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Quantum-mechanical effects in multiple-gate MOSFETs

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Abstract In this work, a self-consistent solution of the 2D Schrödinger-Poisson equations is used to analyze Multiple-Gate MOSFETs. Classical simulations overestimate the peak density compared to quantum simulations and therefore the total electron density considered to calculate the current. The impact of the corner rounding on the electron distribution has also been analyzed. New devices, such as the Omega-gate MOSFETs have been studied as a function of the buried gate length.

Keywords Multiple-gate · Quantum effects · Pi-gate · Omega-gate

1 Introduction

In order to shrink the channel length into the nanometric range it is necessary to prevent the short channel effects (SCEs) that degrade the device performance. Bulk MOSFETs faces different problems when the channel length is reduced to a few nanometers. A high impurity density is necessary to keep SCEs under control. As a consequence, the carrier mobility is reduced and the device performance is degraded. Moreover, in such short channel devices, the random impurity effects are not negligible since they produce a dispersion of fundamental parameters like the threshold voltage. To deal with this situation, an undoped channel is the best choice. However, this solution is not appropriate for a bulk MOSFET due to the increase of penetration of the drain electric field lines in the channel region.

The use of several gates has demonstrated a good electrostatic control of the channel and therefore the possibility of a higher reduction of the channel length compared to traditional bulk MOSFETs. Structures such as FinFETs, Trigates, Gate All Around (GAA), Pi and Omega-gate MOSFETs are included into the category of multiple-gate MOSFETs. All of them take advantage of the SOI technology and their gates are located in different planes. This implies that these new devices are essentially three dimensional. Moreover, quantum effects are dominant in the electrostatic of these devices due to their reduced dimensions.

For these reasons, the main goal of this paper is to carry out a thorough study of the electrostatic of a wide variety of multiple-gate SOI MOSFETs with different geometries, including rounded corners and the influence of the quantum effects.

2 Device simulator

To do so, we have self-consistently solved the Poisson and Schrödinger equations in two dimensions (2D), specifically in a plane perpendicular to carrier transport (from source to drain).

The simulator is prepared to analyze different structures such as: FinFETs, Trigates, GAA, and Pi and Omega-gate MOSFETs. Figure 1 shows the geometry of these devices where for all of them it is possible to specify the silicon width (w), the silicon height (h), the gate oxide thickness (t_{ox}), the buried oxide thickness (t_{oxb}) and the corner radius (r). Different materials can be easily considered at different regions. The simulator offers the possibility of specifying the curvature of the silicon substrate corners, and the

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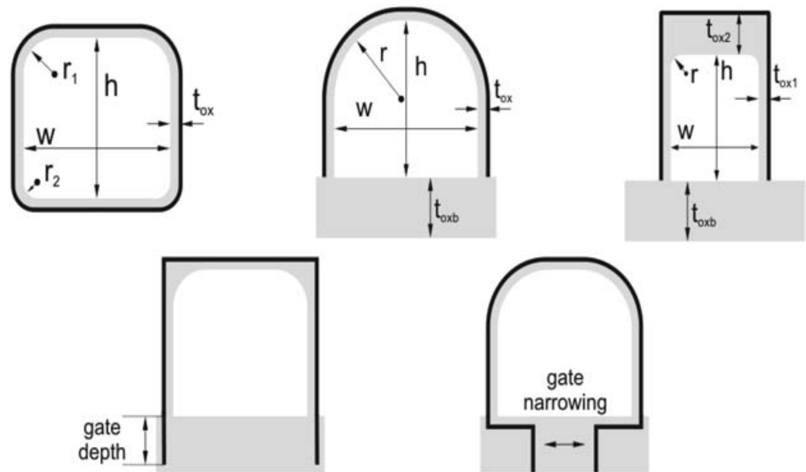

Fig. 1 Geometry of the different structures studied

surrounding oxide, independently. The mesh generator allows a fine grid in the most interesting regions (silicon substrate and interfaces) and a coarser one in the insulator.

