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Precise analytical model for short channel Cylindrical Gate (CylG) Gate-All-Around (GAA) MOSFET

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ABSTRACT

A compact analytical model is presented for device electrostatics of nanoscale Cylindrical Gate (CylG) Gate-All-Around (GAA) MOSFET, using isomorphic polynomial function for potential distribution. The model is based on solutions of 3D Laplace and Poisson's equations for subthreshold and strong inversion region respectively. In this paper, the short-channel effects are precisely accounted for by introducing *z* dependent characteristic length and the developed electrostatics is tested against analysis of crossover point for device under test. Further, the modeled subthreshold slope for lightly doped CylG GAA MOSFET has been improved by introducing *z* dependent characteristic length and the position of minimum center potential in the channel is obtained by virtual cathode position. A new model is proposed for threshold voltage, based on shifting of inversion charge from center line to silicon insulator interface.

1. Introduction

As dimensions of conventional planar Metal Oxide Semiconductor Field Effect Transistor (MOSFET) are scaled down, the close proximity between source and drain reduces the capability of gate electrode to control the potential distribution. Consequently, the bulk-silicon transistor is facing serious problems as a Short Channel Effects (SCEs) that start plaguing of MOSFETs [1,2]. The main short channel effects are threshold voltage roll-off (due to charge sharing), degradation of subthreshold slope and Drain Induced Barrier Lowering (DIBL). As a result, the off state current increases and the ON–OFF current ratio is degraded [3].

In the near future, multiple-gate MOSFETs (MuGFETs) are strong candidates for replacing conventional single gate MOSFETs. The electrostatic control of channel by gate dramatically reduces SCE, such as charge sharing and DIBL [4]. However, the lightly doped channel also helps to alleviate several other problems related to nanoscale MOSFETs, e.g. mobility degradation random dopant fluctuation, compatibility with mid-gap metal gate, etc. [5,6].

The Cylindrical Gate (CylG) GAA MOSFET [7–11] has excellent electrostatic control of the channel, robustness against SCE, better scaling options, no floating body effect, larger number of Equivalent Number of Gate, ideal subthreshold swing, suppress corner effects, nonconfinement of carriers near to Si/SiO_2 interface, reduced natural length as compared to other MuGFETs and gives volume inversion [4,5].

In this paper, the device electrostatics developed for CylG GAA MOSFET has been used for some other important parameters, e.g. crossover point, subthreshold slope, virtual cathode position and threshold voltage. The model is based on isomorphic polynomial potential distribution in the directions perpendicular to the gate in the central region of the device. From this, an analytic long-channel solution for inter-electrode body potential distribution is obtained from the 3D Laplace equation. However, in order to precisely account for short-channel effects of short channel device, we have introduced alternate functional form as a *z* dependent characteristic length. The potential model based on *z* dependent characteristic length has been used to formulate a new model for subthreshold slope. Further, the virtual cathode positions are also studied in this paper to show the effect of drain bias on the position of center potential. A new approach for estimation of threshold voltage is based on the electrostatic effect of capacitive coupling and the electronic charge is equal and opposite at zero drain bias. All the models have been validated against a professional 3D ATLAS [12] device simulator.

The paper is organized as follows: In Section 2, we describe the device electrostatics, while Sections 3 and 4 relate to modeling of subthreshold slope and virtual cathode position respectively.

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Section 5 addresses the development of threshold voltage model. Finally, the conclusions are summarized in Section 6.

2. Device electrostatics

Fig. 1a and b shows the cross-sectional and 3D ATLAS [12] views of CylG GAA MOSFET, where the middle portion is silicon having thickness t_{Si}. The extended portion of channel act as schottky contacts and $a = t_{Si} + 2t'_{ox}$ is the thickness of extended body including the gate insulator. To facilitate the modeling, the gate insulator is replaced by an electro-statically equivalent silicon layer with thickness $t'_{ox} = \frac{t_{ox}\epsilon_{Si}}{\epsilon_{ox}}$ [13], where ϵ_{Si} is the relative permittivity of silicon and a high-k gate insulator with a relative permittivity of $\epsilon_{ox} = 7$.

In order to precisely account for SCE in device and for intact range of potential distribution, we have introduced following isomorphic polynomial in central part of device as

$$\hat{\phi}(\rho,z) = \sum_{k=1}^{n} \begin{cases} \hat{\phi}_{sub}(0,z)\alpha_{sub_k}\left[1-\left(\frac{2\rho}{a}\right)^{2k}\right] & \text{Subthreshold} \\ \hat{\phi}_{str}(0,z)\alpha_{str_k}\left[1-\left(\frac{2\rho}{a}\right)^{2k}\right] & \text{Strong inversion} \end{cases} \tag{1}$$

where $\hat{\phi}(\rho,z) = \phi(\rho,z) - V_{gs} + V_{FB}$ is the body potential relative to the silicon gate interface, V_{gs} is gate to source voltage, V_{FB} is flat band voltage, α_{sub_k} and α_{str_k} are constants for subthreshold and strong inversion domain where $k = 1,2,\ldots,n$.

