ANALYTICAL MODELING OF ENERGY QUANTIZATION EFFECTS IN MOSFETS

Amit Chaudhry
University Centre for Instrumentation and Microelectronics, Panjab University, Chandigarh, India,
Email: amit_chaudhry01@yahoo.com

J.N. Roy
Solar Semiconductor Private Limited, Hyderabad , India

ABSTRACT – **In this paper an analytical model has been developed to study the Energy Quantization Effects occurring in the MOSFETs (Metal Oxide Semiconductor Field Effect Oxide) under various conditions. These effects have resulted in a reduction in drain current and degradation of gate capacitance.**

Index terms: **QME, Energy Quantization, DIBL, BSIM.**

INTRODUCTION

MOSFET 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 nm (nanometer) scale. As CMOS (Complementary Metal Oxide Semiconductor) technology scales down aggressively, it approaches a point, where classical physics is not sufficient to explain the behavior of a MOSFET. At this classical physics limit, Quantum Mechanics has to be taken into account to accurately assess the overall performance of a MOSFET. Therefore, to predict the behavior of these devices and fabricate them at the nanometer scale, a thorough understanding of QME (Quantum Mechanical Effects) is a must. Simple analytical models of the MOSFETs including QME are needed for computer-aided design of digital and analog integrated circuits at nanometer scale containing thousands to millions transistors on a silicon chip. To model a MOSFET in the presence of QME, the Quantization of Energy levels in the direction perpendicular to the oxide/silicon substrate interface need to be properly understood and studied.

The paper is organized as follows: The paper starts with an overview of the basic MOSFET models.

Secondly, modeling of Energy Quantization Effect has been done and its impact has been studied on various MOSFET parameters.

Thirdly, C-V (Capacitance-Voltage) and I-V (Drain Current-Voltage) model is presented by considering the Energy Quantization effect on inversion carrier distribution.

MOSFET MODELS

The Charge based models include the basic SPICE (Simulation Program with Integrated Circuit Emphasis)Level 1, Level 2, Level 3, BSIM(Berkeley Short Channel Insulated gate Field effect transistor model) models and the other advanced models such as BSIM 4 and 5 [1-5]. Secondly, the potential based models include the SP (Surface Potential) model, MOS Model 11, HiSIM (Hiroshima Starc Insulated gate Field effect transistor model) model etc. [6-9] and thirdly, the conductance based models like the EKV(Enz , Krummenacher,Vittoz) model [10]. In the modeling research area, attempts are being made to include the QME in these standard models also. The other models which include the Energy Quantization effects though empirical in nature are Hansch model [11], Van Dort Model [11], Inversion charge model [12] etc. A conclusion can be inferred is, though attempts are being made to include QME in MOSFET models all over the world in IC (Integrated Circuits) industry, yet a MOSFET model largely analytical in nature including QME is still to be developed.

ENERGY QUANTIZATION

The research in the area of Energy Quantization started in the early 1950s. The research [13-17] 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 QME in MOSFETs. But as the MOSFETs are being scaled down to the nm scale, the need of research has risen, to analytically model the QME in MOSFETs.

MODEL, SIMULATION AND ANALYSIS

Solving the Poisson equation in the inverted channel, we get the total charge density "Q_s".

$$Q_s = -(2qN_a\varepsilon_{si}\varepsilon_o)^{1/2}[\varphi_s+V_t\, e^{-2\varphi f/Vt}\,(e^{\varphi s/Vt}-1)]^{1/2} \qquad (3)$$

Similarly, the depletion charge "Q_b"is approximated as

$$Q_b = -\,(2\varepsilon_{si}\varepsilon_o\, qN_a\varphi_s)^{1/2} \qquad (4)$$

Therefore the inversion charge density "Q_{inv}" is given by (3) - (4):

$$Q_{inv} = -\gamma C_{ox}[\{\varphi_s+kT/q \exp q(\varphi_s-2\varphi_f)/kT\}^{1/2} - (\varphi_s)^{1/2}] \qquad (5)$$

Where:

γ =Body Effect Parameter, C_{ox} = Oxide Capacitance, φ_s = Surface Potential, φ_f = Fermi potential, N_a = Substrate concentration, Thermal voltage =V_t = kT/q

The main problem with Eq. 5 is that the surface-potential has to be evaluated explicitly in all the regions of inversion and then only, the Eq. 5 can be solved. An explicit solution has been evaluated in the [18].

