A Simple Electron Mobility Model Considering the Silicon-Dielectric Interface Orientation for Circular Surrounding-Gate Transistor

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ABSTRACT

*A*In this work, a simple model that accounts for the variation of electron mobility as a function of the silicon-dielectric interface crystallographic orientation is presented. Simulations were conducted in order to compute the effective mobility of planar devices and its results were compared to experimental data for several interface orientations. The error between experimental data and the proposed model remained bellow 4%. The model has been applied to nMOS circular surrounding gate (thin-pillar transistor - CYNTHIA) and allowed the observation of current density variations as a function of the interface orientation around the silicon pillar.

Index Terms: Circular, CYNTHIA, Microelectronics, Mobility, MuGFET.

I. INTRODUCTION

The use of Silicon-On-Insulator (SOI) technology allowed the development of smaller devices with better performance than the conventional silicon bulk transistors. Nevertheless, some undesired effects such as short channel effects are still present for smaller transistors. The use of multiple gate devices is pointed as one of the possible solutions to minimize such short channel effects [1]. The Multiple-Gate Field Effect Transistors (MuGFETs) are devices with more than one gate, usually connected at the same potential, and can be built with three-dimensional structures.

The device that is analyzed in this paper is a surrounding gate device called CYNTHIA that is a transistor with a cylindrical vertical silicon pillar with the gate constructed surrounding this pillar, as seen in Fig. 1. The CYNTHIA transistor offers superior device performance, with high sheet electron concentration, ideal subthreshold characteristics, and enhanced electron mobility in the channel [2]. Due to the cylindrical geometry the surface electric field falls isotropically from the interface and shows continuous values around the silicon pillar. Since the CYNTHIA transistor has a cylindrical gate, the silicon-dielectric interface crystallographic orientation varies continuously around the silicon pillar.

The carrier mobility is highly dependent on the crystallographic orientation of the gate silicon-dielectric interface planes [3] and this dependence must be accounted in MuGFETs simulations.

The drain current direction in CYNTHIA transistor is in direction <001> and the surface plane orientation can be considered continuously variable.

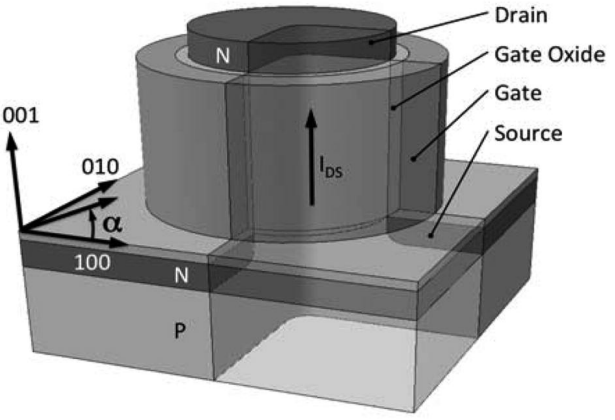

Figure 1. CYNTHIA structure

Although the interface is not really a planar surface for this transistor, considering that the current flows trough a very thin channel close to the surface (typically closer than 3nm [4]) for the considered pillar diameter (65 nm), the tangent plane can be used for mobility calculation and analysis.

In order to compute the effects of the crystallographic orientation, a specific model that take into account the impact of the crystallographic orientation for the mobility must be used, because the surface mobility

may be reduced down to 60% depending on the current and interface crystallographic orientations [5]. Some commercial device simulators are able to account for the current direction influence on mobility, but none of them considers the silicon-dielectric interface plane orientation until now, what has lead some researchers to develop ad hoc solutions, like dividing the transistors in several regions and attributing different initial mobility parameters to each region. Goebel et al.[5], for instance, modeled a 900nm diameter CYNTHIA device in [5] by dividing the vertical sidewall of the cylinder in 72-fold polyhedron, thus the device consisted of 72 discrete parallel MOSFETs with current flowing in the (100) direction. Therefore, the single element's crystallographic orientation was changed by steps of 5 degrees. The total current was obtained by the sum of the terminal currents of each single MOSFET element using 2-D simulations. The authors obtained results very close to experimental but this ad hoc solution is not applicable to smaller devices because the interaction between the transistor slices should be considered.

