Sensing and Bio-Sensing Research 13 (2017) 49–54

Contents lists available at ScienceDirect

Sensing and Bio-Sensing Research

journal homepage: www.elsevier.com/locate/sbsr

Effect of biomolecule position and fill in factor on sensitivity of a Dielectric Modulated Double Gate Junctionless MOSFET biosensor

Ehsanur Rahman *, Abir Shadman, Quazi D.M. Khosru

Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh

ARTICLE INFO

Article history:
Received 11 November 2016
Received in revised form 7 February 2017
Accepted 10 February 2017

Keywords:
Junctionless FET
Nanobiosensor
Biomolecule
Double Gate
Sensitivity

ABSTRACT

In this work, the performance of Junctionless Double Gate MOSFET for the label-free electrical detection of biomolecules like enzyme, cell, DNA, etc. has been investigated with the help of an analytical model. The impact of neutral biomolecules on the electrical characteristics of n-type Si Junctionless Double Gate MOSFET has been analyzed under dry environment situation. The change in the threshold voltage has been used as the sensing metric to detect the sensitivity of the mentioned device architecture for biomolecule detection. Biomolecule position and their fill in factor of the sensing site have been investigated to find out their effect on sensitivity. Moreover, the effect of drain bias on sensitivity has been found to be a crucial factor for the optimization of biosensor's detection capability.

1. Introduction

Currently available technology for detecting tumor markers, antigen-antibody complexes, and pathogens is complex, time-consuming and expensive [1,2]. FET-based biosensors have emerged as a potential candidate in the label-free detection of biomolecules like cancer biomarkers, Protein, DNA and other pathogens in a cost efficient and reliable way, an alternative to optical detection technique. The first concept of electronic pH sensing with ion-sensitive field effect transistors (ISFETs) was suggested by Bergveld [3]. The pH sensitivity (mV/pH) of a conventional single-gated ISFET is defined by the changes of threshold voltage (V_T) at a given amount of pH changes. However, such sensitivity is limited to Nernst limit of 59 mV/pH. To overcome the Nernst limit of sensitivity in single-gated ISFET, recent literature [4–7] has suggested double-gated field effect transistors. A modified version of ISFETs has also been used to detect biomolecules like DNA, Protein, and biomarkers indicative of various diseases. However, there are several problems in detecting biomolecule reliably using ISFET. First of all, the electrical signals from the ISFET biosensor depend on the ionic concentration of the sample solution [8] which is characterized by Debye length. Second, various ionic levels of the sample can significantly change the electrical signal of ISFET biosensors [9]. Third, controlling the ionic concentration accurately of any real human sample, such as blood serum, urine or saliva is difficult [10]. Moreover, the conductance modulation in the FET sensor is caused by the interaction potential and this potential might get partially screened by the high ionic strength of the buffer solution. This screening directly depends on the Debye–Hückel length [10]. Therefore, Debye-screening-free sensors working under the dry environment can provide several advantages over electrolyte-based biosensors. In the present work, Junctionless Double Gate (JL-DG) MOSFET under dry environment condition [11] has been investigated for its application as a biosensor for the label-free electrical detection of the biomolecules. Fabrication feasibility of Nanowire Junctionless MOSFET (JL-MOSFETs) has been already demonstrated by Colinge et al. [12,13]. Immunity to many Short Channel Effects (SCEs) like DIBL, improved on state and transfer characteristics have made JL-MOSFETS more advantageous over their conventional counterparts like junction based FETs [14,15]. Therefore, JL-DG MOSFET with cavity regions functionalized for detecting biomolecule in a dry environment can be a viable solution to the problems associated with biomolecule sensing under aqueous electrolyte condition. In dielectric modulated field-effect transistor (DM-FET), the insulator layer is etched to create a nanogap region underneath the gate material. DM-FET is capable of detecting even neutral biomolecules, which is not possible with conventional ISFET based biosensor. DM-FET based sensor also shows excellent compatibility with standard CMOS process [16–18]. In our work, we have extended the model widely used in the literature [11, 19–23] to incorporate the effect of the position of the biomolecule and their percentage coverage in the sensing site on sensor's performance. The analytical equations governing the electrostatic potential and current in different regions of the biosensor used in this work are briefly described in the following section. Despite the analytical model available in the recent literature, this work is unique in a sense that there has been no report regarding the effect of biomolecules position and percentage coverage of the cavity on the performance of such biosensor

