Analytical Modeling of Junction-Less Surrounding Gate MOSFET Based Biosensor

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Abstract: In this paper, an analytical model of threshold voltage of a junction less surrounding gate MOSFET (JLSRG MOSFET) transistor based biosensor for application in label-free detection of bio-molecules have been presented. Numerous reports exist on the experimental demonstration of nanogap-embedded FET-based bio-sensors, these devices are having low sensitivity. Now in order to increase the sensitivity of the biosensors the concept of a junction-less surrounding gate based biosensor is presented in this letter. The expression of threshold voltage and the surface potentials for different regions of the device have been calculated and Matlab code has been developed for simulation of the analytical model.
Keywords: surrounding gate MOSFET; surface potential; analytical model threshold voltage.

1 INTRODUCTION

Biosensor is basically an analytical device which is used to determine the presence of substances, their concentration and other parameters of biological interest. It basically consists of a bio-transducer which converts biological response into electrical output. The general objective is to provide rapid detection of bio molecules. Biosensors are becoming increasingly important for different applications. There are many potential applications of biosensors of various types. The main requirements for a biosensor approach to be valuable in terms of research and commercial applications are the identification of a target molecule, availability of a suitable biological recognition element, and the potential for disposable portable detection systems to be preferred to sensitive laboratory-based techniques in some situations. Glucose monitoring in diabetes patients.

- Environmental applications e.g. the detection of pesticides and river water contaminants such as heavy metal ions.
- Remote sensing of water quality in coastal waters by describing online different aspects of clam ethology (biological rhythms, growth rates, spawning or death records) in groups of abandoned bivalves around the world.
- Detection of pathogens.

A biosensor typically consists of a bio-recognition component, bio-transducer component, and electronic system which include a signal amplifier, processor, and display.

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The detection of bio molecules has become significantly important for medical, surgical, defence and environmental applications. Till now different versions of biosensor has been implemented such as optical [8], electrochemical [9], a nano-mechanic device [10], an ion-sensitive electrode [11], piezoelectric [12]. But these devices suffer from drawbacks like requirement of labelling process, requirement of expensive equipment, high manufacturing cost, lower sensitivity, etc. These problems have led to the emergence of biosensor based on semiconductor devices. The growth of semiconductor technology can facilitate low cost production minimizing fabrication cost. Also a simpler detection system can be implemented without the use of complicated transducer. Besides, it also aids advantages in terms of standardization, miniaturization and mass production**.**

Among various bio-sensing platforms, biosensors based on field effect transistors (FETs) have emerged as a significant candidate for detection a number of target analytes. FET biosensors have been demonstrated to be effective in recognizing biological species both of charged or polar nature. This utilises the event of varying the electrostatic interaction between gate dielectric and channel in presence of bio-molecules, which causes the modulation of effective conductance of the channel. These biosensors are seen to be an important candidate for implementing point of care testing (POCT) device. This is due to the fact that semiconducting devices have the potential to function as highly sensitive and efficient selective sensors which enables label-free detection pathogenic microorganisms.

The application of FET as a biosensor for label-free detection of charged bio-molecules has seen significant usage [1-3]. The use of the concept of dielectric modulation of a vertical nanogap in the FET's gate due to the presence of bio-molecules has enabled the application of FET biosensors for detecting the presence of charge-free bio-molecules as well [4-8]. The reported dielectric-modulated FET (DMFET) based biosensors show high responsiveness to both dielectric modulation and charge of the bio-molecules, with the two effects often affecting the device parameters in opposite directions leading to reduced sensitivity [8]. In addition, the DMFET shows a sharp dependence of the sensitivity of bio-molecule detection to the nanogap length and a significant fall in sensitivity for short channel lengths [8]**.**

Till now different versions of Dielectric Modulated Field Effect transistor (DMFET) based biosensors has been reported [6]-[8] in the literature. Ji-Min Choi et al. [9] reported analytical modelling of biosensor based on DMFET. Though the Dielectric-modulation based impact-ionization MOS (DIMOS) transistor for label-free bio-sensing application has been introduced by N. Kannan et al. [10], analytical modelling of this device structure has not been reported yet in literature. To obtain better sensitivity of the DIMOS, design parameters need to be optimized for which analytical modelling of the DIMOS based biosensor is indispensable. Capability of label free sensors is one of the most important features of the nanogap embedded biosensor is the. This property enables direct detection of macromolecules**.** Macromolecules are not needed to be priori attached to fluorescent, radioactive or other probe. Therefore the sensor can efficiently fulfil the desired functionality with unlabelled macromolecule. This is a very important aspect of biosensors as most of labelling processes are complex and also expensive. Successful biosensor demonstrations have been already reported for ions, bio-molecules, protein, DNA and viruses. The relative variation in conductance or other characteristics parameter after attachment of the target bio-molecule is defined as the sensitivity of a biosensor. Like in case of protein sensing, the relative change in current changes is used as sensing parameter.

