Effect of Sensing Film Thickness on Sensing Characteristics of Dual-Gate Poly-Si Ion-Sensitive Field-Effect-Transistors

Li-Chen Yen, Ming-Tsyr Tang, Chia-Ying Tan, Tung-Ming Pan, and Tien-Sheng Chao

***Abstract*— We investigate the effect of sensing film thickness on the sensing characteristics of dual-gate (DG) poly-Si ion-sensitive field-effect transistors (ISFETs). The pH sensitivity (from 37.57 to 9.32 mV/pH) of the DG poly-Si ISFET device degrades with the increase in the sensing film thickness (from 20 to 120 nm), whereas hysteresis voltage (from 6.7 to 1.12 mV for a neutral to acid to alkaline to neural loop) and drift rate (from 13.47 to <3 mV/h at pH 7) improve accordingly. An improved hysteresis and drift phenomena are attributed to the reduction in top-gate capacitance of the sensing membrane, causing a smaller capacitive-coupling ratio (top-gate capacitance of sensing membrane to bottom-gate capacitance of tetraethylorthosilicate oxide).**

***Index Terms*— Drift, dual-gate (DG), hysteresis, ion-sensitive field-effect transistor (ISFET), poly-Si, sensitivity.**

I. Introduction

THE ion-sensitive field-effect transistor (ISFET) was first introduced by P. Bergveld in 1970 to replace the fragile glass electrode for the measurement of the pH and concentration of ions [1]. According to the operation principle of ISFET, different pH concentrations will induce various surface potentials at the sensing membrane, leading to the variation of threshold voltage (V_{TH}). The development of high-dielectric constant (high-κ) gate insulator materials has recently become a topic of considerable interest in ISFETs because of their high sensitivity [2]–[4]. However, most of these insulator materials exhibit less than the Nernstian pH sensitivity of 59.5 mV/pH [2], [3], which is also the maximum achievable sensitivity. In contrast, the dual-gate (DG) ISFET could exceed the Nernstian pH sensitivity due to the asymmetric gate oxide thicknesses (top-gate and bottom-gate oxide thicknesses) [5]. The pH response of the DG ISFET was determined as a function of the capacitive coupling. The sensitivity could be enhanced by one order of magnitude [5], [6]. Nevertheless, very few studies have addressed the non-ideal electrical characteristics of the DG ISFET, such as hysteresis and drift phenomena. In this letter, we explore the effect of sensing film thickness on the sensing characteristics (pH sensitivity, hysteresis width and drift rate) of DG poly-Si ISFET devices. We find that the pH sensitivity of the DG poly-Si ISFET decreases as the sensing film thickness increases. Conversely, the hysteresis voltage and drift rate improve accordingly.

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II. Experimental

The fabrication of an ISFET device was started by a 500 nm thick thermal oxide layer grown on a Si wafer at 980 °C. The phosphorus-in-situ doped polycrystalline-Si (poly-Si) layer (150 nm thick) was deposited using a low-pressure chemical vapor deposition (LPCVD) system at 550 °C. Next, a reactive ion etching process was used to define the bottom-gate structure of the device. The deposition of the 25 nm thick tetraethylorthosilicate (TEOS) oxide as a gate dielectric was performed using the LPCVD system. Then, a 50 nm thick amorphous silicon (α-Si) layer was deposited by LPCVD at 550 °C and subsequently converted into a poly-Si film as a channel layer using a solid-phase crystallization process at 600 °C for 24 h in a N_2 ambient. Arsenic ions were implanted into the source/drain (S/D) region using a 36 keV ion energy at a dose of 5×10^{15} cm^{-2}. After the lithography process, the implanted dopants were activated. Afterwards, 600 nm thick Al pads were grown using a physical vapor deposition system followed by wet etching of the Al film. Due to the appearance of a large source-drain leakage current when used in various pH solutions [7], a 200 nm thick oxynitride passivation layer was deposited by PECVD. The sensing area was opened subsequently with the lithography process and followed by wet etching of the oxide film. 20, 70 and 120 nm thick TEOS oxide films as sensing membranes were deposited by PECVD. A H_2 sinter process at 300 °C for 30 min was adopted for the passivation of the defect and dangling bonds between the oxide and poly-Si channel interface. Finally, the microfluidic channel was set up and the pH sensing measurement can be implemented. The cross-sectional view of the DG poly-Si ISFET device is shown in Fig. 1(a).