The present work proposes a very simple local mobility model that was implemented in a 3D numerical simulator, by using the provided C interpreter, for the simulation of the circular surrounding gate transistor CYNTHIA. The implemented model was also combined with doping concentration and temperature dependencies, based on the work of Caughey and Thomas [6] and Selberherr modeling [7,8] for mobility. The analysis of the proposed model was made from three-dimensional simulations of a CYNTHIA device.

II. PROPOSED SURFACE-DEPENDENT ELECTRON MOBILITY MODEL

The numerical device simulators offer a large set of mobility models and options because the mobility depends on different variables as device geometry, materials, bias, and temperature. There is no closed and universal model to carrier's mobility. Thus, some physical issues on mobility degradation nature must be addressed before the proposition of an analytical formula.

In order to facilitate the parameter extraction and simulator implementation the several physical degradation mechanisms are usually modeled separately and then combined using a Matthiessen-like rule. This unrefined approximation if used under the correct conditions and limitations, can lead to very good results [9].

The proposed model considers the mobility variation based on crystallographic orientation and the distance from the interface in addition to the other dependencies such as temperature, doping level, partial ionization of impurities, and transversal field dependencies.

The degradation mechanisms that appear as a result of the substantially higher surface scattering near the interface between semiconductor and insulator [8] occur inside inversion layers and can be associated to the mobility degradation due to interface crystallographic orientation. The surface scattering is highly dependent on the physical interface proximity, due to influence of surface roughness. The carrier-carrier scattering, also affects the inversion layer [1] due to high carrier density that happens in this region. These effects must all be accounted for in order to perform accurate simulations. The transverse electric field is the main parameter that indicates the strength of inversion layer phenomena and varies according to the distance from the silicon-dielectric interface.

The interface roughness depends on the manufacturing process, that is related to the oxide formation process, to the materials, to the silicon etch and also to the crystalline surface orientation. Depending on the surface orientation, the amount of silicon atoms that are exposed to interaction with oxygen and other interface elements may vary, what changes the uniformity of the chemical links, affecting the interface quality and the dielectric thickness. Some authors attribute and model the interface roughness just to the fluctuation of the oxide thickness from its average value [10]. However, there is a strong dependence of the carrier's mobility on the roughness, and consequently on the surface orientation. Table 1 presents some data from two references that show good agreement to each other. The differences between them are expected because the data was extracted from different device types.

Table 1. Relative electron experimental effective mobility for different surface orientations.

Authors (ref)	Reference (100)	Intermediate	(110)
James E. Chung et al [11]	100%	93% (8 deg from <100>)	
B. Goebel at al [5]	100%	97% (10 deg from <100>)	60%

The surrounding-gate transistor CYNTHIA has a circular cross section that implies in continuous variation of crystal orientation at the silicon dielectric interface, where the tangent planes at the interface can be considered to define a specific orientation, as seen on Fig. 2. On the other hand, ordinary multiple-gate devices have different crystallographic orientations to be considered related to defined the interface planes.

In order to define a simple and consistent mobility model, a two-steps strategy was adopted. The first step was defining a function that accounts for the mobility inside the inversion layer and depends on the azimuth angle □. This function should be able to reproduce the surface mobility variation based on the crystallographic orientation over the whole transistor body. The second step was choosing a function that could account for the mobility degradation as a function of the interface distance, which means that the mobility should vary softly from the smaller value at the interface to the greater value at the device body.

The first function, that defines a surface mobility $\mu_S(\alpha)$, must have some properties as consequence of the crystal symmetry properties and the physical mobility issues. The first property is that the maximum value of $\mu_S(\alpha)$ must be acquired at $\alpha = 0$, corresponding to the direction <100> or interface plane (100), and the minimum value of $\mu_S(\alpha)$ must be obtained at $\alpha = \pi/4$, direction <110> or interface plane (110).

The second property to be considered is related to the periodicity of the crystal structure, the crystal structure has period of $\pi/2$, what means that the same values of the mobility will be found at each $\pi/2$ radians added to a reference angle π.

