QUANTIZATION EFFECTS ON THE GATE CAPACITANCE OF A DOUBLE GATE MOSFET

By

Kalyan Mondol, and
Yeasir Arafath

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Approved By

Thesis Advisor	Chairperson
Dr. Khairul Alam	Dr. Halima Begum

Abstract

The MOS technology is continuously scaling down for high performance and therefore the quantum physics becomes necessary to explain the behavior of today's MOSFETs. In this thesis work, we investigate the quantization effects on the gate capacitance of a double gate MOSFET using a self-consistent solution of poisson's and schrödinger's equations of the industry standard simulation tool silvaco. To find the quantization effect we vary the electron and hole effective masses and also the channel thickness. For electron, when we start to reduce the effective mass from a nominal value the quantization effects become noticeable at $m_c<0.1m_o$ and the eigen energy spacing increases significantly which decreases the capacitance value. And the C-V curves become step like in inversion. For hole, when we reduce the hole effective mass, quantization effects become noticeable at $m_v<0.1m_o$ and separation between eigen energies increases significantly which leads to decrease the capacitance. For both hole and electron quantization we notice that the channel inversion switches from surface inversion to volume inversion as the effective mass goes below $0.1m_o$. And finally we reduce the channel thickness for two different effective masses of electron and hole. Here we don't see any step in C-V curve but we see a different phenomenon. When we put $m_c = m_v = 0.5m_o$ and change the channel thickness from 10 nm to 2 nm, the bottom of the C-V curve shifts left and the minimum capacitance is reduced. However, when we put $m_c = m_v = 0.05m_o$ and change the channel thickness from 10 nm to 2 nm, in addition to the shift of the bottom in C-V curve, the capacitance values in accumulation and inversion are also changed.

Acknowledgements

This thesis is the result of eight months of work and at that time we have supported by many people. And finally now we get the opportunity to express our gratitude to all of them.

Firstly we like to thank our supervisor Dr.Khairul Alam, Associate professor of Department of Electrical and Electronic Engineering of East West University for his strong guidance, innovative suggestion from the initial to final stage of this thesis. Without his support it was not possible for us to bring to light this thesis. We owe him lots of gratitude for guiding us with friendly behavior.

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Finally we would like to thank our family for support us all the way of this study, as well as thank to our entire friends for support us mentally.

Authorization

We hereby declare that we are the sole author of this thesis. We authorize East West University to lend this thesis to other institutions or individuals for the purpose of scholarly research.

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Chapter 1: Introduction

In 1926 Julius Edgar Lilienfeld first invented the metal–oxide–semiconductor field-effect transistor (MOSFET) which is a type of transistor used for amplification or switching electronic signals. The MOS (metal-oxide-semiconductor) transistor or MOSFET is the basic building block of most computer chips, as well as of chips that include analog and digital circuits. MOSFET is a four terminal device with source (S), gate (G), drain (D), and body (B) terminals. The body (B) or substrate of MOSFET is usually connected to the source terminal. The MOS transistor connects two external voltage sources which are drain-source voltage V_{DS} and gate-source voltage V_{GS}. This device looks like open circuit between the drain and the source. For small V_{GS} there is no path between the source and the drain and i_{Ds} is zero.When a voltage drop across the oxide induces a conducting channel between the source and drain, a current can flow through the channel.

The silicon MOS capacitor structure uses a heavily doped poly-silicon layer which behaves as a metal. The insulating layer is silicon dioxide and the other plate of the capacitor is the semiconductor layer. The capacitance of the MOS structure depends on the voltage (bias) on the gate since the semiconductor region under the oxide can be either depleted of carriers can accumulate carriers or an inversion layer can be formed. The flat band voltage is an important term which is related to the MOS capacitor. If there is no charge present in the oxide or at the oxide-semiconductor interface, the flat band voltage simply equals the work function difference between the gate metal and the semiconductor. Applied a positive gate voltage larger than the flat band voltage ($V_{GB} > V_{FB}$) positive charge is induced on the metal gate and negative charge in the semiconductor. The only negative charged electrons are available at the surface. This is known as surface inversion. If the applied gate voltage is lower than the flat band voltage ($V_{GB} < V_{FB}$) then a negative charge is induced at the interface between the gate and the oxide, positive charge induced in the semiconductor. This is only possible by pushing the negatively charged electrons away from the surface exposing the fixed positive charges from donors. This is known as surface depletion.

1.1 Objective

Double gate MOSFETs has a great interest in the field of electrical engineering because of its high performance and low power consumption in steady mode. Now a days nano scale MOS like 20 nm MOSFETs are available in market but coming from micro meter to nano meter in MOSFETs technology problems arise like short channel effect, quantization effect etc. To reduce the short channel effect today's technology uses very thin gate oxide and high cannel doping. But because of this thin gate oxide and high cannel doping high electric field is induced at the $Si/Si0_2$ interface that results in serious band banding at the interface. And created potential well becomes narrow enough to quantize the motion of channel carriers in the direction perpendicular to the interface. Because of this quantization the energy band split into the sub bands and the lowest energy level of electron in the potential well does not match with the bottom of the conduction band. The peculiarity of DG MOSFETs is that the top and bottom gates are biased simultaneously to establish equal surface potentials: $V_{G2} = V_{G1}$ for identical gate oxide thickness.

In this paper we try to find out the quantization effect on the gate capacitance of a symmetrical double gate MOSFET. To get more accurate result, atlas uses several quantum models to simulate various effect of quantum mechanism. