SENSITIVITY ENHANCEMENT IN DOUBLE GATE FIELD EFFECT TRANSISTOR pH SENSOR

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Abstract: In this paper, we compare the pH sensitivity of a double gate pH sensor based on front-gate operation and the back-gate operation. Numerical and compact modeling illustrates a simple way to enhance the sensitivity of double-gate field effect transistor (DGFET) sensor. The simulation approach is presented to improve the pH sensitivity. Field effect devices are used for biomolecule detection and pH sensitivity. The model is derived from Poisson's equation in each region and it found the back gated operation of DGFET allows significant signal amplification compare with conventional ISFET. This simulation work concludes with finding the higher pH sensitivity of DGFET sensor.

Keywords: **pH sensitivity, DGFET, Biomolecule.**

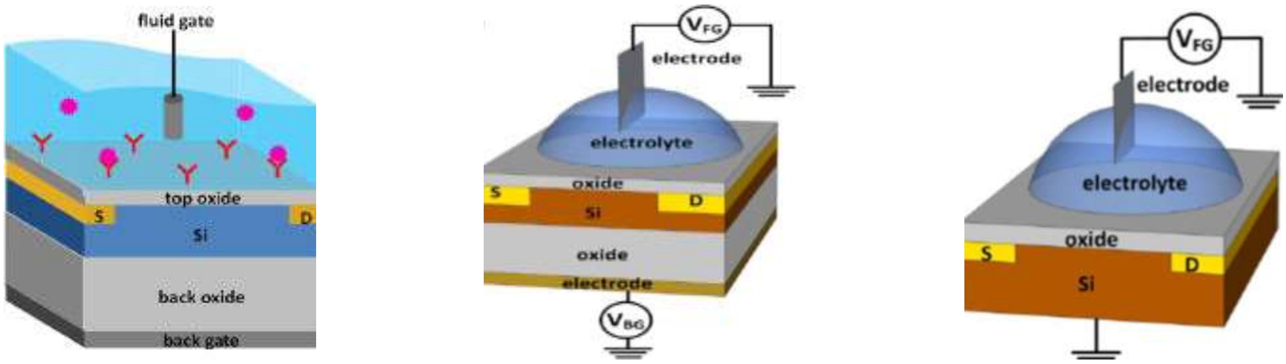
I. INTRODUCTION

Nanoscale FET devices such as nanowire(NW), nanoplate (NP) sensors promise ultrasensitive detection,ease of integration, and lower-cost fabrication and therefore, continue to attract significant research interest [1]. Field effect devices for biomolecule detection and pH sensing have been explored since the 1970's [2]. Most of the biomolecules are charged in solution and the charge being dependent on the pH. Therefore, when the analytes bind to the receptors. The field effect due to the charges bound close to the surface induces opposite charges within the semiconductor channel. which is detected as a change in current or conductance. In the constant current mode, the pH-sensitivity (S) of FET based sensor is defined as the change in gate voltage (ΔVG) necessary to restore the current following a change in pH (ΔpH). In principle, a single-gated pH sensors can achieve the maximum pH sensitivity defined by the Nernstian response of 59 mV/pH [3]. However, in practice semiconductor capacitance and electrolyte screening reduces the sensitivity considerably below the theoretical limit[4]. Recently, a number of groups have reported experimental observation of "super-Nernstian" amplification in a variety of systems, most notably in double gated field-effect transistors or DGFET [3]. The sensitivity of a single gated FET pH is limited by Nernst Limit (59 mV/dec at room temperature). Moreover this limit can be overcome by using a double gated FET. In DGFET pH sensor, one sweeps the metal gate (poly-silicon gate), instead of the fluid gate, to obtain the transistor characteristics ($I_{DS}-V_{MG}$). A fixed bias is applied to the fluid gate (VLG), and the pH sensitivity is measured in terms of the threshold voltage shift of the metal gate ($\Delta_{VT,MG}/\Delta pH$). To enable higher sensitivity, the metal gate capacitance (CMG) should be smaller than the fluid gate capacitance (CLG). The maximum sensitivity that can be achieved with metal gate operation is given by, $S=(\Delta_{VT,MG})/\Delta pH= (C_{LG}/C_{MG})((\Delta V_{T,LG})/\Delta pH)$, where $(\Delta V_{T,LG})/\Delta pH$ is the pH sensitivity (limited by Nernst Limit) with fluid gate operation and a constant metal gate voltage. This high sensitivity occurs when both the fluid gate channel and metal gate channel are inverted.

