High performance of silicon nanowire based biosensors using the solution-processed Al$_2$O$_3$ sensing membrane

Tae-Eon Bae and Won-Ju Cho

Department of Electronic Materials Engineering, Kwangwoon University, 447-1, Wolgye-dong, Nowon-gu, Seoul, Korea 139-701, Phone: +81-2-940-5163, E-mail address: chowj@kw.ac.kr

Abstract
High performance silicon nanowire (SiNW) sensors with SiO$_2$/Al$_2$O$_3$ (OA) sensing membrane using a solution process were fabricated. Compared with the vacuum-processed SiO$_2$ membrane, the solution-processed OA membrane improved sensing performances. Therefore, the SiNW sensors with solution OA sensing membrane are very promising to biological sensors application.

1. Introduction
The silicon nanowire (SiNW) is expected to be a very promising transducer for detecting biological and chemical species in terms of the ultra-high sensitive, label-free, real-time detection, and CMOS compatibility. [1] Moreover, the conductance of the SiNW channel is easily modulated by a small amount of surface charge. The sensing characteristics of SiNW sensors are mainly determined by the inherent properties of the sensing membrane. In a previous work, the SiO$_2$ material was usually used as sensing membrane on SiNWs-based sensors. In general, for deposition of SiO$_2$ sensing membrane, vacuum-processed deposition methods such as sputtering or oxidation are used. However, these process techniques require very expensive equipments, high fabrication cost and long process time despite a good performance.

In this study, we realized the SiNW sensors with SiO$_2$/Al$_2$O$_3$ (OA) sensing membrane using solution based process. Particularly, the thin SiO$_2$ and Al$_2$O$_3$ layers are designed for good interface property and strong immunity against the reactive chemical solutions, respectively. Also, the solution-deposition process provides great advantages in terms of low cost, simplicity, high throughput, and high performance.[2] Furthermore, it can be easily applied to the large-area electronic devices unlike vacuum-process methods.

2. Experimental
P-type silicon-on-insulator (SOI) substrates with a thickness of 100 nm top silicon layer (8.5-22 Ω cm) were used for fabrication of SiNW by the “top-down” method. The initial top Si layer was thinned down to 40 nm by dry oxidation and wet etching, and then implanted with $3 \times 10^{13}$ cm$^{-2}$ of boron ions at 8 keV to form a p-type channel layer. After activation of implanted boron atoms at 950°C for 30 min in a nitrogen ambient, a 5-nm-thick SiO$_2$ layer as buffer oxide was grown by thermal oxidation. As the Al$_2$O$_3$ precursor solution, aluminum chloride (AlCl$_3$) of 0.2 mol was prepared and dissolved it in 2-methoxyethanol (2ME) of 20 mL. The Al$_2$O$_3$ layer was conducted by spin-coating at 6000 rpm for 30 s and the film was heated to improve the adhesion using oven at 180°C for 10 min. The coating-heating procedure was repeated two times to obtain the Al$_2$O$_3$ layer with a thickness of 25 nm. Fig. 1 shows a schematic diagram of spin-coating method. After deposition of Au/Cr/Al (50 nm/5 nm/50 nm) for metal electrodes, a forming gas annealing at 450°C for 30 min in a 2% H$_2$/N$_2$ ambient was conducted. Finally, the reservoir for the injection of the pH buffer solutions was mounted on the top of SiNW sensors using polydimethylsiloxane (PDMS).

3. Results and discussions
The optical micrographs of fabricated SiNW sensor chips on a 2 cm × 2 cm area and scanning electron microscopy (SEM) image of a SiNW channel with a 150-nm-width and 20-μm-length are shown in Figure 2 (a) and (b), respectively.

Fig. 3 presents the channel sensitivity for different pH buffer solutions of the oxidation SiO$_2$ membrane and the solution OA membrane. As the pH level increases, the silicon channel surfaces charged more negatively, which in turn induces accumulation of holes within the p-type nanochannel. Also, the solution-processed OA membrane reveals higher pH sensitivity than the vacuum-processed SiO$_2$ membrane. The relation between channel width and pH sensitivity is shown in Figure 4. Obviously, the sensitivity of the OA membrane is higher than that of the SiO$_2$ membrane irrespective of SiNW channel width.

Fig. 5 shows the drift rate of the different sensing membrane to predict the long-term stability in pH 7 buffer solution for 12 h. The solution OA membrane exhibited more stable drift behavior (1.64 nA/h) than the oxidation SiO$_2$ membrane (4.33 nA/h). This is because the Al$_2$O$_3$ membrane is more robust to the hydration during contact...
with an aqueous solution. Consequently, the solution OA sensing membrane shows higher quality characteristics in terms of the sensitivity, the hysteresis width, and the drift rate as summarized in Table I.

4. Conclusion
We fabricated high performance SiNW sensors with SiO$_2$/Al$_2$O$_3$ (OA) stacked sensing membranes using a solution process. Compared with the vacuum-processed SiO$_2$ membrane, the solution-processed OA membrane has better sensing characteristics such as higher sensitivity, lower hysteresis width and drift rate. Therefore, the SiNW sensors with solution OA sensing membrane are very promising to biological sensors application in terms of low cost, simplicity, high throughput, high performance, and large process area.

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References

Table I. Sensing properties of the SiNW pH sensor with the oxidation SiO$_2$ and solution OA sensing membranes.

<table>
<thead>
<tr>
<th>Sensing membrane</th>
<th>Sensitivity (nA/pH)</th>
<th>Linearity (%)</th>
<th>Hysteresis width (nA)</th>
<th>Drift rate (nA/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxidation SiO$_2$</td>
<td>4.96</td>
<td>99.5</td>
<td>1.30</td>
<td>4.33</td>
</tr>
<tr>
<td>Solution OA</td>
<td>16.18</td>
<td>99.9</td>
<td>0.46</td>
<td>1.64</td>
</tr>
</tbody>
</table>

Fig. 1. Schematic diagram of spin-coating method.

Fig. 2. (a) Optical micrographs of a 2 cm x 2 cm single chip containing 33 channels and (b) magnified SEM image of 150 nm-wide and 20 μm-long SiNW.

Fig. 3. Real-time channel current in different pH of the buffer solutions with oxidation SiO$_2$ and solution OA sensing membrane.

Fig. 4. Channel widths versus pH sensitivity for SiO$_2$ and OA membrane.

Fig. 5. Drift rate in pH 7 buffer solution with the SiO$_2$ and OA sensing membrane, for 12 hours.