MODELING OF QUANTUM MECHANICAL EFFECTS IN NANOMETER SCALE MOSFETs

(Ph.D. Thesis)

ABSTRACT

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 nanometer scale. As CMOS 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 Quantum Mechanical Effects is a must.

Simple analytical models of the MOSFETs including Quantum Mechanical Effects 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 Quantum Mechanical Effects, the Quantization of Energy levels in the direction perpendicular to the oxide/silicon substrate interface, the Quantum Mechanical charge carrier density directly tunneling from source to drain and direct tunneling in the Gate oxide need to be properly understood and studied.

The thesis is divided into the following chapters:
Chapter 1

Chapter 1 deals with a detailed overview of the basic MOSFET models such as Charge based models, Potential based models and Conductance based models. The Charge based models include the basic SPICE Level 1, Level 2, Level 3, BSIM models and the other advanced models such as BSIM 4 and 5. Secondly, the potential based models include the Surface Potential (SP) model, MOS Model 11, HiSIM model etc. and thirdly, the conductance based models like the EKV model. Attempts are being made to include the Quantum Mechanical Effects in these standard models also. A comparison has been drawn out of these three modeling approaches and clearly potential based approach is much better than the other approaches, it being the most physics based approach. Various Quantum Mechanical Effects have been studied and detailed literature survey has been done. Various Quantum Mechanical Effect modeling approaches, developed so far, have also been discussed and analyzed for their merits and demerits.

The review of literature has thrown light on various aspects of the problem of Quantum Mechanical Effects. A conclusion that can be inferred from Chapter 1 is, though attempts are being made to include Quantum Mechanical Effects in MOSFET models all over the world in IC industry, yet a MOSFET model which includes all the non classical phenomena is still desired to be developed.

Chapter 2

In Chapter 2, an attempt has been made to understand the Quantum Mechanical Direct Tunneling effects due to the scaling down of the oxide thickness to angstrom levels. In such extremely scaled oxides, the charge carriers in the inverted channel directly tunnel into the Gate oxide. Both Fowler Nordhiem and Quantum Mechanical direct tunneling have been discussed and modeled. A simple analytical model has been developed which describes the Gate oxide tunneling using the Wentzel-Krammers-Brillouin (WKB) approach. This approach is the standard method to calculate the Gate tunneling transmission probability. Energy Quantization Effect, which is a prominent Quanum Mechanical Effect in MOSFETs has been included in the
Gate tunneling model to accurately measure the direct Gate tunneling density. This model considers both electron and hole tunneling in the Gate insulators. The electron and hole Gate tunneling current densities match closely with the experimental and the numerical simulation results available in the literature. In addition to this, an impact of the Poly Silicon Gate depletion along with doping concentration variation in the Poly Silicon Gate effect has been discussed and analytically modeled. Instead of using silicon dioxide, high-κ gate insulators such as lanthanum oxide, silicon nitride, and aluminum oxide have been used in order to reduce Gate oxide tunneling. The analytical model results show that the Gate oxide tunneling currents reduce to a huge value owing particularly to the increased Gate insulator thickness of these alternative dielectrics. The developed model has been validated against the experimental and numerical results obtained from standard published research work.

The conclusion is, with the continuing scaling down of the MOSFETs, the Gate leakage currents will increase and only solution seen so far is to make use of alternate Gate oxides instead of Silicon oxide.

Chapter 3

In Chapter 3, modeling of Energy Quantization Effect has been done and its impact has been studied on various MOSFET parameters. Two approximations are used to solve Schrödinger’s equation in the MOSFET inverted channel to calculate the surface potential and the inversion charge densities applicable in all the regions of inversion. The techniques used to solve the Schrödinger’s equation are Triangular well approximation and Variation approximation. A comparison is also done between these approaches in order of their accuracy of modeling the Energy Quantization Effect. The results obtained using these approximations have been compared with the BSIM 5 model. The results using the Triangular well approximation predict a much lower inversion charge density and higher electronic potentials as compared with the BSIM 5 results. The results using the Variation approximation match closely with the BSIM 5 results.
The solution of the Schrödinger's equation using Variation approximation has been used to find the energy level shift and hence, the surface potential shift in the channel. The quantum surface potential shift requires the explicit calculation of the inversion charge density and the depletion charge density in the substrate. To calculate these parameters, an explicit expression of the surface potential is required. Normally, in the literature, it is found, that to calculate the shift in the surface potential, some approximations are made and the model accuracy is hence, sacrificed.

