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Analytical modeling of split-gate junction-less transistor for a biosensor application

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ABSTRACT

This paper represents the analytical modeling of split-gate Dielectric Modulated Junction Less Transistor (JLT) for label free electrical detection of bio molecules. Some part of the channel region is opened for providing the binding sites for the bio molecules unlike conventional MOSFET which is enclosed with the gate electrode. Due to this open area, the surface potential of this region affected by the charged and neutral bio molecules immobilized to the open region of channel. Surface potential of the channel region obtained by solving two-Dimensional Poisson's equation by potential profile having parabolic nature through channel region using technique called conformal mapping. By deriving the surface potential model, derivation of threshold model can also be done. For the detection of bio molecule, variation in to the threshold voltage due to binding of bio molecule in the gate underlap region is the sensing metric.

1. Introduction

Scaling down the conventional MOSFET dimension to the nano level continuously giving rise to the Short Channel effects (SCEs) and it influence the performance of the device which cannot be ignored. To reduce the impact of SCEs, many nano devises are introduced like Double gate MOSFET, Fin-FET, Si nanowire, CNTFET, Gate All Around, TFET, Junctionless Transistor etc. These devices can suppress the effect SCEs on the characteristic and also increases the gate controllability over the channel. It is also very difficult to create ultra sharp doping profile between source/drain (S/D) regions with body region at nanoscale level. Several novel MOSFETs design has been developed to defeat the fabrication issue. Colinge et al. [1,2,3], reported Junction less Transistor, this transistor is having lower Drain Induced Barrier Lowering(DIBL) and enhanced on-state and transfer characteristics than that of the usual MOSFETs [4,5,6,7,21,22]. In the recent work, the focus is on the sensor application of Junction less transistor for label free electrical detection of biomolecule. The detection is done by assuming the dry environment. Split-gate devices are also reported in literature [27–29]. Split-gate means in the device the middle part of the gate oxide etched away to form a cavity in between the gate oxides of either sides. This cavity i.e. a gate underlap region is utilizes as the sensing site for the biomolecules. When the bio-molecules are binded with the sensing area i.e. cavity region the characteristics of the transistor get shifted in comparison to the characteristics get in the absence of the biomolecule in the cavity [13,15–19].

In this paper focus is on derivation of an analytical model for split-gate dielectric modulated Junction less transistor that is utilized as a bio-sensor for the label free electrical recognition of biomolecules like cell, enzyme, DNA, protein etc. Etching of gate electrode is done from middle region of channel of DG-JL-MOSFET. The interaction of biomolecule is occurring in the cavity area. The biomolecules either charged or neutral are bind with the gate underlap region, due to which the deviation in the electrical characteristic i.e. drain current, threshold voltage(V_{th}) and surface potential occurs [20,23,24]. For detection of bio molecule, variation in the threshold voltage because of binding of bio molecule in the gate under lap region is the sensing metric [25,26]. Analytical modeling of the split-gate dielectric modulated JLT is done at MATLAB Tool (Table 1).

2. Device architecture used in simulation

2.1. Parameters of split-gate dielectric modulated Junctionless transistor

L_g is defined as the length of the region which is enclosed by gate electrode, L_{cavity} is defined as length gate underlap (cavity) region. t_{cavity}, t_{ox}, tsi are defined as thickness of region where cavity is created which is gate underlap, gate and channel oxide respectively. t_{ox1} is the thickness of SiO_2 layer, the value is 1 nm only. It is used to prevent the further oxidation in the open cavity region. When Si substrate is

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Table 1
Parameters of the device.

S. No.	Parameter	Values
1	Channel length	225 nm
2	HfO_2 thickness	10 nm
3	SiO_2 thickness	1 nm
4	Si thickness	10 nm
5	Doping	$10^{25}/m^3$
6	Length of HfO_2	25 nm

uncovered towards air ambient [8] the SiO_2 layer work as the adhesive layer for binding of biomolecules. The gate underlap region acts as the sensing location, in that location the neutral and charged bio-molecules are binded.

This structure is designed by utilizing process simulation tool i.e. "ATLAS" of Silvaco. The characteristic of simulation affected with neutral biomolecules consisting of different dielectric constant i.e. K > 1. As reported in literature APTES = 3.57 [11]), biotin = 2.63 [10], protein = 2.50 and streptavidin = 2.1 [9].For charged biomolecule, the simulation is done by assuming the fixed positive or negative charge ($N_f = +5 * 10^{15}/m^2$) in the cavity region at the boundary of SiO_2 and gate underlap region.