* Corresponding author.
E-mail address: Ehsaneee@eee.buet.ac.bd (E. Rahman).

http://dx.doi.org/10.1016/j.sbsr.2017.02.002

in a dry environment according to the authors' best knowledge. Moreover, the findings of this work have an immediate practical impact due to two reasons. First of all, it has been demonstrated experimentally that even under the precisely controlled experiments, the complete fill-in is hard to achieve [24]. Secondly, in a practical situation, the capture of biomolecules can be asymmetric, random and quite complex due to low binding probability in a carved nanogap [25]. Hence, along with the fill-in factor, the possible location of biomolecule binding site within the nanogap (cavity) can differ, therefore, should be analyzed. Therefore, the study of the biosensor with partially filled and randomly distributed biomolecule can provide valuable insight to the dependence of sensitivity on biomolecule's position and percentage fill in of nanogap cavity region. Though modeling schemes focused on biosensing using DM-FET are available in the literature, such modeling does not incorporate the practical consideration of randomly distributed biomolecule in sensing sites. In real life application, bio-molecules can be located at any position in the cavity. In this work, we investigate this unexplored field of potentiometric biosensing in a dry environment with a view to understand and explain the effect of the partially filled cavity on biosensor's performance and their implication in practical application. To model the real life situation, we have created three different cavities in gate oxide region as shown in Fig. 1(a). We have considered different cases like-

i). Cavity regions on both sides of the gate oxide are filled with bio-molecule.
ii). Any two of the cavities are filled with bio-molecule, the other one is empty (filled with air)
iii). Any one of the cavities is filled, other two are empty.

Though the results presented in this study is a small subset of the real life situation, our extended analytical model developed in this work can take into account of any distribution profile of the biomolecules simply by changing the length and dielectric permittivity of different cavity regions.

2. Device structure

The device architecture for n-type Si Junctionless Dielectric Modulated Double Gate MOSFET (JL-DM-DG-MOSFET) based biosensors used in this work is depicted in Fig. 1(a). Here, L_1, L_3, and L_4 are the lengths of the nanogap cavity; L_2 is the length of the gate oxide SiO_2. T_{bio}, T_{ch}, T_{ox} are the thickness of the nanogap cavity, channel and gate oxide respectively. For first structure, the typical values of different parameters used here are $T_{bio}/T_{ox} = 9$ nm (plus 1 nm Native SiO_2), $T_{ch} = 10$ nm, $L_1 = 10$ nm, $L_2 = 30$ nm, $L_3 = L_4 = 5$ nm. Nanogap surfaces are properly functionalized for the immobilization of biomolecules. As a result, sensing sites are formed in nanogap cavity regions that can detect the target biomolecules. The surface potential from extended analytical modeling of this study was verified with reasonable accuracy as shown in Fig. 1(b) by comparing it with simulation results from 'Silvaco Atlas', which is commonly used to characterize the electrical properties of the semiconductor devices [26]. Various biomolecules have different dielectric constant (for e.g. streptavidin = 2.1 [27], protein = 2.50, biotin = 2.63 [28], and APTES = 3.57 [29]) [30]. So, the presence of the neutral biomolecules in the nanogap cavity can be simulated by introducing material having dielectric constant ($\epsilon_{bio} > 1$) corresponding to biomolecules in the nanogap cavities (assuming that the cavities are completely or partially filled with biomolecules). Before biomolecule immobilization, the nanogap cavity is filled with surrounding air (dielectric constant, $\epsilon_{air} = 1$). The presence of biomolecules in the nanogap cavity region can be simulated by defining an oxide layer with height of $T_{bio} = 9$ nm and varying its dielectric constant $\epsilon_{bio} = 2, 3, 4, 5, 7$. The height/thickness of the layer is chosen to resemble the practical height of the biomolecules [27,29].