In this work, the shift in the surface potential is computed using surface potential in an explicit way in terms of Gate Voltage. Moreover, inversion charge density and depletion charge density have been calculated explicity and no approximation has been used to calculate these two parameters. The explicit model has been taken from the reference. Hence, the shift in the surface potential is calculated, which is included again in the explicit surface potential expression. This will generate the total surface potential in the presence of Energy Quantization Effects. The results show that due to the Energy Quantization Effect, the inversion carrier density reduces due to the increase in the required surface potential to obtain inversion charge density.

The effect of Poly Silicon Gate depletion on the surface potential and the inversion charge density has been also analyzed. The results indicate a huge decrease in the inversion charge density. The effect of Poly Silicon Gate Quantization on the inversion charge density has also been analytically modeled. The results indicate a further decrease in the inversion charge density in the substrate.

In the classical MOSFETs, the inversion charge density is maximum on the surface of the MOSFET and reduces exponentially. Whereas as per the Quantum Mechanical theory, the inversion layer density at the surface will decrease and reaches to a maximum value inside the substrate. This is called inversion layer Centroid. In this Chapter, the position of inversion layer centroid has also been analytically modeled and the results have been compared with the numerical results in the literature. The results match quite closely.
The major inference from the Chapter is that inversion charge density reduction will take place due to Quantum Mechanical Effects. The Poly Silicon Gate depletion and Poly Silicon Gate Quantization will reduce the inversion charge densities to a great extent. It has been analytically proved in the Chapter.

Chapter 4

In Chapter 4, Capacitance-Voltage and Drain Current-Voltage model is presented by considering the Energy Quantization effect on inversion carrier distribution. A one dimensional CV analysis of MOSFETs has been done using both the Classical theory and in the presence of Energy Quantization in the substrate. Special case of Poly-Silicon Gate depletion has also been taken. A decrease in the capacitance has taken place due to Energy Quantization. A threshold voltage model for the MOSFET has also been developed that includes Energy Quantization. The threshold voltage shows a marked positive shift in case of the Energy Quantization. The output characteristics have been determined using the Charge-sheet model approximations. This model has been upgraded to include the Energy Quantization effect using the Variation approach. The model has been extended to the 80nm channel length by including mainly two short-channel effects i.e. Mobility reduction and Drain induced barrier lowering effect. Drain to Source Saturation voltage has also been evaluated. The analytical model results are in close proximity with the BSIM 5 model. The modeling done shows a decrease in the drain current at nanometer scales. Energy Quantization reduction effect has also been taken by using the strained silicon technology. Empirical modeling has been done to show that use of strained silicon technology result in a large increase in the drain currents. This is due to fact that straining the lattice increases mobility and decreases the energy band gap thus contributing positively to the increase of drain current.
Chapter 5

In Chapter 5, an attempt has been made to understand the Quantum Mechanical tunneling effects due to the scaling down of the Gate length to the nanometer levels (Sub 10nm). In such extremely scaled MOSFETs, the electrons from the source directly tunnel into the p-substrate to the Drain even at zero Gate voltages. An analytical model has been developed which describes the source/substrate/drain tunneling using the WKB approach. Important effects at the sub 10nm scale such as band-gap narrowing, Energy Quantization and Drain induced barrier lowering have been included to model the direct Quantum Mechanical Tunneling current from source to drain. The developed model has been validated against the numerical results obtained from standard published research work.

Chapter 6

Lastly, the work ends with the conclusions and scope for further studies in the present area of nanometer scale technologies. The results obtained using the models developed in the work are well in consonance with the measured and standard models.