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Quasi-3D modeling of surface potential and threshold voltage of Triple Metal Quadruple Gate MOSFETs

Santosh Kumar Gupta*, Mihir Kumar P. Shah

Electronics & Communication Engineering, Motilal Nehru National Institute of Technology Allahabad, Uttar Pradesh 211004, India

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In this paper we present electrostatic model of 3D Triple Metal Quadruple Gate (TMQG) MOSFET of rectangular cross-section based on quasi-3D method. The analytical equations for channel potential and characteristic length have been derived by decomposing TMQG into two 2D perpendicular cross-sections (triple metal double gate, TMDG) and the effective characteristic length of TMQG is found using equivalent number of gates (ENG) method. For each of the TMDG, 2D Poisson's equation is solved by parabolic approximation and proper boundary conditions to calculate channel potential. The threshold voltage expression is developed using inversion carrier charge sheet density method. The developed models for channel potential and threshold voltage are validated using numerical simulations of TMQG. The developed model provides the design guidelines for TMQG with improved HCEs and SCEs.

1. Introduction

Aggressive scaling of conventional metal oxide semiconductor field effect transistors (MOSFETs) has resulted into secondary problems such as Short Channel Effects (SCEs) and Hot Carrier Effects (HCEs). To overcome these problems multiple gate MOSFETs such as double, triple, all around gate etc. are being proposed and investigated. In double gate structure, two gates control the channel; in triple gate MOSFET channel is controlled from three sides; and in all around gate MOSFET channel is controlled from all around improving the electrostatic characteristics over the conventional one [1–5]. Recently, a potential step has been introduced by taking different gate material workfunction (multiple material gates) to the source and drain ends to reduce drain control over channel improving many performance parameters such as drain induced barrier lowering (DIBL), HCEs, and sub-threshold current conduction [6–11]. Silicon-on-insulator, double, triple, quadruple and many other types of gate have already been reported based on multiple metal gate technology. By increasing the number of potential steps in the channel the SCEs and HCEs can further be reduced. It can be done by using three different materials in the gate to induce three potential steps in the channel compared to two potential steps using two different materials in the gate [12–15].

The devices with triple metal gates offer superior characteristics over the conventional MOSFETs as reported by Santosh Kumar Gupta et al. [12,13]. They reported a Gate Engineered Triple Metal Double Gate (TM-DG) MOSFET for Diminished SCEs. Reduced SCEs and HCEs were shown based on results obtained from the TCAD simulations of TMDG MOSFET [12]. They also reported a Junctionless Triple Metal Cylindrical Surround Gate (JLTM CSG) MOSFET to provide better SCEs and HCEs compared

* Corresponding author.
E-mail addresses: skg@mnnit.ac.in (S.K. Gupta), shahmihir.osho@gmail.com (M.K.P. Shah).

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to the conventional MOSFETs [13] based on the TCAD simulations. However, they do not propose any analytical model for the proposed triple metal gate MOSFETs.

To get design guidelines of these devices, better understanding of its behaviour and for circuit simulations; physics based analytical models needs to be developed and validated. Pramod K. Tiwari et al. [14] proposed a 2D analytical model for fully depleted short channel triple-material double gate metal-oxide-semiconductor field - effect transistors by solving 2D Poisson's equation with suitable boundary conditions using parabolic potential approximation in the channel. The lightly doped channel was taken to enhance the device performance in terms of higher carrier mobility and minimum dopant fluctuation. The improved hot carrier effects over the double-material DG MOSFETs were demonstrated. Different length ratios of three channel regions related to different gate materials were optimized to minimize short-channel effects and the effects of device parameters on the threshold voltage was also presented. Visweswara Rao Samoju et al. [15] proposed a quasi-3D model for Dual-Metal Quadruple-Gate (DMQG) MOSFETs based on equivalent number of gates (ENG) method to calculate effective natural length. The effective natural length was used to calculate center channel potential and 'virtual cathode' potential for threshold voltage modeling. A subthreshold current modeling using Pao-Sah's current equation [16] was also developed. T. K. Chiang also developed a novel scaling theory for fully depleted, multiple gate MOSFET, including effective number of gates (ENGs) [17] and a novel quasi-3D threshold voltage model for fully depleted quadruple-gate (FDQG) MOSFETs [18].

In the present work, we consider a Triple Metal Quadruple Gate (TMQG) MOSFET in which the channel is surrounded all around with triple metal gate of rectangular shape as shown in Fig. 1(a). This structure is expected to provide better SCEs and HCEs because the channel is controlled from all around with three potential steps in the channel which reduces the drain bias effects on the potential barrier at the source end. The potential barrier at the source end is the minimum channel potential responsible for the threshold voltage of the devices. To our best understanding, none of the above stated models can directly be used for designing TMQG MOSFETs or predicting its behaviour at short channel lengths. Therefore, it is of worth to study this device and provide design guidelines. Considering the importance of TMQG MOSFET, we develop a quasi-3-D model of surface potential, central potential, and threshold voltage based on Equivalent Number of Gates (ENG) method [19–30].

2. Device structure

Structure of a 3D TMQG MOSFET is shown in Fig. 1(a). Here, L is total channel length, t_{si} is channel thickness, and t_{ox} is oxide thickness. Total channel length is divided in 3 parts of length L1, L2 and L3 such that L1+L2+L3 = L. Work functions for corresponding gate metals are denoted as ϕ_1, ϕ_2 and ϕ_3. Gate metal with highest work function is kept near to source and called as controlling gate. Metal in middle of the gate is called first screen gate and metal near to drain is called second screen gate. These two screen gates induce two extra potential steps in the channel. Whole channel region is doped with very low acceptor type impurity (10^{16} cm^{-3}). Source and drain are highly doped (10^{20} cm^{-3}) with donor type impurity. Channel is assumed to be fully depleted.

3. Model development

For developing analytical model of surface potential of TMQG MOSFET, it is decomposed into two triple metal double gate (TMDG) MOSFETs of which cross-sectional views along XY and XZ planes are shown in Fig. 1(b) and (c) respectively. The Poisson's equation for each 2D cross section of TMQG MOSFET is solved using parabolic approximation with proper boundary conditions [19]. Characteristic length gives important information about device design consideration for reduced SCEs [17]. Therefore, we first calculate the characteristic length of the 3D TMQG MOSFET using ENG method considering these two 2D TMDG MOSFETs [20–22]. Threshold voltage modeling is developed following inversion carrier charge density method [23–25]. Electric field is also calculated by differentiation of potential function to get insight about the HCEs. The developed model is verified with the data extracted from SILVACO technology computer aided design (TCAD) tool using ATLAS device simulator [26].

3.1. Channel potential modeling

Using the TMDG MOSFETs shown in Fig. 1(b) and (c), we develop the model for channel potential $\phi(x,y)$. Assuming $\phi_k(x,y)$ to be potential of channel regions: k = 1, 2 and 3 of the cross section of the TMQG MOSFET in XY plane. The channel potential follows 2-D Poisson's equation given by-

$$\frac{\partial^2\phi_k(x,y)}{\partial x^2}+\frac{\partial^2\phi_k(x,y)}{\partial y^2}=\frac{qN_a}{\varepsilon_{si}} \quad (1)$$

where N_a is the channel doping, q is the unit charge and ε_{si} is the dielectric constant of silicon channel (typical value: 11.7).

The solution to the above Poisson's equation can be obtained using parabolic potential approximation given by K K Young [19].