An Analytical Model of Inversion Layer Quantization and Gate Oxide Quantum Mechanical Tunneling in Nano-p-MOSFETs

Amit Chaudhry and Jatinder N. Roy

***Abstract*—In this paper, an analytical model has been developed to study energy quantization in p type Metal Oxide Semiconductor Field Effect Oxide (MOSFETs). Inversion-layer quantization has been modeled using variation and triangular well approach for n-MOSFETs and p-MOSFETs respectively. The inversion charge density for holes has been found to be much lesser than the electron inversion charge density. The gate capacitance has also been evaluated for p-MOSFETs. It has been found that the inversion layer capacitance of holes in p-MOSFET is lesser than the inversion layer electrons in n-MOSFETs and hence the gate capacitance is much lesser in p-MOSFETs. The hole tunneling across the gate oxide has also been computed. It has been found to be much lesser than the electron tunneling in n-MOSFETs. All the results have been compared with the reported numerical results in the literature.**

***Index Terms*—CMOS, Inversion quantization, BSIM, Holes, Capacitance.**

I. Introduction

MOSFETS modeling is facing difficulties to achieve accurate description of extremely scaled down devices. The reason is that many complicated new phenomena are arising which are not easy to describe. One such phenomenon arising out of down scaling the MOSFET is the failure of classical physics at nanoscale. n-MOSFETs have been studied a lot and at length at nanoscale since their evolution in early 1950s [1]-[5]. Since then scaling down of both p-MOSFETs and n-MOSFETs has been taking place for their use in Complementary Metal Oxide Semiconductor (CMOS) technology. Very less attention has been given to the modeling process of p-MOSFET in lower geometries mainly because of the complex band structure of the valence band. At nanoscale geometries, the electrical fields at the oxide/substrate interface become very high. This is due to extremely thin oxide and high doping concentration in the substrate. This results in the charge carriers occupying quantized two-dimensional sub-bands which behave differently from the classical three-dimensional case. So, the complexity of the valence band further increases. The valence bands under very high electrical fields at the oxide/silicon interface tend to mix up or intermingle and hence simple approach to study hole inversion layers has not been dealt with. Due to this reason, the hole inversion layers have not been studied analytically but mainly experimental work has been done and whatever, theoretical work done already has yielded complex solutions not suitable for device simulation [6]-[13]. This makes simple formulations of hole quantization much more difficult to calculate accurately. Moreover, step wise step analytical formulation is missing in most of the literature yielding very less information about the hole quantization modeling process.

An attempt has been made in this paper to give a simple and yet accurate description of the energy quantization process for both n-MOSFET and in a p-MOSFET. Further, effects on the gate capacitance and gate oxide hole tunneling have also been considered.

A. Chaudhry is with University Institute of Engineering and Technology, Panjab University, Chandigarh, India (e-mail: amit_chaudhry01@yahoo.com).

J. N. Roy is with Solar Semiconductor Private Limited, Hyderabad, India (e-mail: jatin.roy@solarsemiconductor.com).

II. Energy Quantization

A. n-MOSFET

The research in the area of energy quantization started in the early 1950s. The research [1-5] mainly focused on only calculating the inversion charge density in the presence of energy quantization effects using variation approach and triangular well approach in the MOSFET. The use of such techniques required the calculation of surface potentials at the interface of silicon and its oxide. The lack of availability or slow development of surface potential models six decades ago, never allowed the growth of research in the area of modeling inversion layer quantization in MOSFETs. But as the MOSFETs are being scaled down to the nm scale, the need of research has risen, to analytically model the MOSFETs under inversion layer quantization conditions.

Solving the Poisson equation in the electron inverted channel for n-MOSFET, we get the total charge density Q_s.

$$Q_s = -\left(2qN_a\varepsilon_{Si}\varepsilon_0\right)^{1/2}\left[\varphi_s + V_t e^{-2\varphi_f/V_t}\left(e^{\varphi_s/V_t}-1\right)\right]^{1/2} \quad (1)$$

Similarly, the depletion charge Q_b is approximated as

$$Q_b = -\left(2\varepsilon_{Si}\varepsilon_0 qN_a\varphi_s\right)^{1/2}. \quad (2)$$

Therefore the inversion charge density Q_{inv} is given by (1)–(2):

$$Q_{inv} = -\gamma C_{ox}\left[\left\{\varphi_s + \frac{kT}{q}\exp\left(\frac{q(\varphi_s - 2\varphi_f)}{kT}\right)\right\}^{1/2} - \varphi_s^{1/2}\right] \quad (3)$$

γ – body effect parameter, C_{ox} – oxide capacitance, φ_s – surface potential, φ_f – Fermi potential, N_a – substrate concentration, $V_t = kT/q$ – thermal voltage.