The wave function solution of the Schrödinger's equation is given using variation approach is [13]

$$\Psi(x) = \frac{b^{3/2}\, x}{\sqrt{2}} \exp\left(-\frac{bx}{2}\right) \qquad (6)$$

Where b is a constant and given by

$$b = \left[\frac{48\pi^2 m^* q^2}{\varepsilon_{si}\varepsilon_o\, h^2}\{(0.33n_{inv}+n_{dep})\}\right]^{1/3}$$

m* = Effective longitudinal mass of electron in <100> = $0.98m_o$

n_{inv} = Inversion electron concentration = Q_{inv}/q

n_{dep} = Depletion charge concentration= Q_b/q

The corresponding shift in the energy [13] is given by

$$E_o = \frac{3h^2b^2}{8m^*} \qquad (7)$$

The shift in the surface potential is = E_o /q (8)

The Eq. 8 is then included in the explicit surface potential expression given by [18] and the total surface potential is obtained.

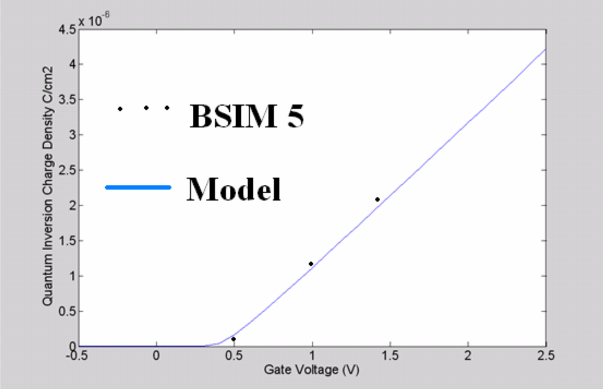

Fig 7: Simulated Results of Quantum Mechanical Inversion charge density using Variation Approach

Energy Quantization effects on carrier distribution in p-type substrate are studied and analytically modeled. The results in figure 7 match quite closely with the BSIM 5 results [19]. The results have been achieved by accurately modeling the shift in the surface potential Eq. 8 by evaluating n_{inv} and n_{dep} from Eq.3 and Eq.4. The results show that the Energy Quantization leads to reduced Inversion charge densities and increased surface potentials in the substrate. It has been analytically proved that the classical theory overestimates the value of inversion layer charge density as compared to the Quantum Mechanical Charge density.

C-V AND I-V MODELING

Approximating the inversion charge density for the weak inversion region and strong inversion regions separately, we get after differentiating the Eq. 5 with respect to surface potential, the weak inversion and strong inversion capacitances as:

The inversion capacitance in the presence of Energy Quantization is

$$C_{invqm}= C_{wi}\,C_{si}/(C_{si}+C_{wi}) \qquad (9)$$

Where

$C_{wi}=(q/kT)Q_{invqm}$ is the weak inversion capacitance.

$C_{si}=(q/2kT)Q_{invqm}$ is the strong inversion capacitance.

Q_{invqm}= Quantum inversion charge density

Total gate capacitance

$$= C_{ox}(C_d+C_{invqm})/(C_{ox}+C_d+C_{invqm}) \qquad (10)$$

Where C_{ox}= Oxide capacitance, C_d = Depletion capacitance obtained by differentiating (4) with respect to surface potential.

The drain current above threshold [20] is given by Eq.11

$$I_{ds1} = -\mu C_{ox}(W/L)[(V_{gs}-V_{fb})(\varphi_{sL}-\varphi_{so})-0.5(\varphi_{sL}^{2}-\varphi_{so}^{2}) - 0.67\gamma(\varphi_{sL}^{3/2}-\varphi_{so}^{3/2})] \qquad (11)$$

Where φ_{sL} is the surface potential at the drain and φ_{so} is the surface potential at the source, μ= Electron Mobility, W= Width, L= Length, V_{fb} = Flatband voltage.