To obtain the potential distribution in subthreshold region for CylG GAA MOSFET, we used $\nabla^2(\phi_{sub}(\rho,z)) = 0$. Along z axis (1) reduces to a 1D equation by using curvatures of potential. Using boundary conditions at source and at drain end and to conquer the issues related to SCE for short channel applications, the long channel potential model of CylG GAA MOSFET can be improved by consideration of z depended characteristic length as [9]

$$\hat{\phi}_{sub}(0,z) = \frac{(V_{bi} - V_{gs} + V_{FB})\sinh\left[\frac{L-z}{\lambda(z)}\right] + (V_{bi} - V_{gs} + V_{FB} + V_{ds})\sinh\left[\frac{z}{\lambda(z)}\right]}{\sinh\left[\frac{L}{\lambda(z)}\right]} \tag{2}$$

Here, V_{bi} is the built in voltage at the two contacts, V_{ds} is the drain to source voltage and

$$\lambda(z) = \lambda_c + \alpha\left[z - \frac{L}{2}\right]^2 \tag{3}$$

where λ_c and α are bias-dependent parameters derived from the center potential $\hat{\phi}_c(0,\frac{L}{2})$ and the electrical field E_s at the center of the source (0,0) as $\lambda_c = \lambda\left(\frac{L}{2}\right) = \frac{L}{2\cosh^{-1}\left[\frac{V_{bi}-V_{gs}+V_{FB}+\frac{V_{ds}}{2}}{\hat{\phi}(0,\frac{L}{2})-V_{gs}+V_{FB}}\right]}$ and $\alpha = \left(\frac{2}{L}\right)\left[\frac{V_{bi}-V_{gs}+V_{FB}}{E_s} - \lambda_c\right]$.

The parameter α_{sub_k} is determined from the potential at the z axis which requires that $\sum_{k=1}^{n}\alpha_{sub_k} = 1$ and the curvature of the potential along the z axis is negative of the sum of the curvatures in the two transverse directions. The obtained value of α_{sub_1} from Laplace's equation along z axis using (1)–(3) can be written as

$$\alpha_{sub_1} = \left[\frac{a^2(V_{bi} - V_{gs} + V_{FB})}{8\hat{\phi}_c(0,\frac{L}{2})\lambda_c^2\cosh\left(\frac{L}{2\lambda_c}\right)}\right]\left[1 + \alpha L\left\{2\coth\left(\frac{L}{\lambda_c}\right) - \coth\left(\frac{L}{\lambda_c}\right)\right\}\right] \tag{4}$$

The value of α_{sub_2} can be obtained from $\alpha_{sub_1} + \alpha_{sub_2} = 1$.

The electrostatic potential distribution in strong inversion for lightly doped CylG GAA MOSFET having a large diameter (>5 nm) to ignore energy quantization can be obtained from 3D Poisson's equation. The Si body is lightly doped with doping density N_A taken as $10^{15}\,\text{cm}^{-3}$ which is much smaller than $n_i e^{\left(\frac{\phi_{str}(\rho,z)}{V_{th}}\right)}$ where, V_{th} is thermal voltage. The highly doped body ($N_A \gg 10^{17}\,\text{cm}^{-3}$ [14]) has adverse effect on mobility [15] and random dopant density fluctuations [16]. We consider only the n-MOSFET with $\left(\frac{\phi_{str}(\rho,z)}{V_{th}}\right) \gg 1$, so the density of hole is negligible [17]. It is worth noting here that, we have neglected the hole concentration, and thus, the model is only valid for $\phi_{str}(\rho, z) \gg 3V_{th}$, where hole concentration will be very less as compared to electron concentration. The electron quasi-Fermi level is approximated to be zero throughout the channel for low V_{ds}. Therefore, the Poisson's equation along Si body takes the following form with only charge (electron) term

$$\nabla^2(\phi_{str}(\rho,z)) = \left[\frac{qn_i^2}{N_A\epsilon_{Si}}\right]e^{\left(\frac{\phi_{str}(\rho,z)}{V_{th}}\right)} \tag{5}$$

In strong inversion region, the inversion charge tends to screen the influence of the source and drain within the interior of the device along the z axis, making the potential quite flat in the central region of the device. Therefore, the double derivative along z axis is zero at $V_{ds} = 0$ except smaller regions near source and drain, while the double derivative along x and y axis can be obtained from isomorphic polynomial for strong inversion region. Hence, the obtained value of α_{str_1} from (1) for strong inversion and (5) at (ρ, z) = (0, z) as

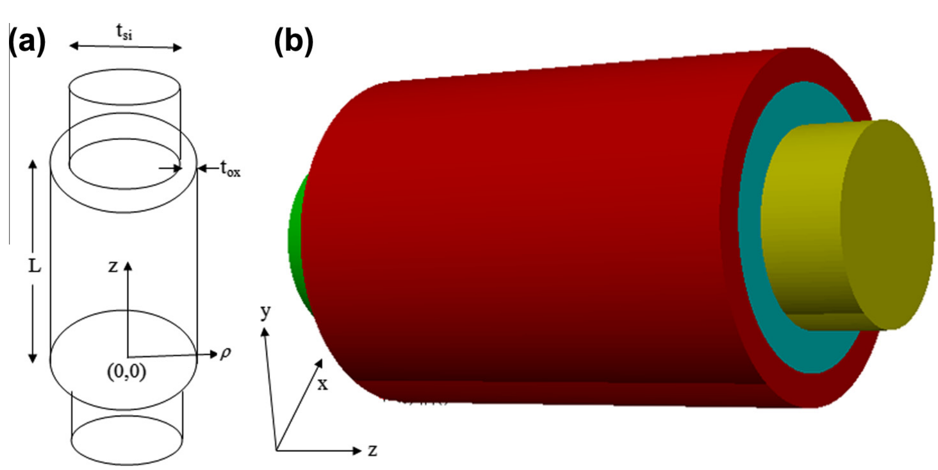

Fig. 1. Cylindrical Gate (CylG) Gate All Around (GAA) MOSFET (a) Cross-sectional view (b) 3D ATLAS view.