In this work, to improved pH resolution of DGFET sensor. The theoretical model is based on self consistent solutions of Drift-Diffusion and Poisson Boltzmann Equations [5]. The model combines the classical theory of the site binding model[6] and MOSFET [7] to investigate the effect of various parameters such as electrolyte concentration, oxide layer thickness, biasing configuration, pH of the solution etc. On the performance of nanoscale DGFET sensor.

II. DOUBLE GATE FET PH SENSOR.

DGFET is an improved version of ISFET. A simplified diagram of single and double- gate field effect transistor is shown in figure 1. The ISFET system generally consists of a nanoscale FET where the traditional metal/polysilicon gate is replaced by an electrolyte and a reference electrode immersed in it [1]. The reference electrode establishes a fixed electrostatic potential inside the solution [9]. The Si-body is grounded, and the drain (D) is biased slightly positive with respect to the source (S). Any change in pH is reflected in the S-to-D channel current. In DGFET system an additional gate is used at the bottom of the transistor (V_{BG}).The back gate is coupled to the channel through a thicker bottom oxide [5]. Fluid gate (FG) immersed in the electrolyte and the back gate (BG) control the current in Si body. Additional gate may allow flexible settings of optimum bias condition. With comparison of conventional FET biosensor activated by single gate, the advantage of double gate FET is that the symmetric/asymmetric biases can be applied to two gates, with precise and independent control on the conduction path.

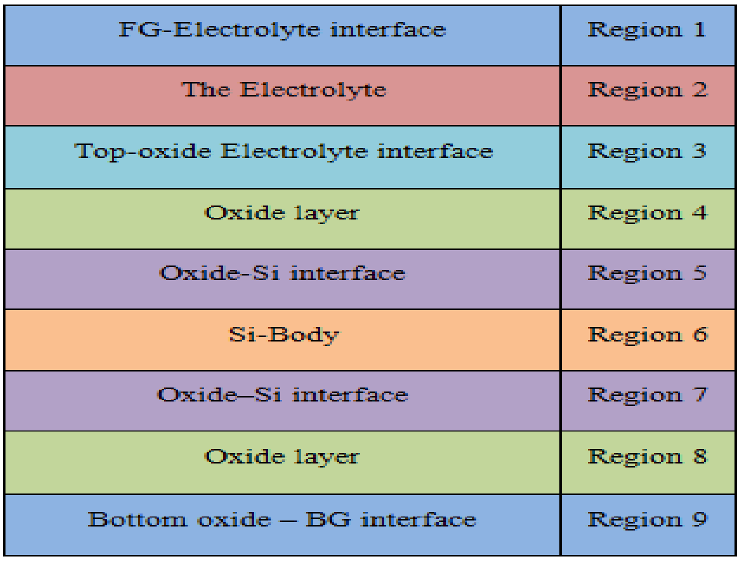


(a) (b) (c)

Figure 1:Device structures of (a) DGFET pH sensor (b) double-gate FET (DGFET) sensor (c) conventional ISFET sensor