The drain current in sub threshold region [20] is given by Eq.2

$$I_{ds2}=-\mu C_{ox}(W/L)V_t[(\varphi_{sL}-\varphi_{so})+\gamma(\varphi_{sL}^{1/2}-\varphi_{so}^{1/2})] \qquad (12)$$

The total drain current is the summation of (11) and (12).

$$I_{ds}=I_{ds1}+I_{ds2} \qquad (13)$$

This drain current expression (13) is upgraded to include the Energy Quantization Effects by replacing the classical surface potential by the Quantum surface potential from (8) and [18]. The degraded mobility and the DIBL parameters are given by [21] and [22] respectively and have been included empirically in (13). The results in figure 8 show that the classical theory overestimates the value of Gate Capacitance. A drain current/drain voltage model including Energy Quantization has been developed. A large drive current loss has been observed as shown in figures 9 and 10.

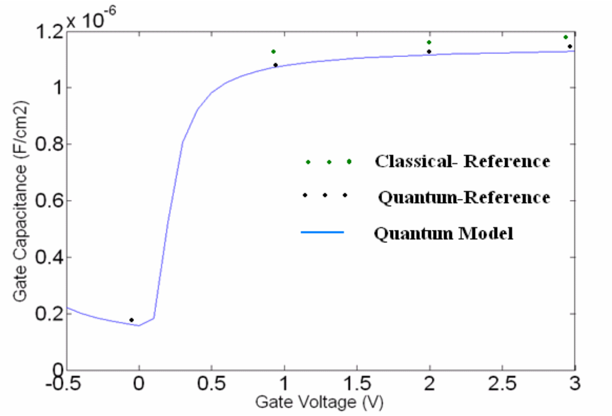

Fig 8: Simulated results of the Total MOSFET Capacitance (F/cm^2) including Energy Quantization in the Substrate [23]

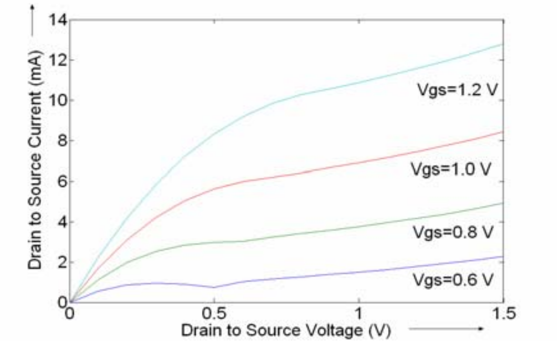

Fig 9: Simulated results of Drain Current without considering Energy Quantization at L=80nm (L_g (Gate length) =130nm (Empirical fit of 0.03 V has been given for PolySilicon depletion effect)

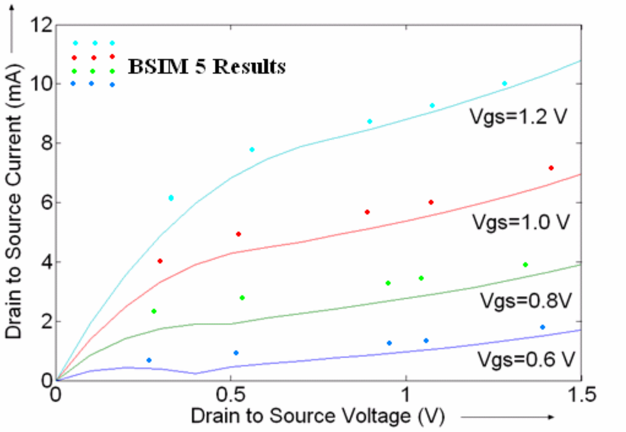

Fig 10: Modeled drain voltage and drain current characteristics at L=80nm (L_g=130nm) with Energy Quantization including Poly Silicon Gate depletion at N_p =10^{19}/cm^3 and V_{bs} (body bias) = -0.75 and are well in range as predicted by [19].

CONCLUSION

In this paper, full model has been developed for the QME in the nanometer scale MOSFET. The MOSFET I-V and C-V characteristics in presence of Energy Quantization Effect have been upgraded to include this effect. This model also includes all short channel related effects including mobility reduction and DIBL. The study shows that the drain current decreases due to the Energy Quantization Effect resulting in the significant loss in the drive current. The value calculated by the analytical model and BSIM5 matches closely.

ACKNOWLEDGMENT

The authors thank the Director , University Centre for Instrumentation and Microelectronics, Panjab University, Chandigarh, India for allowing to carry out the work.

REFERENCES

[1] Foty D, “MOSFET Modeling with SPICE, Principles and Practice”, Prentice Hall, 1997.

