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# Analysis and Modeling on the pH-Dependent Current Drift of Si Nanowire Ion-Sensitive Field Effect Transistor (ISFET)-Based Biosensors

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Although the ion-sensitive field effect transistor (ISFET)-based biosensor has a great potential for point-of-care testing systems, the current drift still remains as a challenging issue for its commercialization. Furthermore, the drift makes the design of readout circuit for a high-resolution biosensor very complicated because it is very sensitive to the amount of ionic species in electrolyte or human serum. However, its chemical/physical origin in neither yet fully understood nor modeled for the circuit design and simulation. In this paper, the mechanism of current drift in ISFET was explained by short term reaction and long term reaction dependent on position of hydrogen ion. Besides, we proposed the analytical drift model of drain current and threshold voltage for different pH levels and various device sizes in the top-down processed SiNW ISFET. We believe that our result is potentially useful for the drift-aware circuit design for high-resolution biosensor system.

**Keywords:** SiNW, ISFET, Biosensor, Stretched Exponential Function, Current Drift, Threshold Voltage Drift, Analytical Modeling, Long Term Reaction, Short Term Reaction.

## 1. INTRODUCTION

As entering the aging society by the development of medical technology, the social requirements for life quality and life prolongation increase. The need of biosensor development is increasing for fast and accurate diagnosis of diseases. Among biosensor candidates, SiNW (Silicon Nanowire) ISFET (Ion Sensitivity Field Effect Transistor) has a great potential for point-of-care testing system, because it has the strong advantages such as label free, real time detection, the detection in small amount or low-density substance due to the high surface to volume ratio,[1] and mass production.[2,3] However, the current drift of SiNW ISFET still remains as a challenging for its commercialization.[4]

To overcome this problem, software compensation,[5] hardware configuration,[6] and a combination of both[7,8] have been used to compensate for the drift, but its chemical/physical origin is neither yet fully understood nor modeled for the circuit design and simulation. In this paper, the pH-dependence of drift is investigated and the origin of current drift is explained. Furthermore, the analytical drift model is proposed for robust circuit analysis.

## 2. EXPERIMENTAL DETAILS

SiNW ISFET sensors to measure the drift phenomenon were fabricated on boron doped ($4 \times 10^{15}$ $cm^{-3}$) silicon on insulator wafer using the top-down processed CMOS technology, and the fabrication process is illustrated in Figure 1(a). A cross-sectional view and scanning electron microscopy (SEM) image of the SiNW ISFET biosensors are shown in Figures 1(b and c), respectively.[9] The $L_{open}$ and height of SiNW are $L+1$ um and 80 nm, respectively.

For linearity of pH sensing,[10] SiNW was functionalized under UV/$O_3$ exposure condition and 3-aminopropyltriethoxysilane (APTES) coating to adopt the amine

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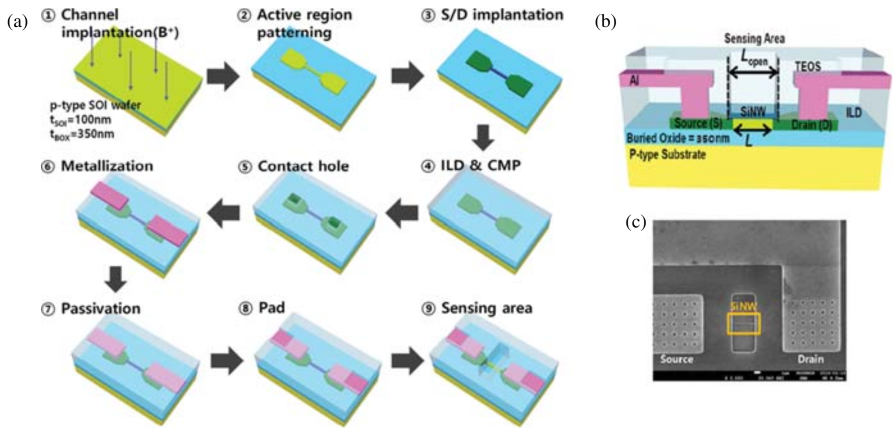


**Figure 1.** (a) Fabrication process flow. (b) The cross-sectional view of SiNW. (c) SEM image of the fabricated SiNW ISFET.