To get a fast convergence, the 2D Schrödinger and Poisson equations have been self-consistently solved using the predictor-corrector scheme proposed by Trellakis et al. [1]. This algorithm has been proved as reliable and robust as far as enough number of eigenvalues and eigenfunctions are included in the calculations. From those magnitudes we are able to calculate the electron density (N_q),

$$N_q = \frac{1}{\pi}\left(\frac{2m^*kT}{\mathrm{h}^2}\right)^{\frac{1}{2}} \sum_n \psi_n^2 \Im_{-\frac{1}{2}}\left(\frac{E_F - E_n}{kT}\right), \tag{1}$$

where m^* is the effective electron mass, k the Boltzmann's constant, T the temperature, ψ_n the wave function corresponding to energy level E_n, E_F the Fermi level and $\Im_{-1/2}$ the complete Fermi-Dirac integral of order $-1/2$. Expression (1) corresponds to a one-dimensional (1D) electron gas since the carriers are confined in two dimensions. The Schrödinger equation is solved three times, each one corresponding to the three pairs of conduction band minima since for each direction we have different effective masses to consider. The degeneracy of each valley (2 in this case), has been taken into account in the calculation.

The total electron density can be calculated integrating N_q in the silicon area:

$$N_{\mathrm{tot}} = \int_{A_{Si}} N_q(x, y)dxdy\ . \tag{2}$$

This magnitude is useful to have an estimation of the current at different devices (assuming similar electron mobility for all of them). To calculate the hole concentration we have considered classical expressions. The algorithm stops when the two-norm of the difference between the values of N_q at the end of two successive iterations is smaller than a fixed value.

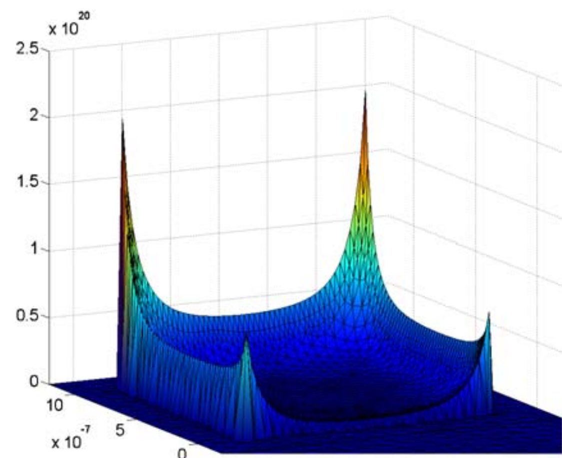

Fig. 2 Classical electron density in a Trigate MOS structure

3 Simulation and results

In all the simulated devices we have considered that the substrate is undoped and a metal gate workfunction of $\phi_m = 4.63$ eV. Figure 2 shows the classical electron distribution (CED) corresponding to a Trigate MOSFET with silicon height (H_{Si}) and width (W_{Si}) of 10 nm, gate oxide thickness (T_{ox}) of 2 nm and gate voltage (V_G) of 1 V.

Figure 3 shows the quantum electron distribution (QED) for the same structure. Important differences are observed between both figures. The CED is concentrated at the Si-SiO_2 interface with a maximum at the corner of 2×10^{20} cm^{-3}. The maximum obtained including quantum effects is 2.5×10^{19} cm^{-3}. The integrated electron density corresponds to $N_{\mathrm{tot,clas}} = 4 \times 10^7$ cm^{-1} for the classical case and $N_{\mathrm{tot,quant}} = 2.52 \times 10^7$ cm^{-1} for the quantum one.

