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

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***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 simulated 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^{-4}A, 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 SiO_2 gate dielectric shows low response sensitivity and poor stability, other inorganic materials, such as Al_2O_3 [5], Si_3N_4 [6,7] and Ta_2O_5 [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

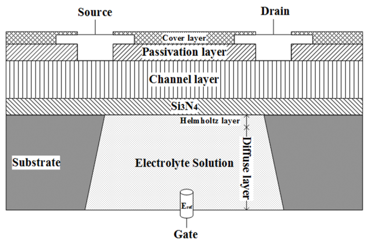

FIGURE I. SCHEMATIC LAYOUT OF THE BACK-GATED ISFET STRUCTURE.

Figure.1 shows the schematic layout of proposed back-gated ISFET structure. The high-mobility n-channel layer is deposited on a Si_3N_4 layer with flexible organic substrate, and the gate of ISFET is achieved on the back side by etching the substrate after fabricating drain and source regions on the right side. In this device simulation, InSb with a doping concentration of $10^{17}cm^{-3}$ is utilized as channel material. The doping concentration of drain and source regions are $10^{20}cm^{-3}$, and the channel length is 6μm. The thickness of the channel layer and the gate dielectric after etching is 160nm and 40nm, respectively.

According to the site-binding and electrical double layer theory [7,14], we considered the Helmholtz layer and diffuse layer in the electrolyte solution as two in series capacitors, thus the potential drop ψ between the electrolyte solution and the surface of the Si_3N_4 dielectric can be expressed as:

$$\psi = \frac{\sigma C_H C_D}{C_H + C_D}, \qquad (1)$$

where C_H is the Helmholtz 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 Helmholtz layer unit-area capacitance C_H can be derived by considering the in series of the inner and outer Helmholtz layers:

$$C_H = \frac{\varepsilon_{IHP}\varepsilon_{OHP}\varepsilon_0}{\varepsilon_{OHP}d_{IHP} + \varepsilon_{IHP}d_{OHP}}, \qquad (2)$$

where ε_{IHP} and ε_{OHP} are the inner and outer Helmholtz plane dielectric constants, ε_0 is the permittivity of vacuum, d_{IHP} and d_{OHP} 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]:

$$C_D = q\sqrt{\frac{2\varepsilon_e c_b}{kT}}, \qquad (3)$$

where T is the temperature, k is the Boltzmann constant, q is the electronic charge, ε_e is the permittivity of the electrolyte solution; c_b is ion concentration in the electrolyte solution. The charge density σ at the electrolyte-insulator interface is given by [14-16]:

$$\sigma = qN_s\left(\frac{[H^+]_b^2 \exp(-\frac{2q\psi}{kT}) - K_{A-}K_{A+}}{[H^+]_b^2 \exp(-\frac{2q\psi}{kT}) + K_{A+}[H^+]_b \exp(-\frac{q\psi}{kT}) + K_{A-}K_{A+}}\right) + qN_n\left(\frac{[H^+]_b^2 \exp(-\frac{q\psi}{kT})}{[H^+]_b^2 \exp(-\frac{q\psi}{kT}) + K_B}\right), \qquad (4)$$

where $[H^+]_b$ =10^(-pH) is the concentration of H^+ at the bulk electrolyte solution, N_s and N_n are the surface densities of the silanol sites and the primary amine sites, K_{A-}, K_{A+}, K_B are the dissociation constants of the silanol sites and the primary amine sites, respectively. Therefore, the relation between ψ and pH can be obtained by solving the equations of eqn(1)-(4).

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

$$V_T = V_{FB} + V_{OX} + 2\phi_F, \qquad (5)$$

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

$$V_T^* = E_{ref} + \chi_{sol} - \psi + V_T, \qquad (6)$$

where E_{ref} is the potential of the reference electrode, χ_{sol} 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.

ε_{IHP}	32	K_{A+}	63.1×10^{-9}
ε_{OHP}	32	K_B	1×10^{-10}
d_{IHP} (nm)	0.1	N_s	3×10^{-18}
d_{OHP} (nm)	0.3	N_n	2×10^{-18}
ε_e	78.5	E_{ref}	0.205
c_b (1/moles)	0.1	χ_{sol}	3×10^{-3}
K_{A-}	15.8	pH	3,5,7,9,11

III. RESULTS AND DISCUSSION

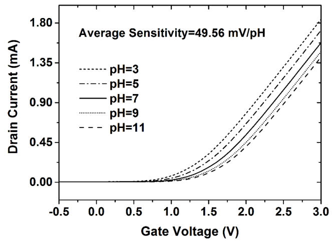

FIGURE II. IDS-VGS TRANSFER CHARACTERISTICS WITH DIFFERENT PH MEASURED AT VDS=0.5V OF THE BACK-GATED ISFET.

The I_{DS}-V_{GS} 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 49.56mV/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 Φ_F of a P-type semiconductor can be expressed as:

$$\phi_F = \frac{kT}{q}\ln\frac{N_A}{n_i}, \qquad (7)$$

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 1.92×10^{16} cm^{-3} and 1.43×10^{10} cm^{-3}, and the work function of InSb and silicon is 4.59eV and 4.17eV, 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.