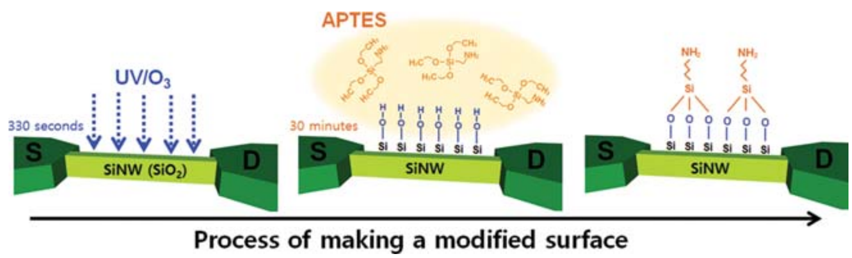


**Figure 2.** Modified $SiO_2$ surface after being exposed to $UV/O_3$ and functionalized with APTES.

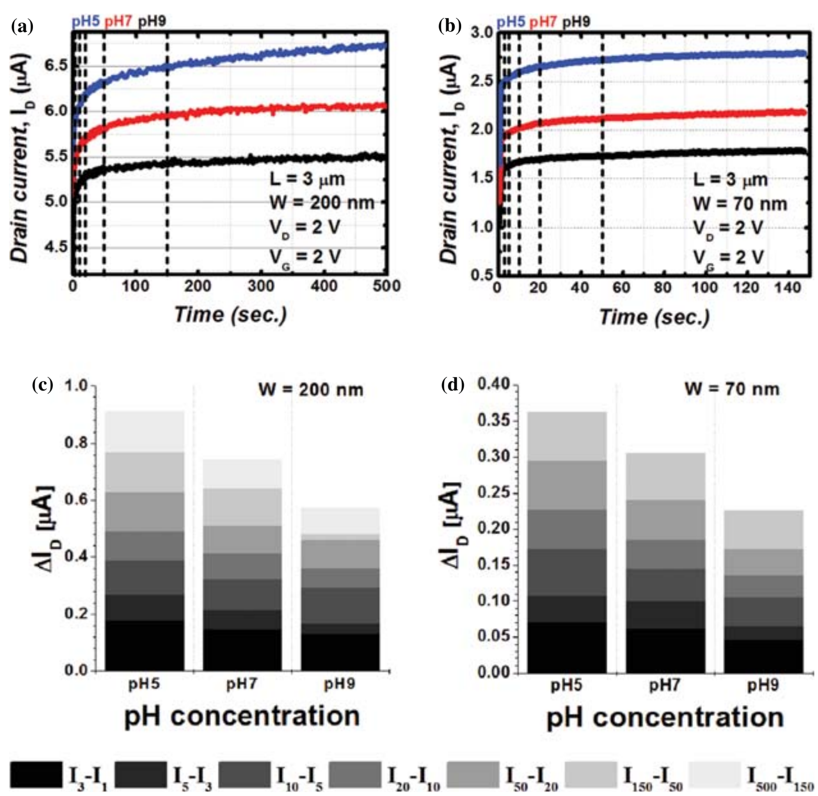


**Figure 3.** Transient curves dependent on pH levels in (a) $W = 200$ nm and (b) $W = 70$ nm. $\Delta I_D$ –pH characteristics in (c) $W = 200$ nm and (d) $W = 70$ nm.

(–$NH_2$) surface, as shown in Figure 2. The levels of pH solution which is based on potassium phosphate buffers are 5, 7, and 9. Keithley 4200 was used for the electrical measurement of SiNW at room temperature.

## 3. RESULTS AND DISCUSSION

Threshold voltage of the device that width of 70 nm is 0.7 V and width of 200 nm is 1 V.

As shown in Figures 3 (a and b), the drain current ($I_D$) increases under constant bias conditions, which liquid gate bias ($V_{LG}$) and drain bias ($V_D$) are both 2 V. This phenomenon is called the current drift, and it is a drawback of SiNW ISFET. Besides, the current drift becomes more severe with the decrease of pH value.[11] For an in-depth analysis dependent on pH level, the current change amount per time interval was plotted on a graph. Here, $\Delta I_D$ is $I_B - I_A$, which is the difference between time A and time B. As you see in Figures 3(c and d), the current drift decreases at the higher pH value regardless of time interval. The current drift is due to the slow movement of hydrogen ion in electrolyte and oxide layer,[11] and the drift term is divided into short and long term reaction. From these parameters, the analytical drift model for current and threshold voltage is defined as a stretched exponential function.[12,13]

$$I_D(t) = \Delta I_0[1 - e^{-(t/\tau)^\beta}] \quad (1)$$

$$V_T(t) = \Delta V_0[1 - e^{-(t/\tau)^\beta}] \quad (2)$$

**Table I.** The fitting parameters for $I_D$ and $V_T$.

| | $\Delta I_0$ [$\mu$A] | $\beta$ | $\tau$ [s] | $\Delta V_0$ [mV] | $\beta$ | $\tau$ [s] |
|---|---|---|---|---|---|---|
| $W = 200$ nm | | | | | | |
| $L = 3$ $\mu$m | | | | | | |
| pH5 | 2.57 | 0.17 | 45 | 2.37 | 0.148 | 65 |
| pH7 | 1.89 | 0.183 | 21 | 1.88 | 0.153 | 45 |
| pH9 | 1.51 | 0.191 | 8 | 1.54 | 0.161 | 12 |
| $W = 70$ nm | | | | | | |
| $L = 3$ $\mu$m | | | | | | |
| pH5 | 1.59 | 0.12 | 22 | 3.83 | 0.115 | 20 |
| pH7 | 1.24 | 0.135 | 16 | 3.38 | 0.122 | 15 |
| pH9 | 0.952 | 0.14 | 6 | 2.93 | 0.127 | 7 |