3. Two dimensional potential model

The proposed device structure given in Fig. 1 will be considered for model development. In device the whole channel region is separated into three regions. Region-1 & region-3 are gate overlap region and region-2 is named as gate underlap region i.e. cavity. The lateral axis explanation of all 3 regions are; region-1 ($0 < y < L_g$), region 2 ($L_g < y < L_g + L_{cavity}$), region-3 ($L_g + L_{cavity} < y < 2L_g + L_{cavity}$). The 2-Dimensional Poisson's equation for channel region of the above device can be written as

$$\frac{d^2\varphi_i(x,y)}{dx^2} + \frac{d^2\varphi_i(x,y)}{dy^2} = \frac{-qN_d}{\epsilon_{Si}} \tag{1}$$

where $i = 1, 2, 3$ for all the three regions. N_d is the channel doping concentration of and ϵ_{Si} is defined as the *Si* permittivity. Quantum effect does not consider in order simplifying the analysis of surface potential. Potential distribution of all 3 regions can be written as

$$\varphi_i(x,y) = C_{0i}(y) + C_{1i}(y)x + C_{2i}(y)x^2 \tag{2}$$

As the region-1 and region-3 have same effective gate oxide capacitance and the flat band voltages of both the regions are same as both the regions are symmetric and can be written as:

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} \tag{3}$$

$$V_{fb1} = V_{fb3} = \varphi_m - \chi_{Si} - \frac{E_g}{2} - \varphi_f \tag{4}$$

where ϵ_{ox} is the gate oxide permittivity i.e. HfO_2, t_{ox} is the thickness of the gate oxide, ϕ_m is the gate metal work function, χ_{si} is defined as electron affinity, E_g is the energy band gap of the Si. φ_f is the Fermi potential of the intrinsic semiconductor which can be represented as:

$$\varphi_f = \frac{KT}{q}\ln\left(\frac{N_d}{n_i}\right)$$

3.1. Surface potential for region 1

Below boundary conditions must be satisfied in the region 1 to make sure the continuity of the surface potential and electric field displacements at the interface of region-1 and region-2

$$\varphi_1(0,y) = \varphi_{fs1}(y)$$
$$\varphi_1(t_{Si},y) = \varphi_{bs1}(y)$$
$$\left.\frac{\partial\varphi_1(x,y)}{\partial x}\right|_{x=0} = \frac{\epsilon_{ox}}{\epsilon_{Si}}\left[\frac{\varphi_{fs1}(y) - (V_{gs} - V_{fb1})}{t_{ox}}\right]$$
$$\left.\frac{\partial\varphi_1(x,y)}{\partial x}\right|_{x=t_{Si}} = \frac{-\epsilon_{ox}}{\epsilon_{Si}}\left[\frac{\varphi_{bs1}(y) - (V_{gs} - V_{fb1})}{t_{ox}}\right]$$

where $\varphi_{fs1}(y)$ defines surface potential of front-gate x and $\varphi_{bs1}(y)$ is the surface potential back gate.

By applying the above mentioned boundary conditions into the Eq. (2), coefficients must be expressed as a function of surface potential of the front-gate i.e. $\varphi_{fs1}(y)$

$$C_{01} = \varphi_{fs1}(y) \tag{5a}$$

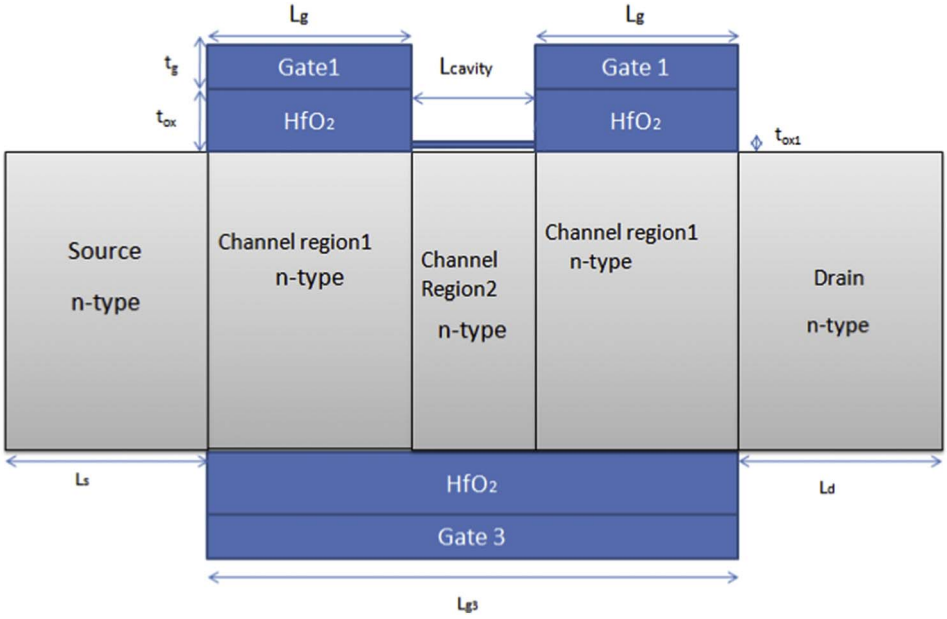

Fig. 1. Schematic of split-gate DM-Junctionless transistor with binding biomolecules in the cavity region.