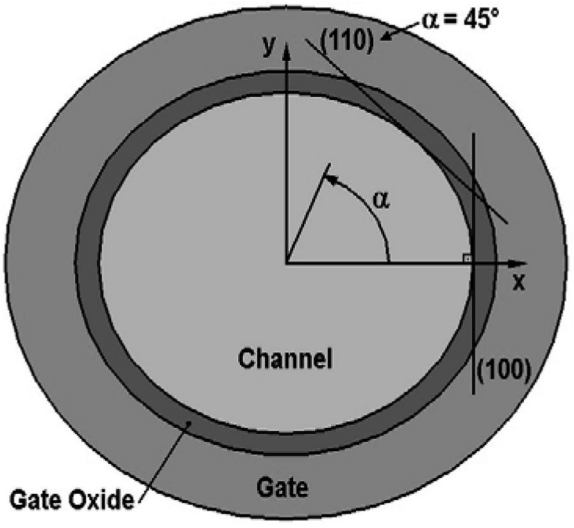

Figure 2. Cross Section of the CYNTHIA Device

The third property defines that the mobility is always greater than zero in any value of the angle α, since physically there is no negative value of mobility.

The fourth and last property is related to the curve definition and defines that the chosen function should be an even function for any value of the angle α and also for $\alpha+\pi/4$. This definition implies that the surface mobility $\mu_S(\alpha) = \mu_S(-\alpha)$ and $\mu_S(\alpha+\pi/4) = \mu_S(-\alpha+\pi/4)$, considering α as a real number.

A Fourier series was considered as a base equation, as seen on equation (1), and removing all the unnecessary terms as defined by the four properties described above.

$$\mu_S(\alpha) = a_0 + \sum [a_n \cdot \cos(n\alpha) + b_n \cdot \sin(n\alpha)] \qquad (1)$$

Since the surface mobility function is an even function, all the b_n coefficients are assumed to be equal zero, because of fourth property and all the coefficients not multiple of four are equal zero, because of the second property. Then, the angle-dependent surface mobility function can be calculated from equation (2).

$$\mu_S(\alpha) = a_0 + \sum_{n=0}^{\infty} 4n \cdot \cos(4n\alpha) \qquad (2)$$

The coefficients used in equation (2) are used as fitting parameters, and these values will be obtained from the mobility values depending on the orientation. The number of coefficients that gives an accurate result is a function of how much the reference mobility function is different from the fundamental sinusoid. In this work, were defined, for comparison, two different equations, as seen on Fig. 3, the first, equation (2a), with the first and second term of equation (2), and the second, equation (2b), with the first, the second, the third, and fourth term of equation (2). Equations (2a) and (2b) were used in comparison with experimental results and both equations have good fit to experimental results and the choice of either equation to use in three-dimensional simulations is a matter of commitment to simplicity and performance against the precision of the calculation.

$$\mu_S(\alpha) = a_0 + a_4 \cdot \cos(4\alpha) \qquad (2a)$$

$$\mu_S(\alpha) = a_0 + a_4 \cdot \cos(4\alpha) + a_8 \cdot \cos(8\alpha) + a_{12} \cdot \cos(12\alpha) \qquad (2b)$$

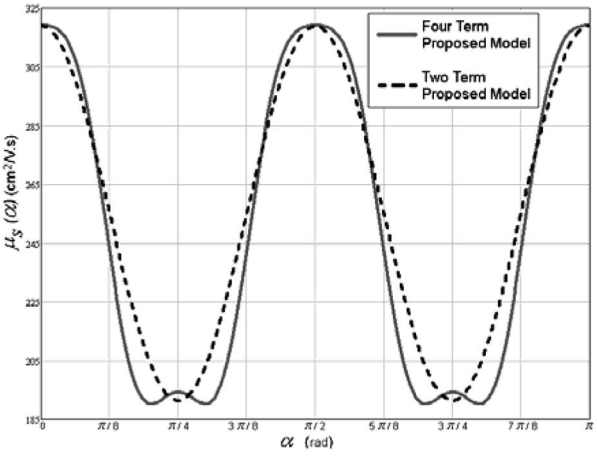

Figure 3. Surface mobility as a function of interface angle

The second function defines the mobility variation as a function of distance from the interface and must be parameterized to fit the mobility value at the surface $\mu_S(\alpha)$, the mobility value at the center of device, now defined as μ_b or body mobility, and the transition from one to other. The transition curve must have soft slope for $\mu_S(\alpha)$ in function of the interface distance. The equation (3) was chosen [8]:

$$F(y) = \frac{2 \times e^{-\left(\frac{y}{y^{ref}}\right)^2}}{1 + e^{-2\left(\frac{y}{y^{ref}}\right)^2}} \qquad (3)$$

