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Sensitivity analysis of nanowire biosensor in the partially depleted and fully depleted mode of subthreshold region

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ABSTRACT

Subthreshold region provides optimal sensitivity for nanowire biosensor. In this paper, sensitivity analysis of nanowire biosensor operating in partially depleted and fully depleted mode of subthreshold region is presented. The analysis is based on analytical radial electrostatic potential functions derived by solving Poisson's equation inside the nanowire for both types of depleted mode of the subthreshold region with available boundary conditions. Characteristics of the plotted conductance and sensitivity curves of the sensor operating in partially and fully depleted mode of subthreshold region show the specificness of these modes of operation on particular types of bio-chemical sensing experiment.

1. Introduction

Nanowire transistors are being successfully used in bio-chemical sensing applications for many years. It has been proved effective as a sensing device in a variety of applications such as sensitive detection of viruses [1], ultra-sensitive detection of a bacterial toxin [2], pH sensing [3], DNA sensing [4], label-free detection of protein molecules [5] and sensing of many other biological and chemical species. Due to the promising features of nanowire as a bio-sensing device, a number of studies have been performed on the analysis of its sensitivity. The size dependence of nanowire sensor for biomolecule detection has been analysed experimentally [6]. Semi-classical modelling of nanowire conductance change due to the capture of bio-molecules on its surface considers the effects of surrounding fluidic environment and electrolyte concentration along with the sensor's device parameters [7]. Analytical model of conductance based on global charge neutrality condition shows the optimization procedure of nanowire performance by tuning doping concentration and different structural parameters [8]. Numerical study on the operation of Si nanowire biosensor based on different physical models describes the key factors and their contribution on the sensitivity, linearity and stability of these sensors [9]. Biasing a nanowire FET in different regions of a device, it has been found that subthreshold region is the optimum one for the sensing purposes [10].

In this paper, we focus on the sensitivity analysis of a nanowire sensor in subthreshold region. We divide the whole subthreshold region into two parts according to the depleted volume of the nanowire due to the applied gate voltage. Our work addresses the difference in nanowire sensor's performance due to this fully depleted and partially depleted condition while operating in the subthreshold regime. We propose a new analytical method for finding radial electrostatic potential of a silicon-nanowire in the whole subthreshold region. Electrostatic potential, conductance and sensitivity for both the partially depleted and fully depleted nanowires in the subthreshold region have been analysed back to back to investigate the significance of these two conditions of the device on different sensing experiments.

2. Electrostatic potential model

The model suggested here for the radial electrostatic potential of a Silicon (Si) nanowire considers a cylindrical gate all around (GAA) structure with a *P* type doping in its body. We consider the conventional definition of the subthreshold region which says that it exists in a device in its depletion region until the device becomes inverted strongly [11]. The gate voltage ranges from the flat band to the threshold level to keep a semiconductor device in the subthreshold region [12].In the subthreshold region, the inner volume of a nanowire remains partially depleted up to a certain voltage level which causes its depletion width to reach the centre of the device. With the further increase in the gate voltage, the device becomes fully depleted and starts to gather inversion charges. Our proposed model separately calculates the radial electrostatic potential of the nanowire for the two depleted conditions

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defined above. This potential calculation requires Poisson's equation to be solved in cylindrical coordinates due to our device consideration. Poisson's equation considers just the fixed charges of doping atom for the both parts of the subthreshold region. This consideration is valid for the whole subthreshold region because in the partially depleted condition the device is not inverted yet and in the fully depleted condition, inversion charges though present but still can be safely neglected for a particular range of doping concentration [13].

2.1. Partially depleted mode

In partially depleted mode, a part of the nanowire inner volume proportional to its depletion width from the surface is occupied with fixed dopant charges. There is no inversion charge in this mode. The nanowire device studied here has a radius of R unit and its undepleted volume has a radius of $R_{\mathrm{d.}}$ unit from its centre. The remaining part of the volume is defined as the depletion region. The electrostatic potential inside the nanowire can be found by solving Poisson's equation in a cylindrical coordinate for the defined geometry.

Poisson's equation in the cylindrical coordinate can be written as

$$\frac{1}{r}\left(\frac{d}{dr}\left(r\frac{d\phi}{dr}\right)\right)=\frac{qN_a}{\varepsilon_{si}};R_d<r\le R \quad (1)$$

[13]

Where

ϕ radial electrostatic potential

r radial distance from centre of the device

N_a doping concentration

ε_{si} permittivity of the silicon.

Integrating Eq. (1) after multiplying by r we get,

$$r\frac{d\phi}{dr}=\frac{qN_a r^2}{2\varepsilon_{si}}+C_1. \quad (2)$$

C_1 is an integrating constant.

Integrating Eq. (2), we get,

$$\phi=\frac{qN_a r^2}{4\varepsilon_{si}}+C_1\ \ln r+C_2. \quad (3)$$

C_2 is another integrating constant. C_1 and C_2 can be evaluated from the available boundary conditions we have.

From Fig. 1, the space between $r=0$ to $r=R_{\mathrm{d.}}$ is free of charges and as a result free of any electric field. Since the nanowire body is unmodulated by the gating effect in this region, according to our considered potential reference described in Fig. 2, the absolute potential of that region can also be considered as zero. The intrinsic Fermi level of the unmodulated body of the nanowire which is $K_T\ \ln\left(\frac{N_a}{n_i}\right)$ unit below the Fermi level has been considered as the reference for all of the device potential in this work.

