Effect of liquid gate bias rising time in pH sensors based on Si nanowire ion sensitive field effect transistors

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A B S T R A C T

In this study, we investigate the effect of rising time (T\textsubscript{R}) of liquid gate bias (V\textsubscript{LG}) on transient responses in pH sensors based on Si nanowire ion-sensitive field-effect transistors (ISFETs). As T\textsubscript{R} becomes shorter and pH values decrease, the ISFET current takes a longer time to saturate to the pH-dependent steady-state value. By correlating V\textsubscript{LG} with the internal gate-to-source voltage of the ISFET, we found that this effect occurs when the drift/diffusion of mobile ions in analytes in response to V\textsubscript{LG} is delayed. This gives us useful insight on the design of ISFET-based point-of-care circuits and systems, particularly with respect to determining an appropriate rising time for the liquid gate bias.

1. Introduction

An important indicator in industries such as food, pharmaceutical, agriculture, biomedical, and environmental monitoring is pH; for example, variations in pH of human blood are signs of serious, potentially fatal diseases [1]. The solubility, stability, and permeability of a drug through biological membrane also depend on pH [2], and therefore, a precise pH measurement technique using a miniaturized sensor is essential. Furthermore, the solubility of heavy metals such as lead, zinc, and copper in soil is dependent on the pH [3], and therefore, pH measurement is important for managing the environment.

Ion-sensitive field-effect transistors (ISFETs) [4] have attracted considerable attention because of their compact structure, low-cost, and ease of fabrication. Recently, ISFET-based pH sensors have been successfully used in human genome sequencing [5–7]. The resolution of an ISFET-based pH sensor depends on its individual technology and geometry. Therefore, optimum operation of the sensor in complex analog circuits where biasing configuration may change over time needs to be anticipated. The transient response of an ISFET-based pH sensor is governed by two processes: the convective/diffusive transport of H\textsuperscript{+} ions to the sensor surface (diffusion time) and the response of the sensor to the changes in proton concentration on its surface (response time). Diffusion time depends on various factors that define the ion transport time to the sensor, such as flow rate and the size/shape of the fluidic channel. However, the transient response to time-varying liquid gate bias (V\textsubscript{LG}) has been rarely investigated despite its importance. To optimize the details of operation, particularly the choice of the saturation time of signals in the ISFET-based point-of-care (PoC) circuits, the influence of the rising time of V\textsubscript{LG} needs to be experimentally characterized. We studied ways to simplify the properties that may affect the way the sensor works. For example, we measured droplets before they entered the microfluidic channel. In this way, we could exclude complicated factors such as convection and diffusion in the analyte.

Conversely, the silicon nanowire (SiNW) ISFET-based biosensors have great potential as essential building blocks for real-time, label-free detection of biomolecules because of their advantages such as direct electrical readouts and high sensitivity and the potential to integrate them with complementary metal-oxide semiconductor (CMOS) circuits [8–11]. Based on the top-down processing in the SiNW/CMOS hybrid circuitry, researchers have already demonstrated electrical optimization sensitivity [12], sensitivity boosting [13], voltage readout [14], noise cancellation [15], and simulation using commercial technology computer aided design (TCAD) [16]. It should therefore be noted that operating the SiNW ISFET in the saturation region is desirable for a robust analog front-end design, although the ISFET sensitivity itself can be better in the sub-threshold rather than the saturation region.

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In this work, the influence of the $V_{LO}$ rising time ($T_{R}$) on transient current response in the top-down processed SiNW ISFET-based pH sensors operating in the saturation region is investigated. By correlating $V_{LO}$ with the internal gate-to-source voltage of ISFET ($V_{G,int}$) at the electrolyte/insulator interface, we have gained new physical and chemical insights into the drift/diffusion of mobile ions in an electrolyte analyte.