Nanogap is basically a gap (<100 nm) between the gate metal and the oxide layer. In absence of the bio-molecules, air (K=1) fills the nanogap. Now in the presence of the bio-molecules, the region is filled with bio-molecules having different dielectric constant (K>1). Due to these higher values of dielectric constant, shift in threshold voltage (VT) occurs which can be used as a metric to detect the bio-molecules. As the change of V_{Th} occurs due to the modulation of dielectric constant owing to the presence of bio-molecules, it can be called as dielectric modulated device.

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2 DEVICE STRUCTURE

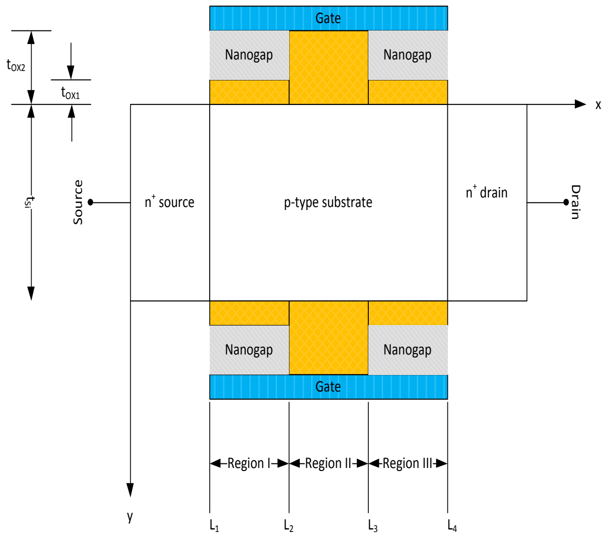

Fig. 1. Structure of proposed JLSRG MOSFET based biosensor.

Fig. 1.1 shows the device structure of the proposed SRG MOSFET based bio-sensor. The device is divided into three regions. Region I and region III are having a nanogap in between the gate and oxide layer. The thickness of the oxide layer in region II (t_{ox2}) = 23 nm. In region I and III the thickness of the oxide layer (t_{ox1}) = 2.9 nm.Thickness of silicon (t_{Si}) =100 nm, total channel length (L_g)= 200 nm. Si channel doping concentration $N_D= 10^{18}$ /cm^3 work function of silicon is taken as 5.5 eV and the work function of gate material is 4.68 eV.

3 ANALYTICAL MODELING OF CHANNEL CENTER POTENTIAL AND THRESHOLD VOLTAGE

3.1 Modeling of Channel-center Potential:

The 2-D Poisson's equation in cylindrical coordinate system for p channel JLSRG MOSFET can be written as

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\Psi(r,z)\right)+\frac{\partial^2\Psi}{\partial z^2}=\frac{-qN_d}{\varepsilon_{Si}} \quad (1)$$

where the variable r is the radius of the cylindrical Si channel measured from the centre of the channel towards oxide–silicon interface, Ψ(r,z) is the 2-D potential distribution in the channel, N_D is the uniform doping concentration of the cylindrical Si channel, ε_{Si} is the relative permittivity of silicon, q is the unit electron charge (1.6×10^{-19}coulomb) and z is the distance along the channel (axial direction) with reference to the source.

The potential profile in the axial direction, i.e., the z-dependence of Ψ(r,z) can be approximated as a simple parabolic function as proposed by Young et al. [13].

$$\Psi(r,z)=C_1(z)+C_2(z)r+C_3(z)r^2 \quad (2)$$

Where $C_1(z)$, $C_2(z)$ and $C_3(z)$ are the arbitrary coefficients.

Applying different boundary conditions we can find the value of the arbitrary coefficients. For different region the value of channel center potential is derived as

Region I: $\Psi_{C1}(z)=a_1e^{\frac{z}{\lambda}}+b_1e^{-\frac{z}{\lambda}}+\varphi_{C1}$

$$(z_1=0)\le z\le(z_2=L_1) \quad (3)$$

Region II: $\Psi_{C2}(z)=a_2e^{\frac{z}{\lambda}}+b_2e^{-\frac{z}{\lambda}}+\varphi_{C2}$

$$(z_2=L_1)\le z\le(z_3=L_1+L_2) \quad (4)$$

Region III: $\Psi_{C3}(z)=a_3e^{\frac{z}{\lambda}}+b_3e^{-\frac{z}{\lambda}}+\varphi_{C3}$

$$(z_3=L_1+L_2)\le z\le(z_4=L_1+L_2+L_3) \quad (5)$$

It is worth mentioning that in order to simplify the modelling, the length of the drain and the source regions is assumed to be zero such that the source/drain contact is placed at the left/right edge of the uniformly doped Si channel.