[2] Foty D, “Perspectives on Analytical Modeling of Small Geometry MOSFETs in SPICE for Low Voltage/Low Power CMOS Circuit Design,” Analog Integrated Circuits and Signal Processing, Journal of, Vol.21, pp.229-252, 1999.

[3] BSIM4.3.0 MOSFET Model- User’s Manual - Department of Electrical Engineering and Computer Sciences,University of California, Berkeley, CA 94720.

[4] Lee W. C and Hu C.M, "Modeling CMOS tunneling currents through ultrathin Gate oxide due to conduction- and valence-band electron and hole tunneling",Electron Devices, IEEE Transactions on, Vol. 48, No. 7, pp. 1366-1373,July,2001.

[5] Xi.X et al, “BSIM5 MOSFET Model”, IEEE, pp.922-923, 2004.

[6] Gildenblat.G, Wang. H, Chen T.L, Gu. X, and Cai. X, “SP: An Advanced Surface-Potential-Based Compact MOSFET Model ,” Solid state circuits , IEEE Journal of, Vol. 39, No. 9, pp. 1394-1406,Sept,2004.

[7] Miura- Mattausch.M, Ueno.H, Mattausch. H.J,Kumashiro.S,Tamaguchi.T and Nakatama.N, “HiSIM: Self -Consistent Surface – Potential MOS model valid down to sub-100 nm technologies,” MSM Workshop,April,2002

[8] HiSIM 1.1.1 User’s manual, Semiconductor Technology Academic Research Centre (STARC)

[9] Suetake.M et al, “HiSIM: A drift Diffusion –Based Advanced MOSFET Model for Circuit Simulation with Easy Parameter Extraction,” IEEE, pp.261-264, 2000.

[10] Enz C, Krummenacher F, Vittoz E, “ An analytical MOS transistor model valid in all regions of operation and dedicated to low-voltage and low-current applications”. Analog Integrated Circuit Signal Processing, Journal of, Vol.8, pp.83-114, 1995.

[11] Yu.Z, Dutton.R.W and Kiehl.R.A, “Circuit/Device Modeling at the Quantum level”, Electron Devices, IEEE Transactions on ,Vol 47, No.10, pp.1819-1825,Oct, 2000

[12] Cheng. Y, “ICM- An analytical inversion charge model for accurate modeling of thin Gate oxide MOSFETs”, IEEE, pp. 109-112, 1997.

[13] Stern.F, "Self-consistent results for n-Type Si inversion layers", Physics Review B, Vol. 5, No. 12, pp. 4891-4899, June1972.

[14] Fang.F.F and Howard W.E, "Negative field-effect mobility on (100) Si surfaces",Physics Review letters, Vol. 16, No. 18, p. 797-799, 1966.

[15] Stern. F and Howard. W.E,” Properties of Semiconductor Surface Inversion Layers in the Electric Quantum Limit”, Physical Review, Vol.163, No.3, pp. 816-815, Nov,1967.

[16] Stern.F,“Surface quantization and surface transport in semiconductor inversion and accumulation layers,’ Vacuum Science and Technology, Journal of, Vol.9, No.2, pp.752-753.

[17] Ando. T, Fowler .A.B, Stern. F,” Electronic properties of two-dimensional Systems”, Review of Modern Physics, Vol. 54, No.2, pp.437-672, April, 1982

[18] Van Langevelde R, Klaassen FM., “An explicit surface-potential-based MOSFET model for circuit simulation”, Solid-State Electronics, Journal of, Vol.44, No.3, pp.409-418, 2000.

[19] He, J, et al, “BSIM 5: An advanced charge based MOSFET model for nanoscale VLSI circuit simulation”, Solid-State Electronics, Journal of , Vol.51, pp.433-444, 2007.

[20] Arora.N, “MOSFET Models for VLSI Circuit Simulation- Theory and Practice”, Austria: Springer,1993.

[21] Garverick.S and Sodini.C, "A Simple model for Scaled MOS Transistors that includes Field Dependent Mobility,” Solid State Circuits, IEEE Journal on, Vol.SC-22, pp.111-114, Jan, 1987.

[22] Graff. H and Klassen.F, “Compact Transistor modeling for circuit design”, Springer, 1990.

[23] Richter CA, Hefner AR, Vogel EM. “A Comparison of Quantum Mechanical Capacitance–Voltage simulators”. Electron Devices Letters. IEEE transactions of , Vol.22, No.1 , pp.35-37, 2001.