Where, y is the distance from the silicon-oxide interface at the calculated point, and y^{ref} is the reference distance from the oxide interface, that is used to set the slope curve. The resulting curve obtained from the equation (3) is shown on Fig. 4.

Equation (4) presents the position dependent mobility, which also takes into account the influence of electric field, as proposed in [8]. It is composed by the two defined functions (Eq. 3 and 2a or 2b), and the additional dependence on the transversal electric field given by Eq. (3).

$$\mu_{pos} = \frac{\mu_S + (\mu_b - \mu_S) \times (1\text{-}F(y))}{1 + F(y) \times \left(\frac{E}{E_{ref}}\right)^{\beta}} \quad (4)$$

Where μ_S is the surface mobility as defined by equations (2a) or (2b), μ_b is the body mobility as defined in [8], *F(y)* is the proximity function defined by equation (3), *E* is the electric field at the calculated point, E_{ref} is the reference electric field, used as an adjusting parameter, and β is the temperature dependent coefficient.

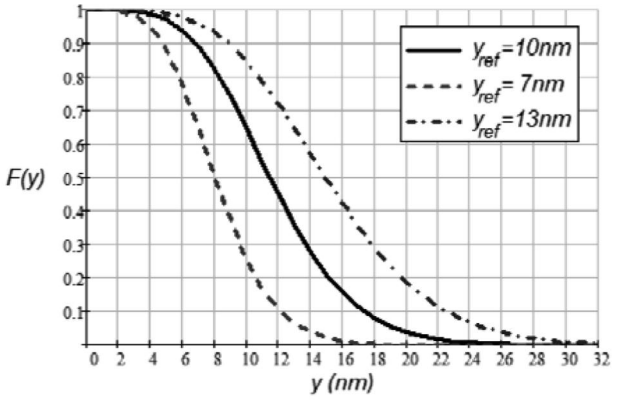

Figure 4. Interface distance transition slope

The value of μ_{POS} is maximum at the center of device because there is no influence of the interface (*F(y) = 1*) and minimal at the interface where there is degradation caused by interface and the electric field is higher.

III. FITTING PARAMETERS

Experimental results that show a 40% decrease in the surface mobility depending on the current and interface crystallographic orientation [5] were used to adjust the $\mu_S(\alpha)$ coefficients. After adjustment of the surface mobility, $\mu_S(\alpha)$, the complete equation of μ_{POS} was implemented considering the standard values presented in [6], [7] and [8]. The complete function of μ_{POS} was computed and plotted for different interface distances from the interface, as seen on Fig. 5, where the values of the applied coefficients a_0, $4a_4$, $8a_8$ and $12a_{12}$ are 0.7825, 0.2264, 0.02236 and -0.0309 (all in cm^2/Vs) respectively. Considering the two effects, the resulting mobility has its lower value at the gate oxide interface and for the alpha angle value of $\pi/4$ rad; and the maximum mobility value is obtained at the device center where the interface crystallographic orientation doesn't have an effect on the resulting mobility independently of the considered angle.

Simulations were conducted and compared with well-known and published results for planar bulk devices in order to verify and set parameters and behavior of the proposed model. The chosen device was a conventional nMOSFETs with channel length of 500 nm, gate oxide thickness of 9 nm, source and drain length of 250 nm and junction depth of 80 nm. The substrate doping concentration (p-type) was $1x10^{17}cm^{-3}$ and source and drain doping concentration (n-type) was $1x10^{20}cm^{-3}$. This specific device was used to compare the results generated by the surface mobility model with the previous published experimental results. This particular device is similar to the one measured by Goebel et all [5], adopted here as a reference.