2. SiNW ISFET: Fabrication and experiments

SiNW ISFET-based pH sensors were fabricated on a boron-doped ($4 \times 10^{15}$ cm$^{-3}$) 6-inch (1 0 0) silicon-on-insulator wafer. The 100 nm-thick Si layer at the top was separated from the Si substrate by a 375 nm thick buried oxide (BOX). To build the buffer oxide as protection for implantation, a 20 nm thick SiO$_2$ layer was formed on top of the Si layer by dry oxidation. As a result, the thickness of the top Si layer was reduced to 90 nm. Subsequently, channel implantation was conducted for the p-type region (B$^+$, energy: 20 keV, dose: $5 \times 10^{13}$ cm$^{-2}$) and the n-
type region (P+, energy: 40 keV, dose: $3 \times 10^{13}$ cm$^{-2}$). After stripping the buffer oxide in a HF solution, the annealing process was conducted at 950 °C for 30 min. Subsequently, the device-active region was patterned on the Si layer via a mix-and-match process of electron-beam (e-beam) lithography combined with conventional photolithography. The 90 nm thick Si layer was anisotropically etched in the HBr/O$_2$-based inductively coupled plasma chamber by using hydrogen silsesquioxane (HSQ) and photoresist (PR) as the etch mask. A PR mask, which covered only the SiNW channel, was used to dope the source/drain regions of the SiNW with As$^+$ ion implantation for an n-type source/drain. After PR stripping, the annealing step followed at 1000 °C for 30 min to activate the dopant. The next step was to deposit a 500 nm oxide as an interlayer dielectric using high-density plasma chemical vapor deposition. Subsequently, we applied chemical mechanical planarization. A contact hole was then formed by photolithography and magnetic-enhanced reactive ion etching (MERIE) in a CHF$_3$/CF$_4$ plasma. After metallization using Al sputtering, photolithography, and MERIE in BCl$_3$/Cl$_2$ plasma, tetraethyl orthosilicate (TEOS) was deposited as a passivating oxide to protect the metal lines. For electrical measurement, the oxide layer on the metal pad region was etched by photolithography and MERIE in CHF$_3$/CF$_4$ plasma. Finally, we removed the TEOS passivation oxide using MERIE in CHF$_3$/CF$_4$ plasma so that the sensing area on the SiNW channel region became open and connected with the SiNW surface and the biomolecule analyte. The completion of alloy fabrication marked the end of the entire process. A photograph of the fabricated chip is shown in Fig. 1(a). Scanning electron microscope images of the SiNW ISFET biosensor and the SiNW itself are shown in Fig. 1(b) and (c). The measurement environment is shown in Fig. 1(d) and (e); Fig. 1(e) shows the enlarged liquid gate contacting the reference electrode (RE).

In the pH-sensing experiments, the SiO$_2$ surface of the SiNWs was modified with 3-aminopropyltriethoxysilane (APTES). A schematic bird’s eye view of the surface-modified SiNW is shown in Fig. 2(a). Surface-modified SiNW ISFET was then exposed to 0.1 × potassium phosphate buffer solutions with three different pH values (i.e., pH 5, 7, and 9) by dropping buffer solutions onto a polydimethylsiloxane (PDMS) container as seen in Fig. 1(d). The drain current ($I_D$) is measured at room temperature at a constant drain/source voltage ($V_D$/$V_S$) of 0.9/0 V while $V_{LG}$ was swept from $-1$ to $1.2$ V with 25 mV steps by using an Ag/AgCl reference electrode, as seen in Fig. 1(e). The transfer characteristics of the n-type SiNW FET for the three different pH values are shown in Fig. 2(b). The gate leakage current is negligible. As the pH levels increase, the conductance of the n-type SiNW FET decreases, resulting in a positive shift of the threshold voltage ($V_T$). This can be explained by the protonation/deprotonation of $-\text{NH}_2$ and $-\text{SiOH}$ groups on the functionalized SiNW surface. At low pH levels, the $-\text{NH}_2$ group is protonated to $-\text{NH}_3$, resulting in a positive charge. By contrast, at high pH levels, the $-\text{SiOH}$ group is deprotonated to $-\text{SiO}^-$ and results in a negative charge[17]. The average $V_T$ shift ($\Delta V_T$) is 20 mV per pH [Fig. 2(c)], which is below the Nernst limit as expected. Small $\Delta V_T$ is caused by non-ideal interfaces between the gate insulator layer and electrolyte[18]. Although the $\Delta V_T$ sensitivity is lower than
our previous works \cite{8,13,15}, herein the transient response of ISFETs is paid attention to rather than the sensitivity itself in DC response. More importantly, it should be noted that our main conclusions, including explanation, model, and method, will be generally available irrespective of the ISFET sensitivity.

The pH-sensing signal needs to be acquired after waiting for at least a certain amount of time, called the saturation time, if it takes a significant time for the drain current to reach a steady-state value after the time-varying liquid gate voltage is setup. To systematically determine the optimal saturation time, the transient drain current was measured at a fixed V\textsubscript{D} = 0.9 V, while V\textsubscript{LG} was ramped up from 0 V to 0.9 V during TR, as illustrated in Fig. 3(a). Here TR was varied over 0.2, 1, 5, and 10 s. In this way, the transient drain current was measured with varying TR and pH, as seen in Fig. 3(b). The saturation time (t\textsubscript{sat}) was defined as the time difference between the time spot when V\textsubscript{LG} arrived at 0.9 V and t\textsubscript{sat,end}. The saturation time was symbolized as t\textsubscript{sat} and the time spot at \( \partial \text{ID} / \partial t = 1 \text{nA/s} \) (t\textsubscript{sat,end}) which means the moment when ID reached at the pH-dependent steady-state value, as indicated in Fig. 3(b). The measured IDs as the function of pH and TR are summarized in Fig. 3(d), and the experimentally extracted t\textsubscript{sat} is shown in Fig. 3(c) and Table 1.