The main problem with equation (3) is that the surface-potential has to be evaluated explicitly in all the regions of inversion and then only, the equation (3) can be solved. An explicit solution has been evaluated in the [14].

The wave function solution of the Schrödinger's equation is given using variation approach is [1] to study electron inversion layers as:

$$\Psi(x) = \frac{b^{3/2}x}{\sqrt{2}}\exp\left(-\frac{bx}{2}\right) \quad (4)$$

where b is a constant and given by

$$b = \frac{\left[48\pi^2 m^* q^2\left\{\frac{11}{32}n_{inv} + n_{dep}\right\}\right]^{1/3}}{\varepsilon_{Si}\varepsilon_0 h^2}$$

where: m^* – effective longitudinal mass of electron in <100>=$0.98m_0$, $n_{inv}=Q_{inv}/q$ – inversion electron concentration, $n_{dep}=Q_b/q$ – depletion charge concentration.

The corresponding shift in the energy [1] is given by

$$E_{oe} = \frac{3h^2 b^2}{8m^*} \quad (5)$$

The shift in the surface potential is

$$\delta\varphi_{se} = \frac{E_{oe}}{q} \quad (6)$$

The equation (6) is then included in the explicit surface potential expression given by [14] and the total surface potential is obtained. Then a model of quantum inversion charge density is obtained from equation (3) by including surface potential from [14].

$$Q_{invqm} = -\gamma C_{ox}\left[\left\{\varphi_{sqm} + \frac{kT}{q}\exp\left(\frac{q(\varphi_{sqm} - 2\varphi_f)}{kT}\right)\right\}^{1/2} - \varphi_{sqm}^{1/2}\right] \quad (7)$$

where φ_{sqm} is the quantum surface potential [14].

B. p-MOSFET

The hole inversion layers are studied using the triangular well approximation for solving the Schrödinger's equation [15].

$$E_i = \left(\frac{h^2}{8m_1\pi^2}\right)^{1/3}\left[1.5\pi q E_s\left(i + \frac{3}{4}\right)\right]^{2/3} \quad (8)$$

E_i – airy function, $E_s=(\eta Q_{inv}+Q_{depl})/\varepsilon_{Si}\varepsilon_0$ – surface electrical field, η=0.8 – for holes [15], m_1=$0.16m_0$ [16] for (100) surface.

The equation (8) gives the energies of the holes in the quantized potential well at the Si/SiO_2 interface. The hole energy in the first energy state can be found by putting i=0 in equation (8)

$$E_{oh} = \left(\frac{h^2}{8\pi^2 m_1}\right)^{1/3}\left(1.1\pi q E_s\right)^{2/3}. \quad (9)$$

The shift in the surface potential is obtained using equation (6) as:

$$\delta\varphi_{sh} = \frac{E_0}{q} \quad (10)$$

The equation (10) is then included in the explicit surface potential expression given by [14] and the total quantum surface potential is obtained and the quantum inversion charge density is obtained given by equation (7).

Energy quantization effects on carrier distribution in n-MOSFET and p-MOSFET are studied and analytically modeled. The results in Fig. 1 show that the hole density is much lower than the electron density showing that the energy quantization effect is more severe in p-MOSFETs than the n-MOSFETS. This is due to the smaller effective mass perpendicular to Si/SiO_2 interface for inversion-layer holes on a (100) surface as compared to the electron effective mass. The electron inversion layers are matched with the BSIM 5 results [16].