The simulations were computed using α angle measured from (100) plane orientation, and ranging from 0 to $\pi/4$ rad, with device biased in triode with 100mV between source and drain and gate voltage varying from 0 to 1.2V.

Fig. 6 shows the maximum transconductances extracted by the first derivative method. The resulting curve presents the same trend of the surface mobility.

Fig. 7 shows the effective mobility normalized by the mobility value of the $\alpha = 0$ direction. Results obtained from proposed model were compared with the experimental and the results show that the Four Term Proposed

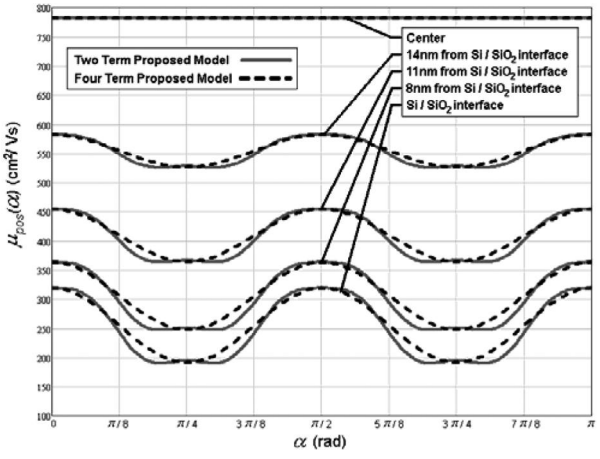

Figure 5. Position Dependent Mobility Functions plotted with Two and Four Term Proposed Models for different interface distances.

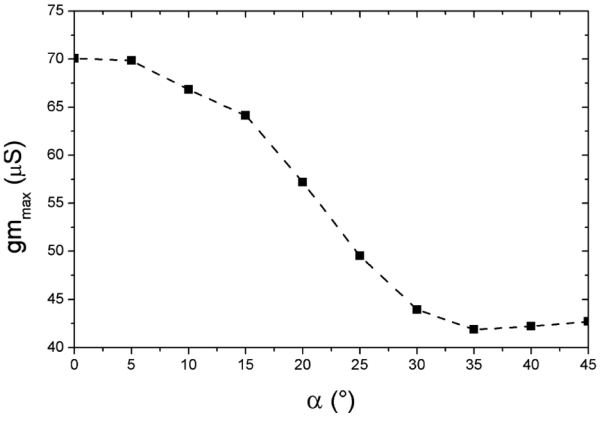

Figure 6. Maximum transconductances in function of α obtained using the Four Term Proposed Model from α = 0 to 4 °.

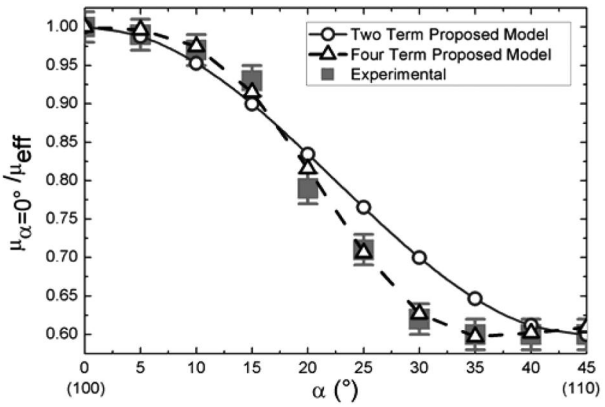

Figure 7. Normalized Effective Mobility of Proposed Models compared with Experimental Results [5]

Model gives an excellent fit to experimental data and the Two Term Proposed Model has the same trends but the results are less accurate.

IV. CYNTHIA SIMULATION

CYNTHIA transistors were simulated using two different mobility models, the proposed model (surface mobility degradation model) and the low field mobility model proposed by Caughey and Thomas [6] (Analytic). The simulated devices were nMOS transistors with channel length of 130, 150 and 180nm, diameter of 20, 30, 45, 55 and 65nm, gate oxide thickness of 2.5nm, source and drain length of 65nm. The doping concentrations were $1x10^{20}cm^{-3}$ at source and drain and $1x10^{15}cm^{-3}$ at the channel. The studied devices were biased in triode with 50mV between source and drain and the gate voltage ranged from 0 to 1.2V.