For the steady pH responses, all DG-ISFET devices were immersed in deionized water for 12 h [8]. The drain current versus gate voltage (I-V) curves for various pH buffer solutions were measured using an Agilent B1500A semiconductor

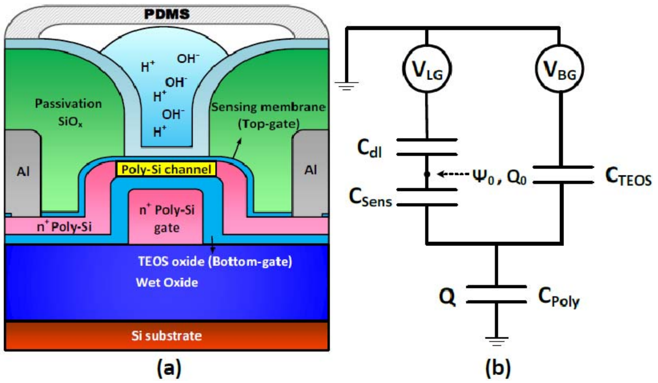

Fig. 1. (a) The cross-sectional view of the double-gated poly-Si ISFET device. (b) In equilibrium when no source-drain voltage is applied, the charge states are defined by the capacitors shown in this equivalent circuit. C_{dl} denotes the electrolyte double-layer capacitance, C_{Sens} is the top-gate capacitance of sensing membrane, C_{Poly} denotes the capacitance of the inversion layer in poly-Si channel, C_{TEOS} is the bottom-gate capacitance of TEOS oxide, Q stands for the induced charge in the poly-Si channel, and Q_0 and ψ_0 represent the charge and potential at the oxide-electrolyte interface, respectively.

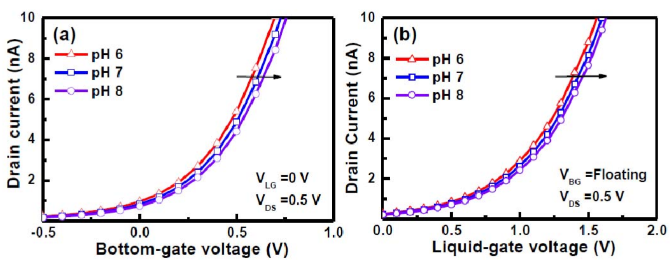

Fig. 2. The transfer characteristics of the DG poly-Si ISFETs with 20 nm sensing membrane measured various pH solutions from pH 6 to pH 8 and operated under (a) bottom-gate and (b) liquid-gate modes.

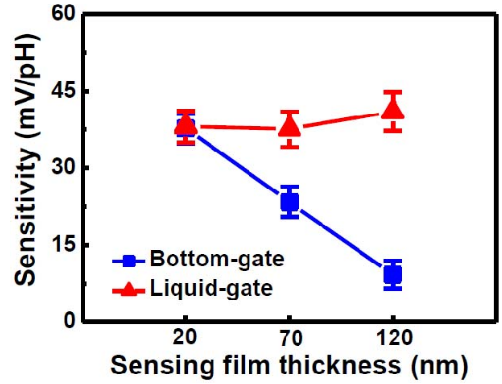

Fig. 3. The sensitivities of the DG poly-Si ISFETs with 20, 70 and 120 nm sensing membranes operated under liquid-gate and bottom-gate modes.

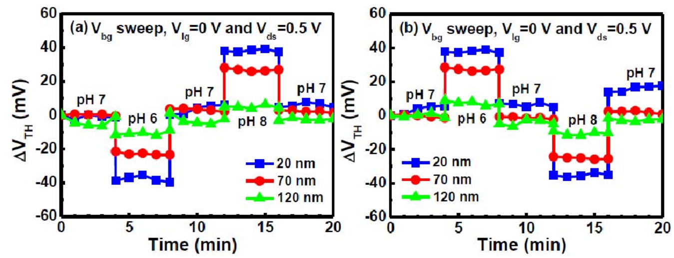

Fig. 4. The hysteresis curves of the poly-Si ISFETs using 20, 70 and 120 nm sensing membranes operated under bottom-gate mode and measured in pH loops of (a) pH 7 →6 →7 →8 →7 and (b) pH 7 →8 →7 →6 →7.

parameter analyzer and a commercial Ag/AgCl reference electrode. In order to avoid the light and noise interference, electrical measurement was performed in a dark box. The effective capacitance network is shown in Fig. 1(b). The various capacitances are the double-layer capacitance C_{dl} at the electrolyte-oxide interface, the top-gate capacitance of the sensing membrane C_{Sens} on top of the poly-Si channel, the bottom-gate capacitance of TEOS oxide C_{TEOS} at bottom of the poly-Si channel, and the inversion layer capacitance C_{Poly}.

III. Results and Discussion

Figs. 2(a) and (b) show typical I–V characteristics of the DG ISFETs operated at liquid-gate mode (bottom-gate voltage floating, drain voltage of 0.5 V and liquid-gate sweep) and bottom-gate mode (bottom-gate sweep, drain voltage of 0.5 V and liquid-gate grounded) for different pH solutions (pH 6, 7, 8), respectively. The I–V curve shifts to a more positive threshold voltage value with increasing the pH value due to the sensing membrane being exposed to negatively charged hydroxyl (−OH) groups. Hence, the change in the surface charge density caused by the variation of pH value can be described by the site-binding model [9], considering the protonation and de-protonation process of OH groups.