3. Analytical model development

To obtain an analytical expression for potential distribution and drain current, the channel is divided into four regions as follows:

$$\text{Region I} : 0 \le x \le t_{si}, 0 \le y \le L_1 \tag{1}$$

$$\text{Region II} : 0 \le x \le t_{si}, L_1 \le y \le L_1 + L_2 \tag{2}$$

$$\text{Region III} : 0 \le x \le t_{si}, L_1 + L_2 \le y \le L_1 + L_2 + L_3 \tag{3}$$

$$\text{Region IV} : 0 \le x \le t_{si}, L_1 + L_2 + L_3 \le y \le L_1 + L_2 + L_3 + L_4 \tag{4}$$

Potential distribution is obtained by solving the Poisson's equation separately in each region as follows:

$$\frac{\partial^2 \phi_i(x,y)}{\partial x^2} + \frac{\partial^2 \phi_i(x,y)}{\partial y^2} = -\frac{qN_d}{\varepsilon_{si}} \tag{5}$$

where $i = 1, 2, 3, 4$ for region 1, 2, 3 and 4, respectively. $\phi_i(x,y)$ is the *2-D* potential distribution in the silicon channel, N_d is the doping in the silicon channel, q is the electron charge, t_{si} is the channel thickness and ε_{si} is the dielectric permittivity of silicon. Using parabolic approximation and relevant boundary conditions, we can convert the differential Eq. (5) to the form

$$\frac{\delta \phi_{mi}(y)}{\delta y^2} - \frac{\varphi_{mi}(y) - V_{gs} + V_{fbi}}{\eta_i^2} = -\frac{qN_d}{\varepsilon_{si}} \tag{6}$$

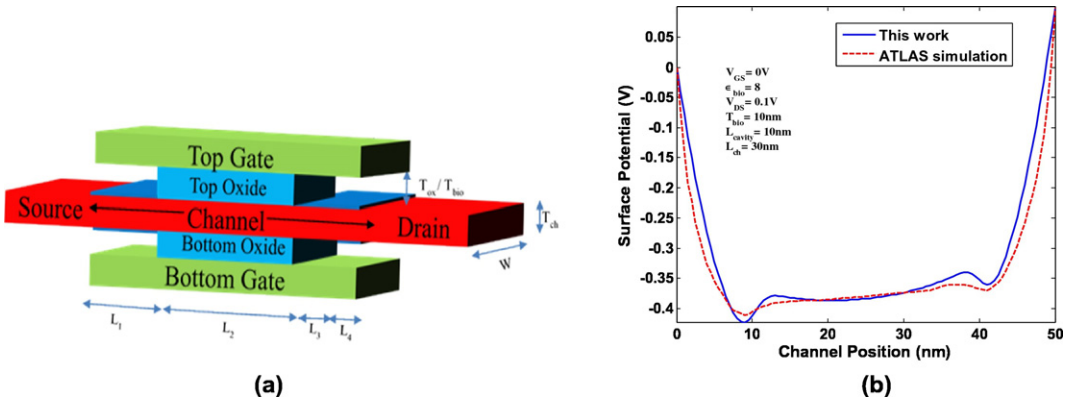

Fig. 1. (a) Schematic initial structure of Junctionless DM-DG-MOSFET biosensor. Different parameters considered here are as follows, $T_{bio}/T_{ox} = 9$ nm, with 1 nm SiO_2 considered on both side of the channel in the cavity regions. $T_{ch} = 10$ nm, $L_1 = 10$ nm, $L_2 = 30$ nm, $L_3 = L_4 = 5$ nm. Doping in the source, drain, and the channel is 1×10^{25} m^{-3}. (b) Comparison of surface potential obtained from analytical model and ATLAS simulation for the device in (a).