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A new explicit and analytical model for square Gate-All-Around MOSFETs with rounded corners

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ABSTRACT

The scaling of MOSFET transistors makes the use of new device geometries, such as multigate FETs, a need to solve the limitations of the conventional bulk technology. In this context we introduce an analytical model for square Gate All Around (GAA) MOSFETs with rounded corners including quantum effects. The modeling of rounded corners in GAA and FinFET devices is imperative because there are no perfectly square corners in the cross-section of real devices. In this model the 2D inversion charge distribution function (ICDF) is described analytically for devices of different sizes and for different operation regimes. The model reproduces accurately simulated data obtained with a state-of-the-art simulator that solves self-consistently the Poisson and Schrödinger equations in the devices under consideration. The analytical ICDF is used to better understand the device physics and to calculate the inversion charge centroid and the gate-to-channel capacitance for different device geometries and biases for modeling purposes.

1. Introduction

Within the aggressive scaling landscape in the microelectronics industry, different device geometries such as Multiple-gate (MuG) MOSFETs are regarded to be key players to overcome the limitations of conventional bulk technology. MuG MOSFETs have very interesting features such as reduced threshold voltage roll-off, DIBL, leakage in the off-state, and nearly ideal subthreshold swing values [1–4]. The use of MuG MOSFETs could allow the reduction of channel lengths below 14 nm, taking into account the possibility of using undoped channels due to reduced short channel effects (SCEs). Apart from that, a reduced doping leads to lower random impurity effects, such us threshold voltage and the sub-threshold slope dispersion [5,3,2].

Several compact models have been developed for Gate-All-Around (GAA) MOSFETs (square and cylindrical) in the last few years [2,6–13]. Nevertheless, new efforts are required in this field to develop the circuit simulation infrastructure needed by the designers of future ICs. Quantum mechanical effects (QMEs) in MuG MOSFETs are very important due to their nanometric dimensions, and therefore the effects of this quantum confinement have to be included in models for circuit simulation.

In this manuscript we will analyze and model square GAA MOSFETs with rounded corners. As far as we know, the effects linked to the curvature of the corners in the cross-section of real devices have not been modeled analytically in a rigorous manner. We do so here by enhancing the features of a previous model [11] taking into consideration quantum effects. Cylindrical GAA MOSFET models can be simplified because the device symmetry around the transport axis allows a 1D analysis [6,7]; however, for square GAA MOSFETs we have to use other techniques, mostly if we take into account that the cross-sections of real devices are not perfectly square. When a square GAA device is manufactured, the materials suffer from chemical attacks which lead to a rounded corner square shaped structure. This effect, although undesired, is inevitable because of the collateral effects caused by the current technology [14–16]. In this paper we model the ICDF by using an analytical and explicit equation that accounts for rounded corner square shaped devices. Once we determine the ICDF function, we will be able to model the inversion charge centroid (ICC) and the gate-to-channel capacitance (C_{GC}).

The manuscript scheme is the following: in Section 2 we describe the simulator. We develop the ICDF model in Section 3. The ICC and the C_{GC} are analyzed and studied in Sections 4 and 5, respectively. Finally, the main conclusions are given in Section 6.

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2. Simulator description

The simulation data presented in this work have been obtained by using a numerical tool previously developed [17,18]. The geometry of the GAA MOSFET studied is shown in Fig. 1, where t_{ins} and t_{Si} are the insulator thickness and the semiconductor thickness. The gate surrounds the rounded corner square conductive semiconductor channel. The 2D Poisson and Schrödinger equations have been self-consistently solved using a predictor–corrector scheme [19] for fast-convergence purposes. Wave function penetration within the insulator has been considered. More details in the simulator can be found elsewhere [17,18].

In this geometry we consider a 1D electron gas since electrons are confined perpendicularly to the transport axis. The following expression allows the calculation of the quantum charge density [17,19]:

$$\rho(y,z) = q\left(\frac{2mk_BT}{\pi\hbar^2}\right)^{\frac{1}{2}}\sum_n \Psi_n^2(y,z)\Im_{-\frac{1}{2}}\left(\frac{E_F - E_n}{k_BT}\right) \quad \left[\frac{C}{cm^3}\right] \tag{1}$$

where q is the electron charge, E_F is the Fermi level, Ψ_n is the wave function belonging to energy level E_n, $\Im_{-1/2}$ the complete Fermi–Dirac integral of order $-1/2$ and the remaining symbols have their usual meaning.

For our simulations we have taken into account a gate made of a metal with a work-function of 4.61 eV, an undoped substrate ($N_A = 10^{14}$ cm^{-3}) and a silicon dioxide insulator of 1 nm. The t_{Si} values employed were 10 nm and 20 nm.