The simulation results of the proposed model showed lower values of drain current in comparison with the results obtained with the standard model, even though both have started with the same initial mobility, as shown on Fig. 8, due to the degradation of mobility depending on the interface proximity and the mobility variation as a function of the crystallographic orientation.

The observation of important internal variables of the device, such as current density at the surface of device, was possible due to the implementation of the proposed model using the C Interpreter of ATLAS Simulator, such observation was not possible with other models, because the mobility computation did not take into account the crystallographic orientation, what leaded to a unreal distribution of mobility values at the whole device body.

Another internal variable that was studied was the electric field, seen on Fig. 9. The lower values occur at the center of device and, the higher values occur at the silicon-dielectric interface, because the electric field is radially uniform and, decreases as the distance from interface gets high.

The potential distribution is also radially constant, like the electric field and there is no variation of the values as function of the angular position.

The mobility profiles given by the proposed model implemented in Atlas device simulator of the CYNTHIA transistor are plotted in Fig. 10 considering the cut lines starting at the center of the device and stopping at the silicon-dielectric for several values of α angle, considering α=0º at the plane (100) and α=45º at the plane (110). The plot shows clearly the variation of mobility at the edges of the device and the maximum mobility value achieved in the center of the device. The difference between the curves remarks the different mobility profiles according to the variation of crystallographic orientation.

The electron current density shows different distribution and the values are greater at 0º, 90º, 180º and 270º due to the greater mobility at these locations. Fig. 11 presents the profiles of electron current density as a function of the α angle obtained at V_{GS} = 1,2V.

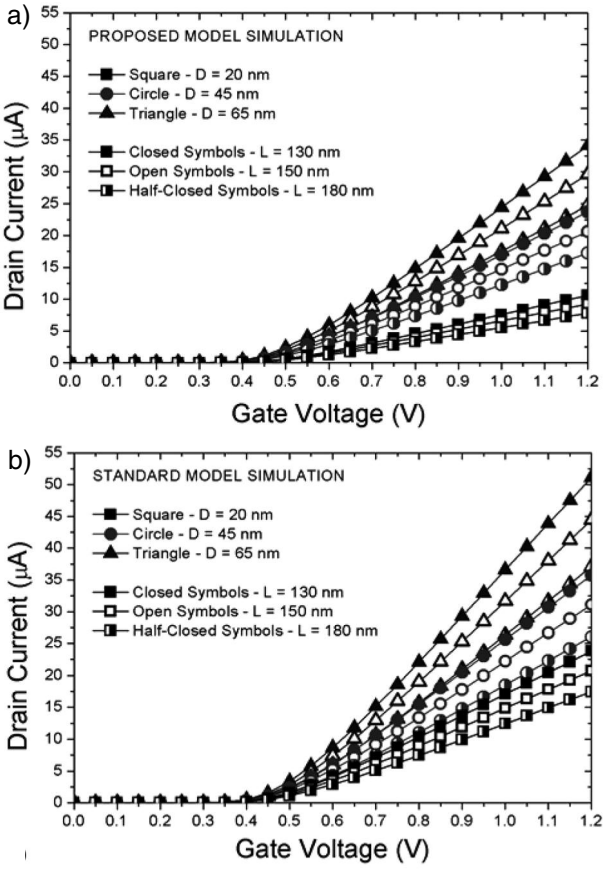

Figure 8. Drain Current results for a) Proposed Model and b) Standard Model.

It's also observed that the center of the body remains with the lowest current density, due to the lower carrier availability. The variation of the electron current density has the same tendency that the variation of mobility, as function of the angle α.