3.2 Modeling of Threshold Voltage

In a conventional MOSFET (with junctions) the Threshold Voltage V_{Th} is defined as the minimum gate voltage for which the minimum surface potential is twice the bulk potential to induce a conducting channel at the surface of the MOSFET. Now to determine the value of the threshold voltage the location of the minimum-channel central potential needs to be determined. We have found that the minimum value of channel centre potential is lying in the region II.

4 RESULTS AND DISCUSSIONS

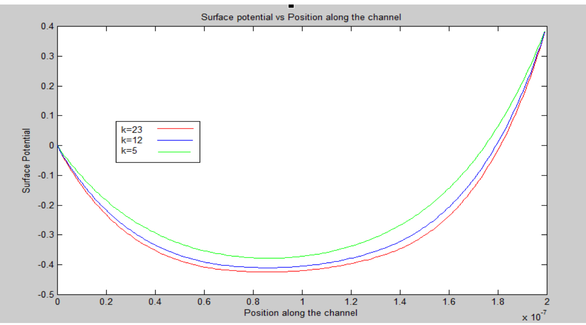

Fig. 2. Variation of Surface Potential along the Channel for Different Value Permittivity of the Oxide (For K= 12, 23, 5).

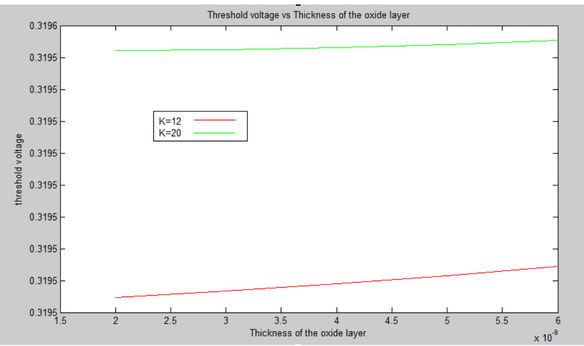

Fig. 3. Variation in threshold voltage with thickness of the oxide layer for different permittivity of the oxide (K=12, 20).

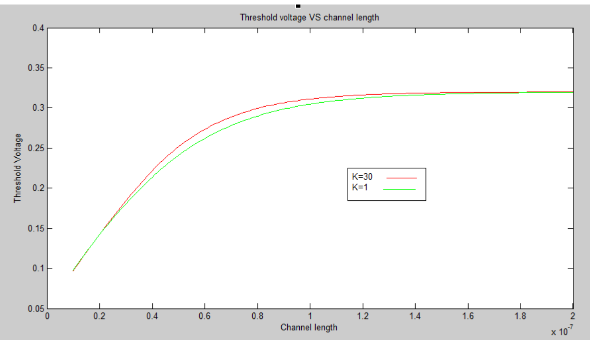

Fig. 4. Variation in threshold voltage with the variation in channel length for different permittivity of the oxide (K=1, 30).

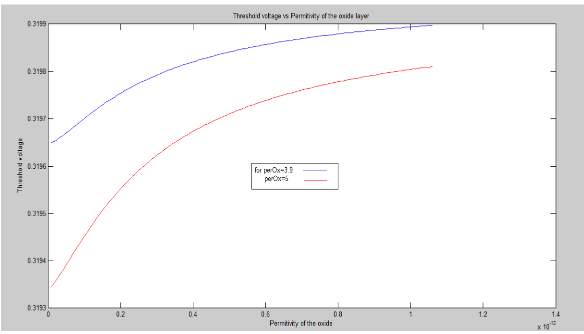

Fig. 5. Variation in threshold voltage with the variation with different value permittivity of oxide.

So by finding $\left.\frac{d\Psi_{C2}(z)}{dz}\right|_{z=z_{min}} = 0$

We get the value of $z_{min} = \frac{\lambda_2}{2}\ln\left(\frac{b_2}{a_2}\right)$

Substituting V_{GS}=V_{Th} in $\Psi_{C2,min}$ =0 and solving for $V_{Th,}$ the threshold voltage can be expressed as

$$V_{Th} = V_{fb} + \frac{h_2 \pm \sqrt{h_2^{\,2} - 4h_1h_3}}{2h_2} \tag{6}$$

5 CONCLUSION

In this paper an analytical model of surrounding gate MOSFET based bio-sensor has been proposed. By developing the MATLAB code for the surface potential and threshold voltage the variation of the surface potential and the threshold voltage with respect to different parameter have been shown.

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