3. Results and discussion

The rate of time-varying ID can be formulated as follows:

\[
\frac{\partial I_D(t)}{\partial t} = \frac{\partial V_{\text{LG}}(t)}{\partial t} \times \frac{\partial V_{\text{GS,int}}(t)}{\partial V_{\text{LG}}(t)} \times \frac{\partial I_D(t)}{\partial V_{\text{GS,int}}(t)}
\]

where the first term of the right-hand side increases as TR becomes shorter. The second term suggests the delay of V\textsubscript{GS,int} in response to the time-varying V\textsubscript{LG}, which is due to the retardation of mobile ions in the electrolyte.

In the transient model of ISFETs, the second term is frequently modeled by combining the electrolyte resistance, double-layer capacitance, stern capacitance, and the capacitance due to the charging/discharging of the surface ionizable groups \cite{19}. However, the second term should be carefully modeled because the electrolyte and the FET cannot be decoupled from each other, and the relation between V\textsubscript{GS,int} and V\textsubscript{LG} is complicatedly non-linear.

Furthermore, our observation in Fig. 4 suggests that the second term depends on either the first term (\( \partial V_{\text{LG}}/\partial t \)) or the pH. In the case of short TR, mobile ions cannot respond to the time-varying speed of V\textsubscript{LG}. It is also noteworthy that as mobile ions drift more quickly to the electrolyte/gate oxide interface, in other words, the more abruptly proton ion concentration, i.e., [H\textsuperscript{+}], increases at the electrolyte/gate oxide interface, the larger the flux of ions diffuses backward away from the electrolyte/gate oxide interface. It takes a longer time, therefore, for I\textsubscript{D} to
Fig. 5. Proton ion concentration ([H+]¹) in the electrolyte/gate oxide interface from different TR at (a) t = 0, (b) 0 < t < tsat,end, and (c) t = tsat,end. Illustration of relation (d) between VLG and VGS,int and (e) between VGS,int and ID from different TR.

Fig. 6. Proton ion concentration ([H+]¹) in the electrolyte/gate oxide interface from different pH at (a) t = 0, (b) 0 < t < tsat,end, and (c) t = tsat,end. Illustration of relation (d) between VLG and VGS,int and (e) between VGS,int and ID from different pH.
reach the steady-state value, i.e., $t_{sat}$ increases, because the $I_D$ reaches a steady-state after the drift and diffusion of mobile ions balance each other, as shown in Fig. 5(a)–(c). Consequently, before $T_R$, the $V_{GS,int}$ is more deviated from the $V_{LG}$ in a short $T_R$ case rather than in a long $T_R$ case, as observed in Fig. 4(a) and as illustrated in Fig. 5(d) and (e). With respect to $T_R$ dependence, our model is highly consistent with the observations in Fig. 3 and Table 1.

The rate of $\frac{dV_{GS,int}}{dV_{LG}}$ also depends on the $[H^+]$ concentration of electrolyte, i.e., the pH value. As the $[H^+]$ increases and the pH gets lower, it takes a longer time for the drift and diffusion of mobile ions to be balanced by each other and the $t_{sat}$ increases, as illustrated in Fig. 6(a)–(c). Consequently, during $T_R$, $V_{GS,int}$ deviates more from $V_{LG}$ in a low pH case rather than in a high pH case as observed in Figs. 4(c), 6(d), and (e). Our model is also consistent with the observation in Fig. 3 and Table 1 in terms of pH dependence.

Therefore, a longer hold time for $V_{LG}$ biasing is required as the $T_R$ becomes shorter and the pH decreases.

4. Conclusion

The influence of both $T_R$ of $V_{LG}$ and pH on the transient $I_D$ response has been experimentally investigated in SiNW ISFET-based pH sensors. As $T_R$ becomes shorter and the pH value decreases, it takes a longer time for the ISFET current to saturate to the pH-dependent steady-state value. Before the time arrives at $t = t_{sat,end}$, $V_{GS,int}$ deviates more from $V_{LG}$ in either of the two cases, the shorter $T_R$ case or the lower pH case. Our model, which is based on the time taken for mobile ions in the electrolyte to be balanced between drift and diffusion, explains the observation very well. Our results supply the experimental background for more exact transient ISFET modeling, e.g., double-layer, Stern, and charging/discharging capacitance, and give useful insights on the design of rising time of $V_{LG}$ bias in ISFET-based point-of-care circuits and systems.

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Reference