3. Inversion charge modeling

In order to develop an inversion charge analytical model for this device, firstly we introduce a parametric function $s(\alpha)$ with α being the rotation angle as shown in Fig. 1. This function defines the external shape of the device to model (the shape of the semiconductor–insulator interface). Secondly, we define a function $\rho(r)$ that reproduces with accuracy the ICDF from the semiconductor channel center to the semiconductor-oxide interface, for different device sizes and applied gate voltages. By combining $s(\alpha)$ and $\rho(r)$ in an appropriate manner we obtain a 2D function $\psi(r,\alpha)$ that reproduces the inversion charge density function in the active region of the structure shown in Fig. 1. We will make use of the numerical simulator presented in Section 2 to accurately characterize $\psi(r,\alpha)$.

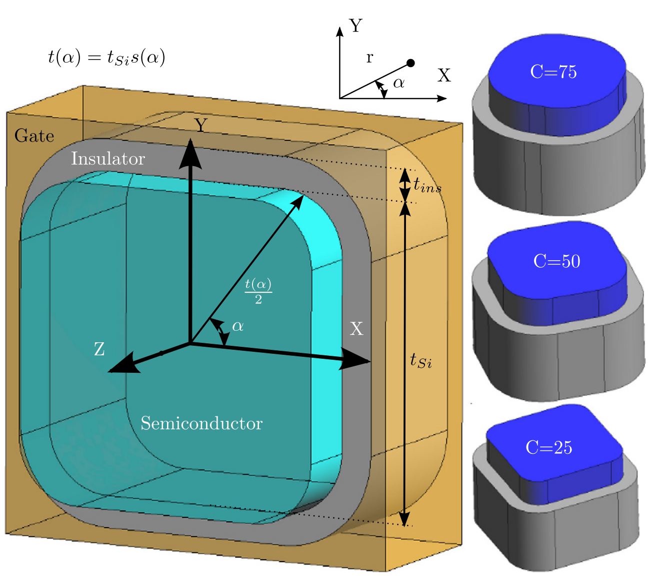

Fig. 1. GAA with rounded corners where only the semiconductor core and the gate insulator are sketched. The main parameters of the geometry are indicated. On the right, three geometries with rounding percentage C = 75, 50 and 25 are depicted. The definition of C can be found in Appendix A.

The resulting ICDF is connected with the inversion charge density as follows:

$$n(r,\alpha) = N_{inv}|\psi(r,\alpha)|^2 \tag{2}$$

where N_{inv} represents the integrated total electron density over the device cross section area.

3.1. The squircle function $S(r,\alpha)$

The superellipse formula [20] allows a parametric representation of squares with rounded corners, which is also called *squircle*, in terms of a few parameters that control not only the curvature, but also the number of corners (or sides of the geometrical figure):

$$s(\alpha) = \left\{\left|\frac{\cos\left(\frac{sides}{4}\cdot\alpha\right)}{r_a}\right|^{n_2} + \left|\frac{\sin\left(\frac{sides}{4}\cdot\alpha\right)}{r_b}\right|^{n_3}\right\}^{-\frac{1}{n_1}} \tag{3}$$

The parameter *sides* controls the number of corners, and r_i the ratio between height and width of the rectangle. In our case, we use $sides = 4$ and $r_a = r_b = 1$. The parameters n_i control the curvature of the corners. Therefore, they are related to the device curvature as explained in Appendix A. However, in order to attain a differentiable $\psi(r,\alpha)$ function, we have employed an alternative expression for the squircle formula, $S(r,\alpha)$:

$$S(r,\alpha) = \left(|\cos(\alpha)|^{n_s(r,C)} + |\sin(\alpha)|^{n_s(r,C)}\right)^{\frac{-1}{n_s(r,C)}} \tag{4}$$

where $n_s(r,C)$ is defined in (A.4). The role of Eq. (4) is to capture the angular dependence of the ICDF. Using this approach we can improve the fitting provided by Eq. (A.4) when simulation data are used, the comparison with the simulated ICDF is given below.

3.2. ICDF modeling and description of the r dependence

Here we propose a 2D model to analytically describe the GAA MOSFETs ICDF along the radial direction. We use an approach that follows the work of Ge et al. for Double-Gate MOSFETs (DGMOSFETs) with symmetrical gates (Eq. (4) in Ref. [21]). Based on this work, a 2D analytical model for the ICDF of perfectly square devices was developed in [11]. There, the 1D eigenfunctions proposed by Ge et al. were generalized to model the 2D ICDF of perfect square devices, and here, following a similar scheme, we propose the following function:

$$\rho(r,\alpha) = \left[\cos\left(\frac{\pi r}{t(\alpha)}\right)\right]^a \left[\cosh\left(\frac{rb}{t(\alpha)}\right)\right]^{(1+\gamma\sqrt{r})} \tag{5}$$

where the function $t(\alpha) = t_{Si}s(\alpha)$ accounts for the distance from the device center to the gate-insulator interface for a given α angle (see Fig. 1). This model solely depends on three fitting parameters which can be found using a minimization algorithm. The values are given below:

- a connects with the shape of the device and here we employ $a = \frac{19}{10}$.

Table 1
Values of parameter b.

t_{Si} (nm)	V_g (V)									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
10	3.55	3.55	3.55	3.55	3.70	4.50	5.20	5.50	5.66	5.68
20	3.26	3.26	3.26	3.26	3.67	4.27	4.63	4.80	4.87	4.90