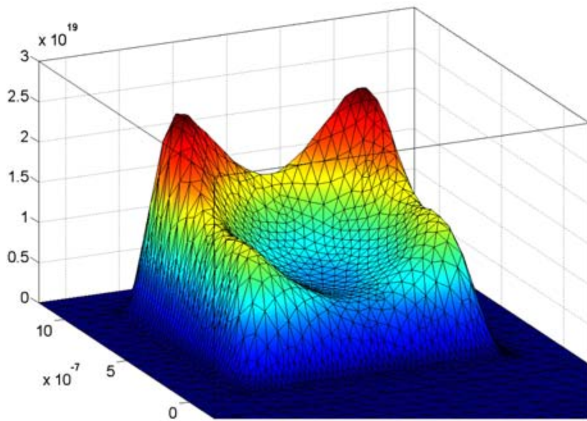

Fig. 3 Quantum electron density in a Trigate MOS structure

Thus, classical simulations over-estimate the total charge involved in the current calculation.

This simulator is able to deal with rounded geometries since it employs finite elements instead of finite differences. Thus, the curvature of the silicon substrate corners, and of the surrounding oxide, can be specified independently. This fact allows us to study the electrostatic behavior of different geometries.

Figure 4 represents the QED in a Trigate MOSFET with square cross section where $H_{\mathrm{Si}} = W_{\mathrm{Si}} = 20$ nm, $T_{\mathrm{ox}} = 2$ nm and $V_G = 1$ V. As can be observed, the electron density reaches a maximum near the corners and a lower density in the rest of the silicon surface. This peak density is caused by the coupling between different gates which produces an electrostatically favourable area for the flow of carriers [2].

Figure 5 shows the QED in the same Trigate MOSFET where the upper corners of the silicon slab have been completely rounded (a curvature radius of 10 nm has been employed). Now, the electron distribution is quite uniform along the Si-SiO_2 interface. To explain this phenomenon, we have

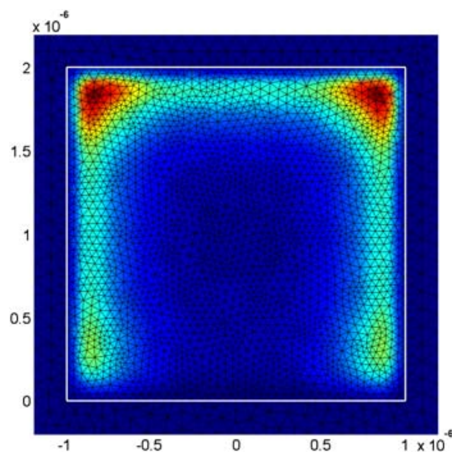

Fig. 4 Electron density reaches a maximum in the corners of the square cross section devices

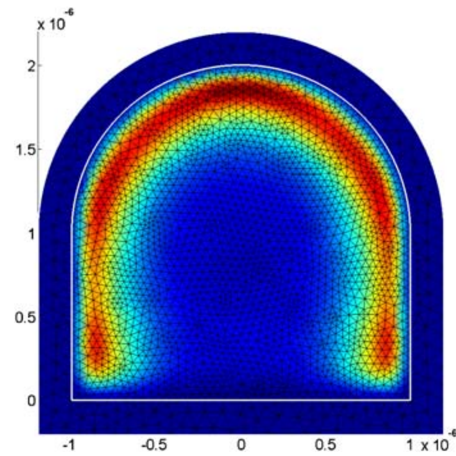

Fig. 5 Corner rounding produces a uniform electron distribution along the Si-SiO_2 interface

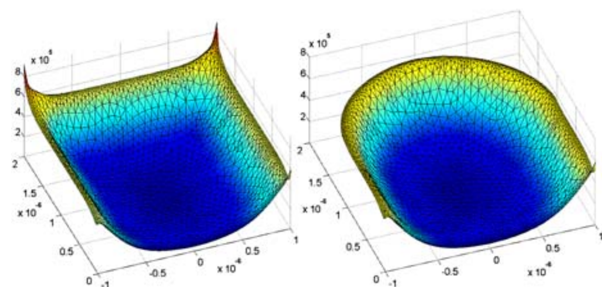

Fig. 6 Electric field in a Trigate MOSFET with square and rounded cross sections

represented in Figure 6 the electric field in both devices. For the square cross section device, a peak is found in the corners originating a maximum in the electron density. On the other hand, a constant field is observed at the Si-SiO_2 interface of the rounded device.