III. C-V Modeling

Approximating the inversion charge density for the weak inversion region and strong inversion regions separately, we get after differentiating the equation (7) with respect to surface potential, the weak inversion and strong inversion capacitances as:

The inversion capacitance in the presence of energy quantization is

$$C_{invqm} = \frac{C_{wi}C_{si}}{C_{si} + C_{wi}} \quad (11)$$

where: $C_{wi}=(q/kT)Q_{invqm}$ is the weak inversion capacitance, $C_{si}=(q/2kT)Q_{invqm}$ is the strong inversion capacitance, and

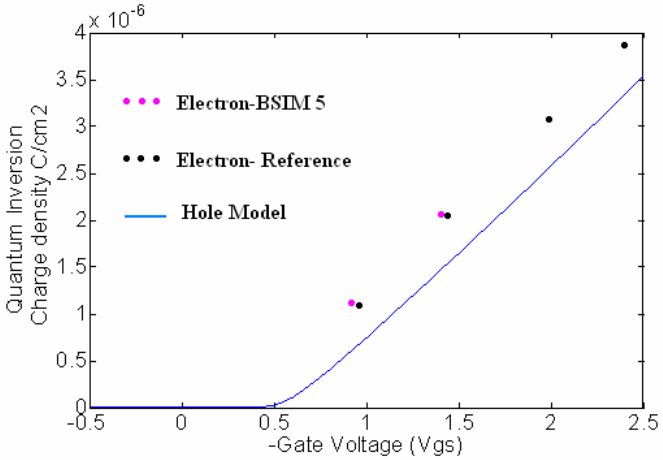

Fig. 1. Simulated results of quantum mechanical electron inversion charge density using variation approach and hole inversion charge density using triangular well approach.

Q_{invqm} – quantum inversion charge density from the equation (7).

Total quantum gate capacitance is equal to

$$\frac{C_{ox}\left(C_d + C_{invqm}\right)}{C_{ox} + C_d + C_{invqm}} \tag{12}$$

where C_{ox} – oxide capacitance, C_d – depletion capacitance obtained by differentiating (2) with respect to surface potential.

Energy quantization effects on gate capacitance in n-MOSFET and p-MOSFET are studied and analytically modeled. The results in Fig. 2 show that the hole gate capacitance is much lower than the electron density showing that the energy quantization effect is more severe in p-MOSFETs than the n-MOSFETS. The hole gate capacitance matches closely with the numerical results [7].

IV. Gate Oxide Hole Tunneling

In extremely scaled oxides, the charge carriers in the inverted channel directly tunnel into the gate oxide. A model has been developed which describes the gate oxide tunneling using the Wentzel-Krammers-Brillouin (WKB) approach [17,18]. Energy quantization effect has been included in the gate tunneling model to accurately measure the direct gate tunneling density. The developed model considers both electron and hole tunneling in the gate insulators for n-MOSFETs and p-MOSFETs respectively.

A. n-MOSFET

The main issue in the current density calculation is transmission probability *T(E)*. The general expression for the transmission probability is given by [17, 18]:

$$T(E) = \exp\left[-2\int_{x_1}^{x_2} |k(x)|\,dx\right] \tag{13}$$

where *k(x)*, wave factor is given by

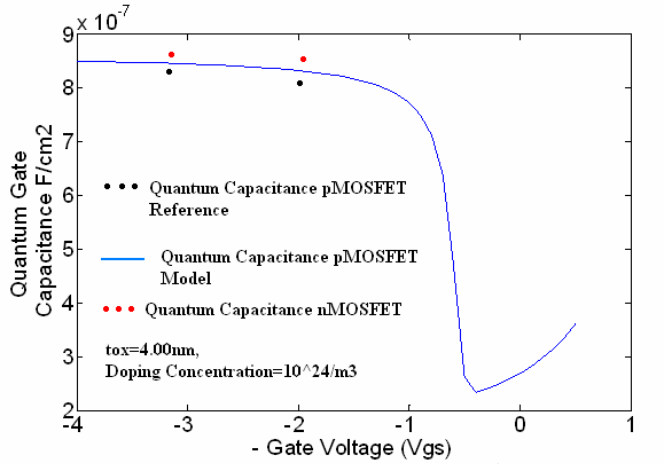

Fig. 2. Simulated results of the gate capacitance (F/cm^2) including energy quantization in the substrate. The reference is reported in [7]. The parameters are oxide thickness=4nm and substrate doping =1x10^{18}/cm^3.

$$\left[\frac{2m_{ox}\left(V(x)-E\right)}{\hbar^2}\right]^{1/2}$$

where m_{ox}=0.32m_0 is the effective electron mass in the silicon oxide [19], $\hbar$ – effective Planck's constant.