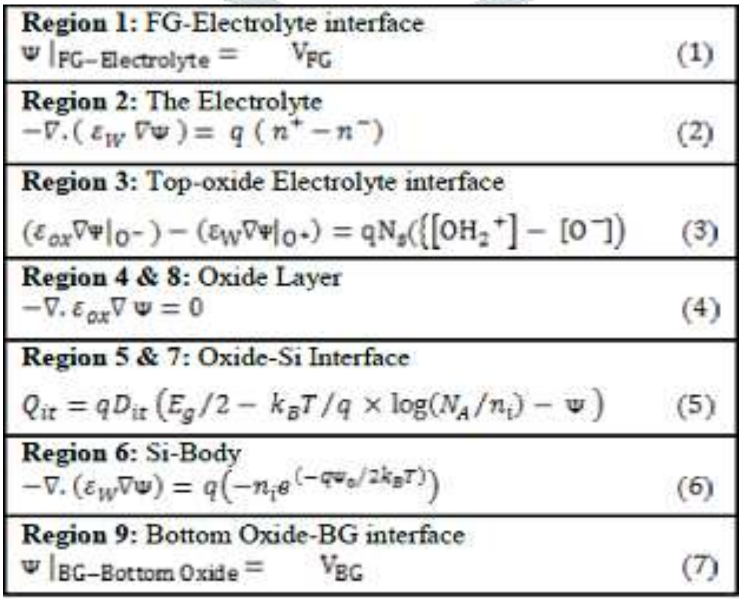
III. SYSTEM MODELING

Bio sensor lab is a tool to evaluate and predict the performance parameters of biosensors.In this work, this lab is used for the numerical solution of the compact model presented in figure 2. To determine the electrostatics of the system the entire DGFET system is divided into 9 regions (figure 2).



FG-Electrolyte interface	Region 1
The Electrolyte	Region 2
Top-oxide Electrolyte interface	Region 3
Oxide layer	Region 4
Oxide-Si interface	Region 5
Si-Body	Region 6
Oxide–Si interface	Region 7
Oxide layer	Region 8
Bottom oxide – BG interface	Region 9

Figure 2: Model structure of DGFET based pH sensor



Region 1: FG-Electrolyte interface $\psi\,|_{FG-Electrolyte} = \quad V_{FG}$	(1)
Region 2: The Electrolyte $-\nabla.(\varepsilon_W \nabla\psi) = q\,(n^{+} - n^{-})$	(2)
Region 3: Top-oxide Electrolyte interface $(\varepsilon_{ox}\nabla\Psi|_{O^-}) - (\varepsilon_W\nabla\Psi|_{O^+}) = qN_s(\{[OH_2{}^{+}] - [O^{-}])$	(3)
Region 4 & 8: Oxide Layer $-\nabla.\,\varepsilon_{ox}\nabla\,\psi = 0$	(4)
Region 5 & 7: Oxide-Si Interface $Q_{it} = qD_{it}\,(E_g/2 - k_BT/q \times \log(N_A/n_i) - \psi)$	(5)
Region 6: Si-Body $-\nabla.(\varepsilon_W\nabla\psi) = q\left(-n_i e^{(-q\psi_s/2k_BT)}\right)$	(6)
Region 9: Bottom Oxide-BG interface $\psi\,|_{BG-Bottom\,Oxide} = \quad V_{BG}$	(7)

Table 1: Model equations at each regions illustrated in figure 2.

The model equations for each region are presented on table 1. Assumption made in this model for FG-electrolyte interface and Bottom oxide-BG interface (Region-1 and 9) is that, the reference electrode is faradaic, that can exchange charge with electrolyte and the FG and BG have the same electrode work function [3]. The potential at the interfaces are given by equations 1 and 7. The electrolyte (Region -2) is assumed to be 1:1 such as NaCl, KCl [3]. The Poisson equation is used to calculate the overall potential within the electrolyte system given in equation 2 where the water permittivity, ε_w is 80 ε_0 (vacuum permittivity, ε_0 is8.854×10^{-14} F/cm^2), n^+ is the number of cations and n is the number of anions.

The distribution of cations and anions follows Boltzmann distribution [3] and are given by equation 8 and 9.

