Analysis and Simulation on an ISFET with Back-Gated Structure and High-Mobility Channel Material

X. Wu, A. Z. Jia
School of Microelectronics and Solid-State Electronics
University of Electronic Science and Technology of China
China

Abstract—A back-gated structure for ion-sensitive field-effect transistor (ISFET) has been proposed. The characteristics of the device based on this proposed structure and with high-mobility channel material have been investigated and analyzed by Silvaco TCAD. The modeling and simulation methodologies have been investigated, and an average sensitivity approximate 49.56mV/pH is obtained. The detectable average sensitivity of drain current is about 54.23µA/pH with a high saturated drain current which is at the magnitude of 10^3A, indicating a promising application in biological, biochemical and medical fields.

Keywords-ISFET; modeling and simulation; high mobility; back-gated; average sensitivity

I. INTRODUCTION

The ion-sensitive field-effect transistor (ISFET) has received a lot of interest, since it was first reported by Bergveld in 1972[1]. Due to the promising application in biological, biochemical and medical detection [2-4], the ISFET based on a metal-oxide-semiconductor field-effect transistor (MOSFET) structure has been extensively studied. In particular, much effort has been made on investigating pH-sensitive ISFETs, which device structures and pH-sensing membranes have been studied to improve the sensitivity and stability of the ISFETs [4-6]. It is well known that the gate dielectric is in direct contact with the electrolyte solution, which determines the beginning sensitivity of these devices. As SiO₂ gate dielectric shows low response sensitivity and poor stability, other inorganic materials, such as Al₂O₃ [5], Si₃N₄ [6,7] and Ta₂O₅ [8] with enhanced stability and sensitivity have been investigated. Moreover, the drain-source voltage of the ISFET based on a MOSFET structure also affects the ionic charges with a horizontal electric field in the electrolyte solution, resulting in a non-uniform charge distribution at the electrolyte-insulator interface. The operation mechanism of a pH-sensitive ISFET is the change of potential between the electrolyte solution and the gate dielectric surface, thus leading to an increased or decreased output current of the ISFET. Although the impurity doping could improve the properties of semiconductor materials [9-10], the pH-sensitive ISFETs with high-mobility channel materials, such as InSb and graphene [11,12] may have intrinsic advantages of low response delay and high sensitivity, and the output current of the ISFET can be also increased.

We proposed a back-gated ISFET structure, in which the back-gate of thin-film transistor can be fabricated by etching the substrate and the electrolyte solution is separated from the drain/source electrodes. In this paper, the characteristics of the device based on this proposed structure with high-mobility channel material have been investigated by Silvaco TCAD. The simulation is based on the detection of pH, as the pH-sensitivity ISFET has the most accurately model and their physical and chemical behaviour had been studied extensively. The response of pH-sensitive devices in electrolyte solutions is commonly explained by using the site-binding theory [13].

II. DEVICE STRUCTURE AND MODEL

![Figure 1. Schematic Layout of the Back-Gated ISFET Structure.](Image)

According to the site-binding and electrical double layer theory [7,14], we considered the Helmholz layer and diffuse layer in the electrolyte solution as two in series capacitors, thus the potential drop ψ between the Helmholz layer and diffuse layer can be expressed as:

\[
ψ = \frac{σC_HC_D}{C_H + C_D},
\]

where \(C_H\) is the Helmholz layer unit-area capacitance, \(C_D\) is the diffuse layer unit-area capacitance and \(σ\) is the charge density at the electrolyte-insulator interface, respectively. The Helmholz layer unit-area capacitance \(C_H\) can be derived by considering the in series of the inner and outer Helmholz layers:
where \( \varepsilon_{\text{HDP}} \) and \( \varepsilon_{\text{CQP}} \) are the inner and outer Helmholtz plane dielectric constants, \( \varepsilon_0 \) is the permittivity of vacuum, \( d_{\text{HDP}} \) and \( d_{\text{CQP}} \) are the insulator–non-hydrated ion and the insulator–hydrated ion distances, respectively. The diffuse layer unit-area capacitance \( C_D \) is given by [14]:

\[
C_D = \frac{2\varepsilon_e d_{\text{HDP}}}{kT},
\]

where \( T \) is the temperature, \( k \) is the Boltzmann constant, \( q \) is the electronic charge, \( \varepsilon_e \) is the permittivity of the electrolyte solution; \( c_b \) is ion concentration in the electrolyte solution.

\[
\text{The charge density } \sigma \text{ at the electrolyte-insulator interface is given by [14-16]:}
\]

\[
\sigma = q\left[ \phi_i \left( H^+ \right) \right]_{\text{HDP}} = \frac{1}{kT} \ln \left( \frac{\left[N^+\right]_{\text{HDP}}}{\left[N^-\right]_{\text{HDP}}} \right),
\]

where \( [H^+]_{\text{HDP}} = 10^{\phi_{\text{HDP}}} \mu \) is the concentration of \( H^+ \) at the bulk electrolyte solution, \( N_i \) and \( N_s \) are the surface densities of the silanol sites and the primary amine sites, \( K_{\Lambda A}, K_{\Lambda B}, K_B \) are the dissociation constants of the silanol sites and the primary amine sites, respectively. Therefore, the relation between \( \psi \) and \( \phi \) can be obtained by solving the equations of eqn(1)-(4).