The fitting parameters of Eqs. (1) and (2) for Figures 4 and 5 are listed in Table I, where $\beta$ and $\tau$ are short term parameter and long term parameter, respectively. Because beta changes the early part of the graph and tau changes the latter part of the graph.

Short-term reaction means phenomenon that hydrogen ion gather immediately on SiNW surface. Next, long-term reaction is a phenomenon that hydrogen ion penetrating into the SiNW and that occurred from diffusion.

As shown in Table I, short term parameter $\beta$ increases, and long term parameter $\tau$ decreases with the increase of pH value. In low pH, since a lot of hydrogen ions in the electrolyte quickly gather on the SiNW/electrolyte interface, the short term reaction early finishes. On the other hand, it takes a long time to be saturated because many hydrogen ions penetrate into the SiNW.

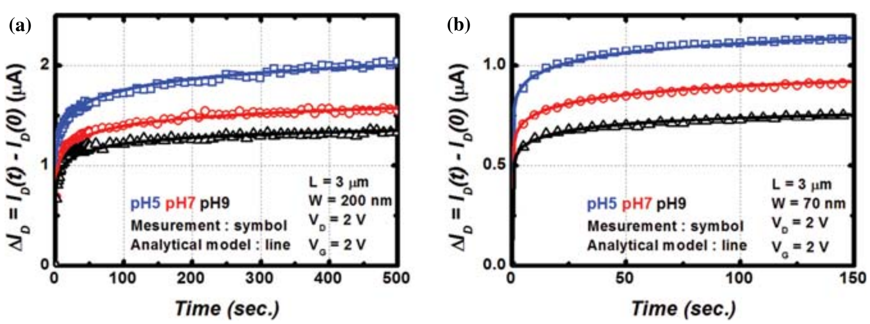


**Figure 4.** $\Delta I_D$–time characteristics in measurement and analytical model in (a) $W = 200$ nm, and (b) $W = 70$ nm.

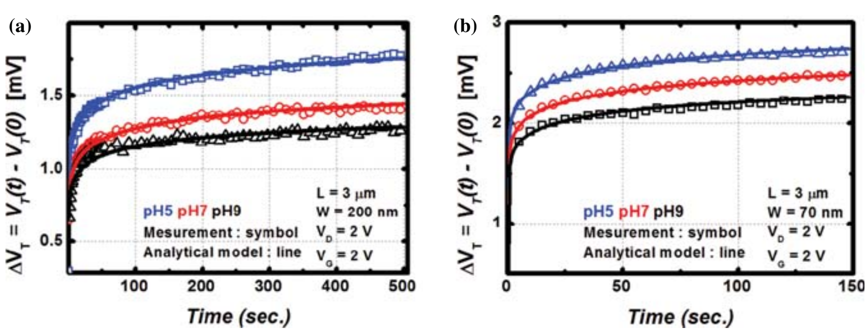


**Figure 5.** $\Delta V_T$–time characteristics in measurement and analytical model in (a) $W = 200$ nm, and (b) $W = 70$ nm.

For robust analytical drift model, the current in SiNW devices with various width sizes is measured at pH 5 level, as shown in Figure 6. As the device width increases, the drift seems like severe. To analyze the drift characteristic in unit width, the current and threshold voltage were normalized with each value at 500 sec. These results are shown in Figures 6(c, d) and the fitting parameters for Eqs. (1) and (2) are listed in Table II.