The direct tunneling current density in the gate oxide is given as [18]

$$J_T = \frac{4\pi m_t q}{h^3}\int_0^V \left\{\int_0^\infty \left[f_S(E) - f_D(E)\right]dE_t\right\} T(E_x)\,dE_x \tag{14}$$

where: $f_S(E)=1/\{1+exp(E-E_{fs})/kT\}$ – electron distribution at the source/substrate interface, $f_D(E)=1/\{1+exp(E-E_{fd})/kT\}$ – electron distribution at the drain/substrate interface, E_{fs} – Fermi energy at the source, E_{fd} – Fermi energy at the drain, E – total energy of the electrons, E_x – energy in the direction of tunneling, i.e. from source to drain, E_t – energy in transverse direction, and m_t=0.19m_0 – electron transverse mass.

Using (13) and (14), the tunneling current density in the gate oxide can be calculated.

B. p-MOSFET

The hole tunneling into the gate oxides becomes important when the p-MOSFET are operated in the circuits such as CMOS inverters. The process of the hole tunneling process in the valence band is the same as that for electrons in the conduction band. The most significant difference between electron tunneling and hole tunneling lies in the average barrier height. Holes face a barrier from the valence band edge of silicon to the valence band edge of gate oxide. This barrier is more in case of valence band tunneling.

The parameters used for the calculation for the hole tunneling are transverse mass of hole in silicon m_h*=0.45m_0 [20], hole mass in oxide m_{hox}= 0.30m_0 [20], oxide barrier height for holes E_b=4.5eV–$qVox/2$, where V_{ox} – oxide potential.

In Fig. 3, the hole tunneling current density in a p-MOSFET is smaller than the electron tunneling current density in an n-MOSFET because of the high barrier height and large effective transverse mass for holes. The results match quite closely with the reported results from the reference [20].

V. Conclusion

A detailed study has been done to evaluate the electrical parameters like C-V and inversion charge density in the p-MOSFETs. Based on the variation approach and triangular well approach, all these parameters have been derived. In the presence of energy quantization, the inversion charge capacitance has been obtained. The total gate capacitance with quantum mechanical effects in p-MOSFETS reduces as compared to the n-MOSFETs. This is due to reduced charge density at interface of the substrate and the oxide. The tunneling of holes into the oxide cannot be ignored which increases as the oxide thickness falls but it is lesser than the electron gate oxide tunneling.

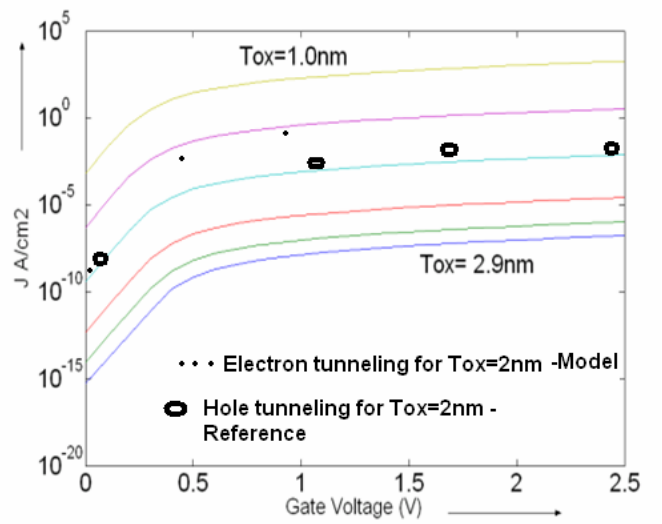

Fig. 3. Gate hole tunneling current density at various gate to source voltages $|V_{gs}|$ = (0-2.5V) at substrate donor concentration (N_d=4x10^{17}/cm^3) and oxide thickness varying as 2.9nm, 2.75 nm, 2.48nm, 2.0 nm, 1.5nm to 1.0 nm.

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