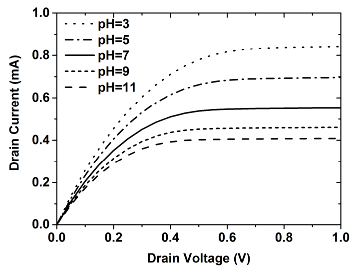

FIGURE III. IDS-VDS CHARACTERISTICS WITH DIFFERENT PH MEASURED AT VGS=2.0V OF THE BACK-GATED ISFET.

Figure.3. shows the I_{DS}-V_{DS} characteristics with different pH measured at V_{GS}=2.0V of this back-gated ISFET. The drain current of this device decreased with the increased pH, and the detectable average sensitivity of drain current is about 54.23μA/pH. The saturated drain current is at the magnitude of 10^{-4} A. As the saturated drain current is proportional to the mobility, this high-mobility ISFET undoubted has a high drain current, resulting a large detectable current signal of the pH response. The introduction of high-mobility channel material 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

[1] Bergveld, P., Development, operation, and application of the ion-sensitive field-effect transistor as a tool for electrophysiology. Biomedical Engineering, IEEE Transactions on, (5), pp. 342-351, 1972.

[2] Bratov, A., Abramova, N. & Domínguez, C., Investigation of chloride sensitive ISFETs with different membrane compositions suitable for medical applications. Analytica chimica acta, 514(1), pp. 99-106, 2004.

[3] Lee, C.S., Kim, S.K. & Kim, M., Ion-sensitive field-effect transistor for biological sensing. Sensors, 9(9), pp. 7111-7131, 2009.

[4] Sakurai, T. & Husimi, Y., Real-time monitoring of DNA polymerase reactions by a micro ISFET pH sensor. Analytical chemistry, 64(17), pp. 1996-1997, 1992.

[5] Chen, S., Bomer, J.G., Carlen, E.T. & van den Berg, A., Al2O3/silicon nanoISFET with near ideal Nernstian response. Nano letters, 11(6), pp. 2334-2341, 2011.

[6] Niu, M.N., Ding, X.F. & Tong, Q.Y., Effect of two types of surface sites on the characteristics of Si3N4-gate pH-ISFETs. Sensors and Actuators B: Chemical, 37(1), pp. 13-17, 1996.

[7] Harame, D.L., Bousse, L.J., Shott, J.D. & Meindl, J.D., Ion-sensing devices with silicon nitride and borosilicate glass insulators. Electron Devices, IEEE Transactions on, 34(8), pp. 1700-1707, 1987.

[8] Kwon, D.H., Cho, B.W., Kim, C.S. & Sohn, B.K., Effects of heat treatment on Ta2O5 sensing membrane for low drift and high sensitivity pH-ISFET. Sensors and Actuators B: Chemical, 34(1), pp. 441-445, 1996.

[9] Jia, Z., Zhang, M.M. & Ren, T.L., Modulation Effect of Lead Zirconate Titanate for Zinc Oxide Channel Resistance in Ferroelectric Field Effect Transistor. Ferroelectrics, 421(1), pp. 92-97, 2011.

[10] Jia, Z., Xu, J.L., Wu, X., Zhang, M.M., Zhang, N.W., Liu, J.Z., Liu, Z.W. & Liou, J.J., Metal-Semiconductor-Insulator-Metal Structure Field-Effect Transistors Based on Zinc Oxides and Doped Ferroelectric Thin Films. 2013 MRS Fall Proceedings, 1633, pp. mrsf13-1633, 2014.

[11] Fu, W., Nef, C., Knopfmacher, O., Tarasov, A., Weiss, M., Calame, M. & Schönenberger, C., Graphene transistors are insensitive to pH changes in solution. Nano letters, 11(9), pp. 3597-3600, 2011.

[12] Semenov, Y.G., Kim, K.W. & Zavada, J.M., Spin field effect transistor with a graphene channel. Applied Physics Letters, 91(15), pp. 153105, 2007.

[13] Yates, D.E., Levine, S. & Healy, T.W., Site-binding model of the electrical double layer at the oxide/water interface. Journal of the Chemical Society, Faraday Transactions 1: Physical Chemistry in Condensed Phases, 70, pp. 1807-1818, 1974.

[14] Martinoia, S. & Massobrio, G., A behavioral macromodel of the ISFET in SPICE. Sensors and Actuators B: Chemical, 62(3), pp. 182-189, 2000.

[15] Grattarola, M., Massobrio, G. & Martinoia, S., Modeling H+-sensitive FETs with SPICE. Electron Devices, IEEE Transactions on, 39(4), pp. 813-819, 1992.

[16] Dutta, J.C., Ion sensitive field effect transistor for applications in bioelectronic sensors: A research review, Computational Intelligence and Signal Processing (CISP), 2012 2nd National Conference on. IEEE, pp. 185-191, 2012.