**Table II.** The fitting parameters of normalized $I_D$ and $V_T$.

| W/L [nm/$\mu$m] | 50/3 | 120/3 | 60/11 | 300/11 |
|---|---|---|---|---|
| $I_0$ | 1.585 | 1.585 | 1.584 | 1.584 |
| $\tau$ [s] | 500 | 500 | 500 | 500 |
| $\beta$ | 0.065 | 0.062 | 0.021 | 0.0205 |
| $V_0$ | 1.6 | 1.595 | 1.59 | 1.58 |
| $\tau$ [s] | 500 | 500 | 500 | 500 |
| $\beta$ | 0.185 | 0.19 | 0.15 | 0.16 |

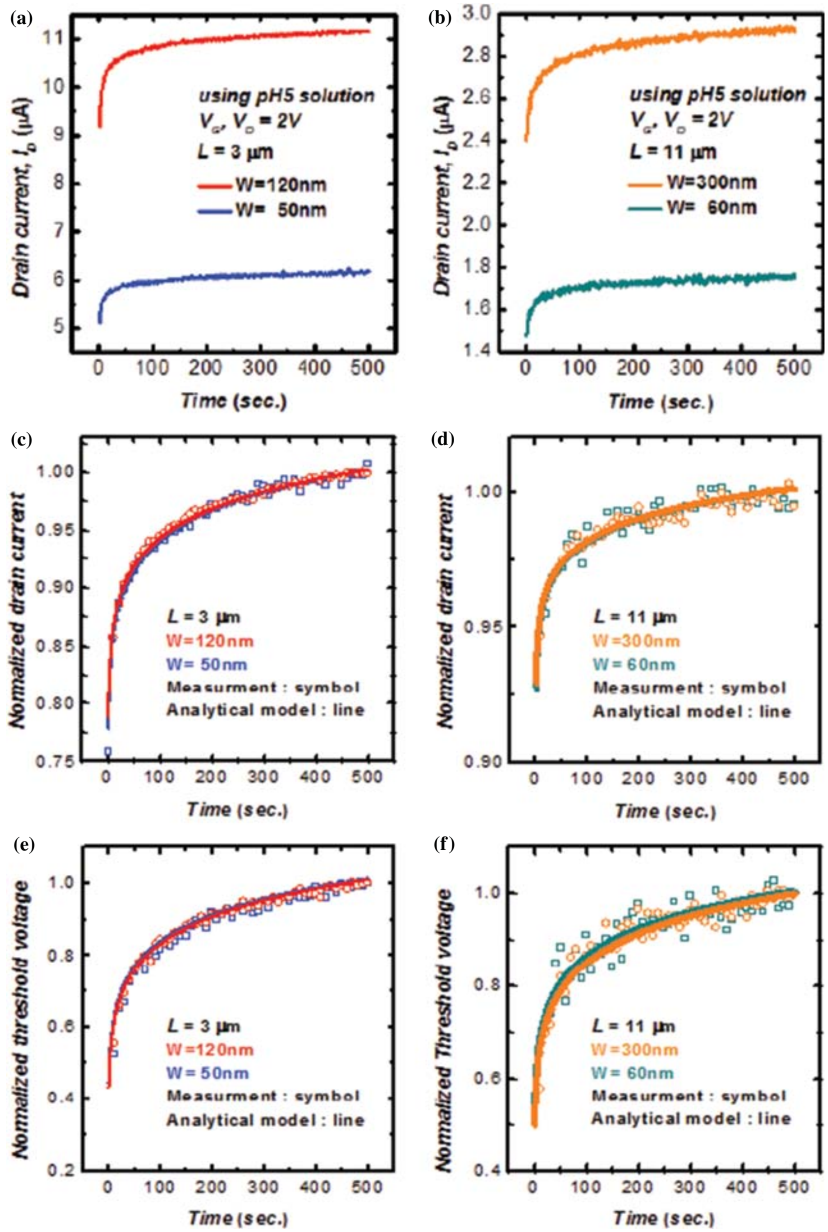


**Figure 6.** $I_D$–time characteristics in measurement and analytical model in (a) $L = 3$ $\mu$m, and (b) $L = 11$ $\mu$m. Normalized $I_D$–time characteristics in measurement and analytical model in (c) $L = 3$ $\mu$m, and (d) $L = 11$ $\mu$m. Normalized $V_T$–time characteristics in measurement and analytical model in (e) $L = 3$ $\mu$m, and (f) $L = 11$ $\mu$m.

As you can see in Figure 6 and Table II, there is no difference of the normalized drift amount. As a result, the short term reaction and long term reaction under unit width condition don't change. That means that our model is able to be applied in various device sizes and predict the drift amount.

## 4. CONCLUSION

We have explained the drift causes and proposed the analytical model dependent on pH level for the robust circuit analysis in SiNW ISFET. The analytical drift model for $\Delta I_D$ and $\Delta V_T$ was derived from a stretched exponential function, the parameters for short and long term reaction were used.

As a result of comparing the model and measurement, it was verified that this model is well matched with measurement result in various device sizes. In addition, we analyzed the physical meaning of the extracted parameter in accordance with the pH value and the width variation. Therefore, it is possible to predict the drift dependent on time and pH level, and our result is potentially useful for the drift-aware circuit design.

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