Fig. 3 presents the pH sensitivity of the DG ISFETs with different sensing membranes operated under liquid-gate and bottom-gate modes. The measured sensitivities of DG ISFETs under liquid-gate mode were 37.68, 38.04 and 41 mV/pH for 20, 70 and 120 nm sensing membranes, respectively. The pH sensitivity of the liquid-gate mode is independent of the sensing membrane thickness. According to the site-binding model, the threshold voltage shift of ISFET is primarily attributed to an interfacial potential at the insulator-electrolyte interface [10], indicating that the sensitivity of the liquid-gate mode mainly depends on the material of the sensing membrane. On the other hand, the pH sensitivities of the DG ISFETs with 20, 70 and 120 nm sensing membranes operated under bottom-gate mode are 37.57, 23.4 and 9.32 mV/pH, respectively. The pH sensitivity operated under bottom-gate mode decreases with increasing the sensing membrane thickness. The decreased sensitivity could be explained by the classical coupling relation [6]:

$$\Delta V_{TH,BG} = \frac{C_{Sens}}{C_{TEOS}} \Delta V_{TH,LG} = -\frac{C_{Sens}}{C_{TEOS}} \Delta \psi_0 \qquad (1)$$

where ψ_0 is the surface potential. In comparison with a regular ISFET, the change in threshold voltage is modified by the capacitive coupling C_{Sens}/C_{TEOS}. The sensitivity degradation of ISFET under bottom-gate mode may be attributed to the decrease in the C_{Sens} (or increase in the sensing membrane thickness).

Figs. 4(a) and (b) show the hysteresis effect of the DG ISFETs with different sensing membranes measured for the

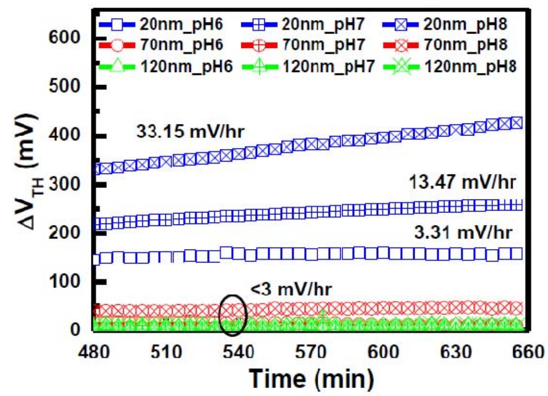

Fig. 5. Drift rates of the DG ISFETs using 20, 70 and 120 nm sensing membranes operated under bottom-gate mode and measured in solutions at pH 6, 7 and 8.

following pH loops: a 7→6→7→8→7 cycle (acid-first cycle) and a 7→8→7→6→7 cycle (base-first cycle), respectively. It is found that the hysteresis widths of 20, 70 and 120 nm sensing membranes measured in the acid-first are 6.7, 2.01 and 1.12 mV, while the base-first cycle are 12.73, 2.39 and 2.44 mV. The results show the asymmetric hysteresis between the acid-first and base-first cycles. A hydrogen ion (H^+) is attracted to the negative end of a polar water molecule and bonds with it to form a hydronium ion (H_3O^+), which is quite stable. The H_3O^+ represents a H^+ in aqueous solution. The OH^- ions are smaller in size than the H_3O^+ ions, hence, the diffusion rates of the OH^- ions into the buried sites of the sensing membrane are faster than the H_3O^+ groups, leading to an asymmetric hysteresis phenomenon [11]. In addition, the hysteresis width decreases as the sensing membrane thickness increases. The results indicate that the increase in sensing membrane thickness causes a smaller capacitive-coupling ratio (C_{Sens}/C_{TEOS}). As a consequence, the hysteresis phenomenon of an ISFET device using a sensing membrane thickness over 70 nm performed under the bottom-gate mode becomes insignificant.

Fig. 5 shows the long-term response of the DG ISFET devices fabricated at different sensing membrane thicknesses and measured in different pH values under bottom-gate mode. The formation of Si-OH buried sites occurred at the oxide surface because of the penetration of ions into the oxide film. Therefore, the change in the oxide charge leads to a decrease in the insulator capacitor with time, which could cause a temporal increase in the threshold voltage [12], [13]. The drift rate increases with increasing the pH value, which is consistent with previous reports [14]–[16]. Furthermore, the drift behavior is also reduced when the sensing membrane becomes thick, suggesting a decrease in the C_{Sens}/C_{TEOS} ratio. Consequently, the drift behavior under the bottom-gate mode becomes insignificant when the sensing membrane thickness is more than 70 nm (<3 mV/hr). In practical applications of a DG poly-Si ISFET, a trade-off between sensitivity and non-ideal effect should be considered.

IV. Conclusion

We investigated the pH sensitivity of a DG poly-Si ISFET using various sensing film thicknesses performed under liquid-gate and bottom-gate modes. The non-ideal phenomena of hysteresis and drift were also evaluated. It is found that the pH sensitivity of the DG poly-Si ISFET increases as the sensing film thickness decreases, while hysteresis voltage and drift rate increase accordingly. This behavior is attributed to the increase in the C_{Sens}/C_{TEOS} ratio.

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