The observed large current density variation may lead to a wide variation range of local degradation and to higher local temperatures, which may reduce the device reliability. Some previously considered symmetry advan-

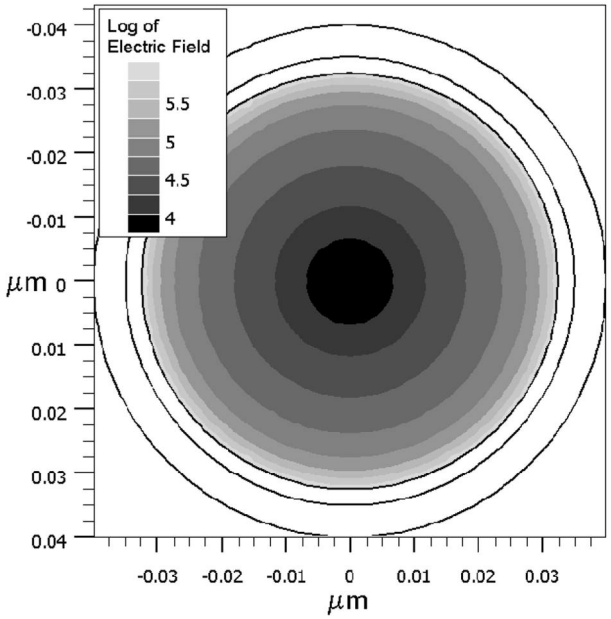

Figure 9. Distribution of electric field, in log scale, in the cross section of CYNTHIA device

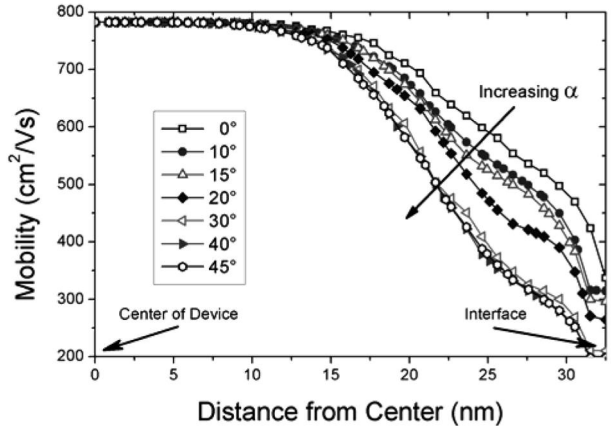

Figure 10. Mobility profiles of a cross section of the simulated CYNTHIA device as function of the α angle.

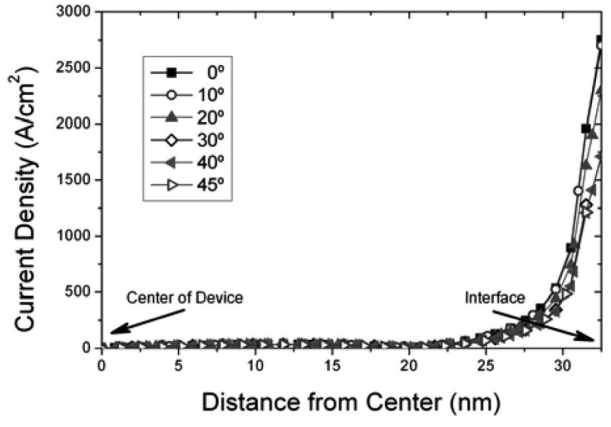

Figure 11. Electron current density profiles in the cross section of CYNTHIA device as function of the α angle.