Unlike the double-gate or the GAA structure, the Pi-gate SOI MOSFET can readily be manufactured from a conventional SOI CMOS fabrication process [3]. The Pi and

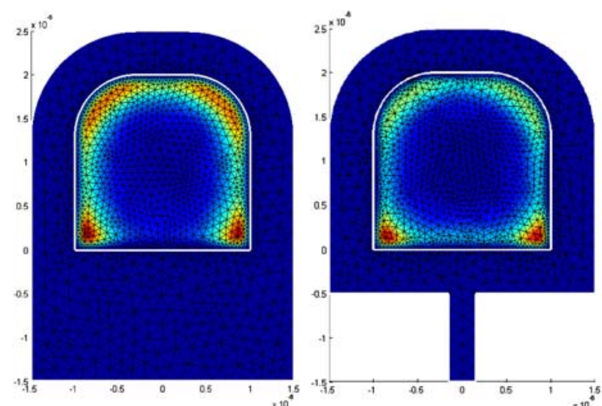

Fig. 7 Electron density in an Omega-gate MOSFET. Left: $L_{\mathrm{ext}} = 0$ nm (Trigate). Right: $L_{\mathrm{ext}} = 80\%$ of W_{Si}. L_{ext} equal to 100% would correspond to a GAA MOSFET

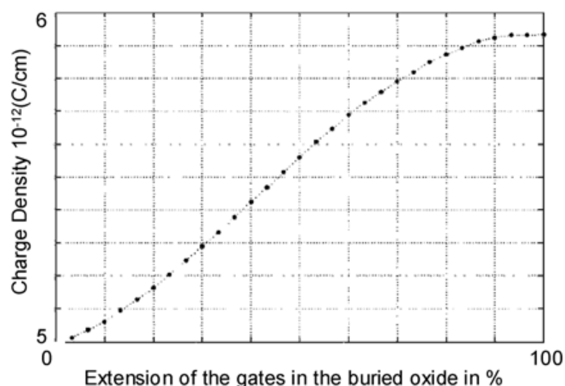

Fig. 8 Total charge density as a function of L_{ext}. $L_{ext} = 0\%$ corresponds to a Trigate and $L_{ext} = 100\%$ to a GAA MOSFET

omega-gate structures can be obtained by extending the lateral gates under the body of the device. The extension of the gates in the buried oxide (L_{ext}) will determine the electron density present in the device. To analyze this behavior, we have calculated N_q as a function of L_{ext} . $L_{ext} = 0$ nm corresponds to a Trigate structure while a GAA would corresponds to a gate extension that covers the whole buried oxide.

Figure 7 shows the electron density at two extreme cases. First, when there is no extension, $L_{ext} = 0$ nm, and second when the extension covers the 90% of the buried oxide. For the first case, a peak electron density of 2.8×10^{19} cm^{-3} has been calculated while in the second one 4.1×10^{19} cm^{-3} was the maximum. The electron density per unit length in both cases was 2.74×10^7 cm^{-1} and 3.1×10^7 cm^{-1} respectively.

As it could be expected, when the value of L_{ext} increases, the total charge density contained in the device also increases and the behavior of the device resembles more and more to a GAA FET. However, from Figure 8 it can be observed that whenL_{ext} reaches an 85% of the total length, the charge contained in the device is saturated and it does not increase anymore. This conclusion is important since a higher extension could mean a higher production cost per device without a corresponding performance improvement.

4 Conclusions

A 2D Schrödinger-Poisson solver applicable to a wide variety of Multiple-gate MOSFETs geometries has been developed. Classical simulations clearly overestimate the peak electron density and the total charge. Corner rounding has been demonstrated as an efficient way to reduce corner effects and obtain a more uniform electron density. Finally, we have investigated Omega-gate MOSFETs as a function of the extension of the gates in the buried oxide. When L_{ext} reaches an 85% of the total length the charge contained in the device becomes saturated.

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