$$n^+ = n_0 \exp\left[\frac{-q(\varphi - V_{FG})}{k_B T}\right] \qquad (8)$$

$$n^- = n_0 \exp\left[\frac{q(\varphi - V_{FG})}{k_B T}\right] \qquad (9)$$

Where, the electrolyte strength n_0 is 100mm, Boltzmann constant kB is 1.38×10^{-23} Jk^{-1}and Temperature T in Kelvin is 300K.The Oxide permittivity (ε_{ox}) is $3.9\varepsilon_0$, Surface group density (Ns) is$5*10^{14}$cm^{-2} for SiO_2 and $8*10^{14}$cm^{-2} for Al_2O_3. Protonation constant (pk_a) is -2 for SiO_2 and 6 for Al_2O_3. Deprotonation constant (pk_b) is 6 for SiO_2 and 10 for Al_2O_3. Oxide Layer(Region 4, 8) can be made of Silicon dioxide (SiO_2) or Aluminum oxide (Al_2O_3). Generally Thickness of back oxidelayer is much thicker than that of top oxide layer [3]. The electrostatic potential for oxide layers can be calculated from equation 4. Thickness of top oxide layer (Tt_{ox}) is 4nm and of the back oxide layer (Tb_{ox}) is 150nm. The model equation for Oxide-Si interface (Region 6, 8) is found by solving 1-D Poisson – Boltzmann equation and is given byequation 5, where band gap of Si(E_g) is 1.1 eV, Si doping density(NA) is 10^{15} cm^{-3}, Si intrinsic carrier density (Ni) is 1.1×10^{10}cm^{-3}and interface trap density is 4.1×10^{11} cm^{-2} eV^{-1} . The DGFET sensor is long- channel device, with small drain to source voltage ($V_{ds} \approx 0.1$ V) [3]. Drift-diffusion formalism is usedfor charge transport inside the semiconductor channel [5]. Equation 6 gives the potential and carrier distributions inside theSi channel as function of V_{FG} and V_{BG} where the Si-body (Region7) is assumed to be undoped and Si permittivity ε_{si} is $11.9\varepsilon_0$.

IV. PH SENSITIVITY SIMULATION

The design of a nanoscale sensor greatly depends on the parameters related to the sensor application environment that seriously affect the sensor performance. Transfer characteristics of DGFET sensors, their pH sensitivity and effect of fluid-gate oxide layer and bottom oxide layer thickness on thesensor performance are analyzed.

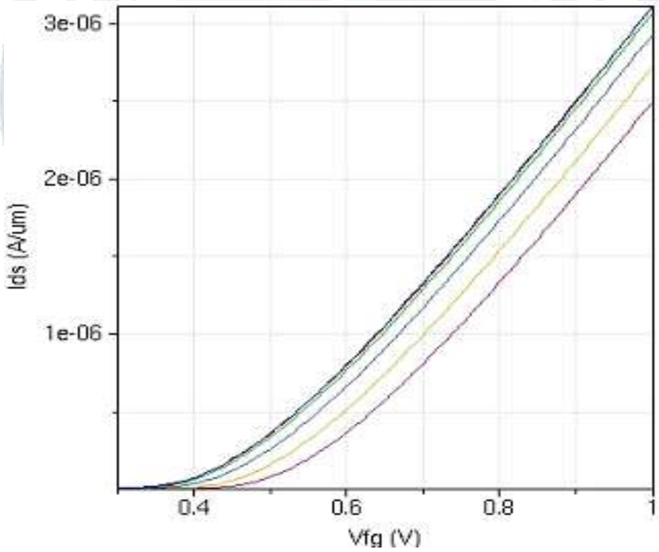


Figure 3: Transfer characteristics(Ids vs Vfg) in front gate operation

Figure 3 shows transfer characteristics of front gate DGFET biosensor for Fluid-Gate operation. Also it shows the transfer charactristics (Ids vs Vfg) of the device for 6 different pH values (pH= 2 to 7). The results are obtained by taking SiO_2 as both top and bottom gate oxide and for small drain to source voltage (Vd=0.1v). The bottom gate voltage for DGFET sensor is taken as fixed (VBG = 0V). It clearly indicates that DGFET have better transfer characteristics over ISFET. The slope of V_T vs pH determined from this values the pH sensitivity is obtained less than the Nernst Limit (59 mV/pH). This slope is called pH sensitivity of the device.