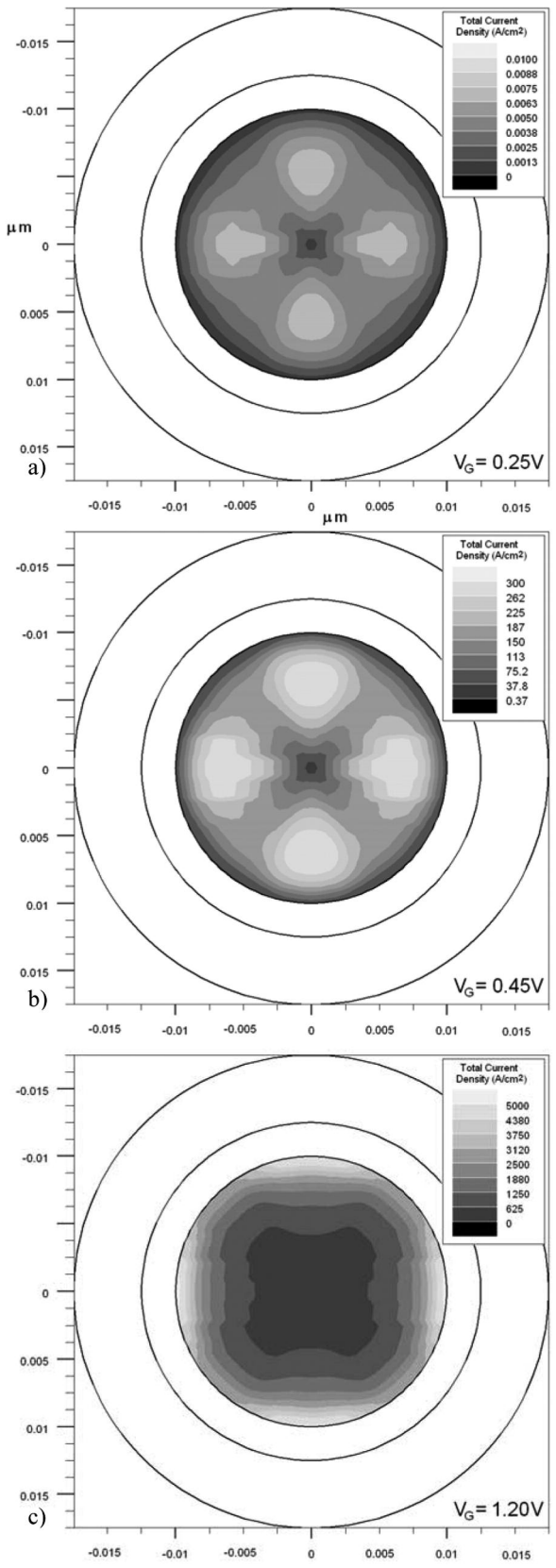

Figure 12. Distribution of current density in the cross section of CYNTHIA device biased with a) 0.25V, b) 0.45V and c) 1.2V at the gate.

tages of CYNTHIA devices over squared cross-section devices [2] must be readdressed after the new possibility of observing the interface orientation influences, trough the proposed model.

The current density analysis that follows shows different behaviors for different gate bias. The transistor with the gate biased in subthreshold region (V_{GS} = 0.25V, V_{TH} = 0.45V) presents four channels with higher current density aligned to the angles that show higher values of mobility, as seen on Fig. 12 a.

With gate biased at the threshold voltage the current density begins to migrate from these center channels to the silicon-dielectric interface (Fig. 12 b). The current distribution keeps the same four channels of the previous plot, but with higher values near the interface.

The current density plotted with the gate biased at strong inversion (V_{GS} = 1,2V) shows higher values at the interface, as seen on Fig. 12 c, and lower values at the center of the device. The whole interface is inverted, but there are still four regions of higher current density, because the mobility is also higher.

V. CONCLUSIONS

The proposed model adds the possibility of studying some very important effects of the interface orientation on carriers' mobility of CYNTHIA transistors that were not studied before due to the lack of three-dimensional mobility models, The proposed model considers the experimentally observed mobility properties, as well as the silicon crystal symmetry properties and is able to be used combined with other mobility models. The proposed model was implemented through a C interpreter in a commercial numeric device simulator. The effective mobility extracted from simulations of planar devices with several interface orientations showed excellent agreement to experimental data.

The simulations of CYNTHIA transistors were conducted by using the proposed model, in order to perform more investigations about the effects of its continuously varying crystallographic interface orientation. The variation in current density over the whole body of the transistor reflects the superficial mobility variation, despite of the constant electric field and potential, as well as the variation of current density in several inversion parameters.

The observation of the current density variation at the dielectric interface proposed model was possible because the computed surface mobility is a function of the crystallographic orientation, and were not possible before.

The proposed model will be useful in the future investigations of the CYNTHIA transistor and may be considered, adapted and implemented for future investigations of other multiple-gate devices with variable interface crystallographic orientation, such as triple-gate transistors.

ACKNOWLEDGEMENTS

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