%</td>
<td>31.29 mV</td>
<td>3.05 mV/h</td>
</tr>
<tr>
<td>OHA</td>
<td>57.1 mV/pH</td>
<td>99.94%</td>
<td>1.85 mV</td>
<td>0.80 mV/h</td>
</tr>
</tbody>
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