The general threshold voltage \( V_T \) of a MOS structure is given by:

\[
V_T = V_{FB} + V_{OX} + 2\phi_F,
\]

where \( V_{FB} \) is the flatband voltage, \( V_{OX} \) is the voltage drop at the gate dielectric, \( \phi_F \) is the Fermi-potential. The threshold voltage \( V_T^* \) of this proposed device can be expressed as [16]:

\[
V_T^* = E_{\text{ref}} + \chi_{\text{sat}} - \psi + V_F,
\]

where \( E_{\text{ref}} \) is the potential of the reference electrode, \( \chi_{\text{sat}} \) is the surface dipole potential of the gate insulator-electrolyte, which are both constants. The parameters [14-16] used in simulation are list in table 1.

**TABLE I. THE PARAMETERS USED IN THIS DEVICE SIMULATION.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_{\text{HDP}} )</td>
<td>32</td>
</tr>
<tr>
<td>( \varepsilon_{\text{CQP}} )</td>
<td>32</td>
</tr>
<tr>
<td>( d_{\text{HDP}} ) (nm)</td>
<td>0.1</td>
</tr>
<tr>
<td>( d_{\text{CQP}} ) (nm)</td>
<td>0.3</td>
</tr>
<tr>
<td>( \varepsilon_e )</td>
<td>78.5</td>
</tr>
<tr>
<td>( c_b ) (1/moles)</td>
<td>0.1</td>
</tr>
<tr>
<td>( K_A )</td>
<td>15.8</td>
</tr>
<tr>
<td>( \chi_{\text{sat}} )</td>
<td>63.1×10^6</td>
</tr>
<tr>
<td>( \chi_{\text{sat}} )</td>
<td>8.3×10^14</td>
</tr>
<tr>
<td>( \chi_{\text{sat}} )</td>
<td>2×10^14</td>
</tr>
<tr>
<td>( \psi )</td>
<td>0.205</td>
</tr>
<tr>
<td>( \chi_{\text{sat}} )</td>
<td>3×10^17</td>
</tr>
<tr>
<td>( \chi_{\text{sat}} )</td>
<td>5.3, 7, 9, 11</td>
</tr>
</tbody>
</table>

III. RESULTS AND DISCUSSION

The IDE−VGS transfer characteristics curves with different pH measured at \( V_{DS}=0.5 \) V of proposed back-gated ISFET are shown in Figure 2. It can be seen that the threshold voltages of this device increased with the increased pH. The simulation average sensitivity of this device is about 49.56 mV/pH, which is in the range of 25 to 58 mV/pH with a potential/pH response of silicon nitride devices [7]. It is also of interest to note that the use of InSb material can lead a low threshold voltage compared with silicon ISFET at the same doping concentration of channel. As the Fermi-potential \( \Phi_F \) of a P-type semiconductor can be expressed as:

\[
\Phi_F = \frac{kT}{q} \ln \frac{N_A}{n_i},
\]

where \( N_A \) is the doping concentration of channel, \( n_i \) is intrinsic carrier concentration of the semiconductor. The intrinsic carrier concentration of InSb and silicon is \( 1.92\times10^{16} \) cm\(^{-3}\) and \( 1.43\times10^{16} \) cm\(^{-3}\), and the work function of InSb and silicon is 4.59 eV and 4.17 eV, respectively. Therefore, it can be obtained from eqn(6) and eqn(7) that the InSb ISFET has a low threshold voltage compared with silicon ISFET at the same doping concentration of channel, allowing addition of sensing membranes which can further improving the device sensitivity and enlarging the application fields of the device in biological, biochemical and medical detection.
and the etching of substrate as a gate dielectric lead a low response delay and a large detectable current signal, also indicating a promising application in biological, biochemical and medical detection.

IV. CONCLUSION

In summary, the characteristics of the ISFET device based on proposed back-gated structure and with high-mobility material for the channel have been simulated and analyzed. We focus on the modeling and simulation methodologies of the ISFET device used for the detection of pH, as the accurate model can be achieved by using the site-binding theory. A simulation average sensitivity approximate 49.56 mV/pH is obtained, and the device exhibits a low threshold voltage compared with silicon ISFET at the same doping concentration of channel. The detectable average sensitivity of drain current is about 54.23 µA/pH with a high saturated drain current which is at the magnitude of 10⁻⁴ A, exhibiting a large detectable current signal with low response delay. The simulation results of the detection of pH indicate that this ISFET may have a promising application in biological, biochemical and medical detection by addition of sensing membranes.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Science and Technology Program of Chengdu for the support. If you have any questions, please directly contact the corresponding author by E-mail at ze.jia@ieee.org.

REFERENCE