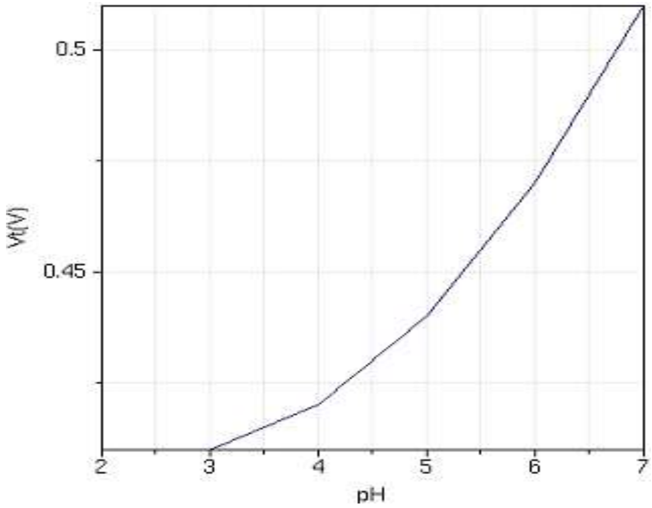


Figure 4: Threshold voltage as a function of pH in front gate operation

The figure 4 shows the pH sensitivity i.e. slope of V_T vs. pH curve is 30 mV/pH. Note the pH sensitivity is less than the Nernst Limit (59 mV/pH) at room temperature. This is the maximum achievable limit for front gate operation.

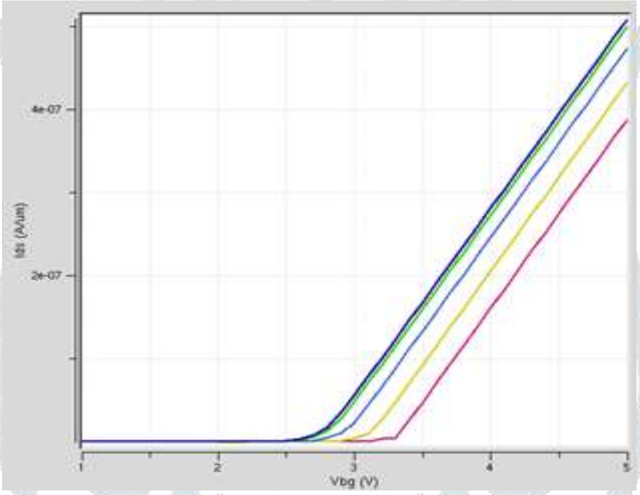


Figure 5:Transfer characteristics(Ids vs Vbg) in back gate operation

The figure 5 shows the back gate operation with Vfg=0, Vds=0.1, Vbg in range 1.0 to 5V .It gives results of the sensitivity larger than the Nernst Limit(59mV/pH).

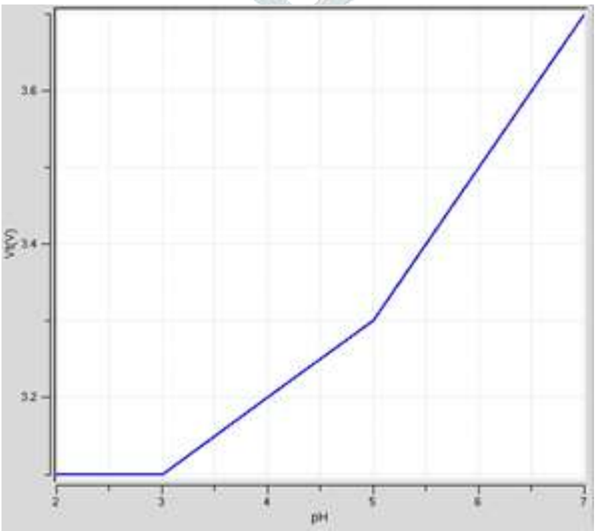


Figure 6: Threshold voltage with pH in back gate operation mode

The pH sensitivity is given by 170 mV/ pH. Note this limit is greater than Nernst limit. Since, the signal (at the fluid gate/top oxide interface) amplifies the noise does amplify as well.

V. CONCLUSION

In this paper, we are presented the structures, modeling and simulation methods of the DGFET biosensor for pH sensitivity. In this simulation used to found the Bottom-Gate operation of DGFET sensor gives higher pH sensitivity than the front gate operation. The bottom gate pH limit is greater than the Nernst limit. This simulation study concludes with remarkable finding. Double gate operation leads to amplification in signal/noise as well.

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