The electric field, $\frac{d\phi}{dr}|_{r=Rd}=0$ yields $C_1=\frac{-qN_aR_d{}^2}{2\varepsilon_{si}}$ from Eq. (1) and $\phi|_{r=R_d}=0$ yields $C_2=\frac{qN_aR_d{}^2}{4\varepsilon_{si}}(2\ \ln(R_d)-1)$ from Eq. (2). Now we are only left with the value of unknown $R_{\mathrm{d.}}$ to find the electrostatic radial potential in the partially depleted part of the sub-threshold region inside the nanowire. Combining electric flux continuity and the Gauss Law at the silicon–oxide interface, we get another boundary condition that relates surface potential, $\varnothing_s$ and gate-source voltage, v_{gs} to the total charge inside the nanowire [14].

$$C_{ox}(V_{gs}-\phi_{ms}-\phi_s)=\frac{qN_a\pi\left(R^2-R_d{}^2\right)L}{2\pi\mathrm{RL}} \quad (4)$$

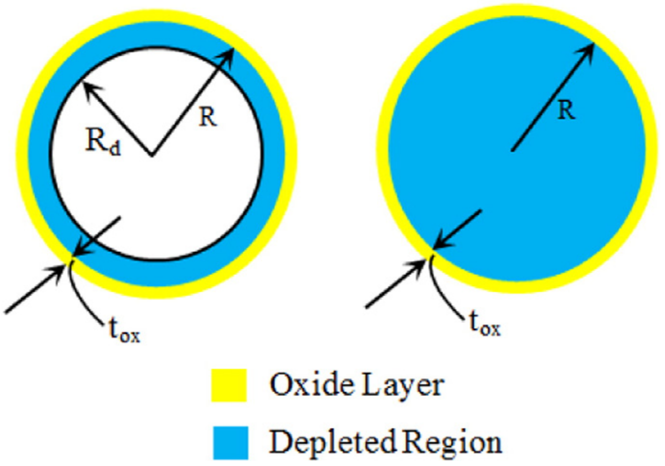

Fig. 1. Cross section for the partially depleted and fully depleted nanowire.

Here, $C_{ox}=\frac{\varepsilon_{ox}}{(R\ \ln(1+\frac{t_{ox}}{R}))}$ is the gate oxide capacitance [15],ε_{ox} is the permittivity of the oxide, t_{ox} is the oxide thickness, and $\varnothing_{ms}$ is the metal semiconductor work function difference.

Putting $r=R$ in Eq. (3) we get,

$$\phi_s=\phi\Big|_{r=R}=\frac{qN_aR^2}{4\varepsilon_{si}}+C_1\ \ln R+C_2 \quad (5)$$

By combining Eqs. (4) and (5) we get the following equation, the solution of which gives the value of $R_{d.}$

$$\frac{qN_a}{4\varepsilon_{si}}\left(R^2-R_d{}^2\right)+\frac{qN_aR_d{}^2}{2\varepsilon_{si}}\ \ln\left(\frac{R_d}{R}\right)=V_{gs}-\phi_{ms}-\frac{qN_aR}{2C_{ox}}+\frac{qN_aR_d{}^2}{2RC_{ox}}. \quad (6)$$

All of the analysis performed in our work considers a nanowire device of radius 10 nm, length 300 nm and gold (Au) as the gate electrode. In Fig. 3(a) and (b), electrostatic potential for a partially depleted nanowire for different gate voltages has been shown for two doping concentrations Na = 1 × 10^{24} $\mathrm{m}^{-3}$and Na = 1 × 10^{25} m^{-3}respectively. The partial depletion mode of a nanowire within the subthreshold region starts with the flat band gate voltage and ends with the gate voltage for which the depletion width reaches the centre of the device.

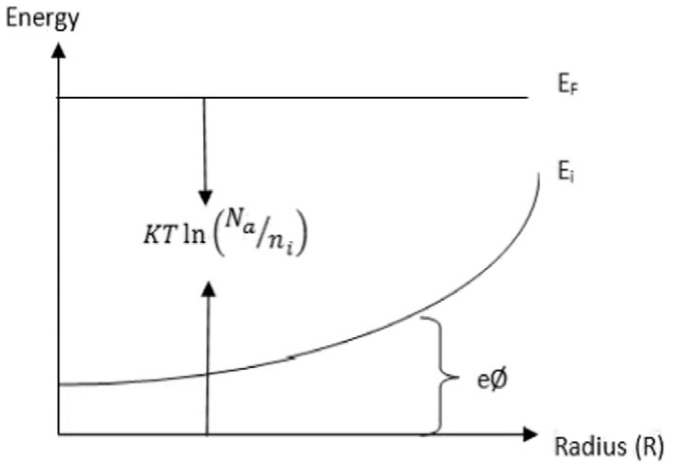

Fig. 2. Energy band diagram and electrostatic potential reference. The intrinsic Fermi level of the bulk nanowire body is considered as the radial electrostatic potential reference. All potentials are considered as the deviation of the intrinsic Fermi level from that of the unmodulated bulk nanowire.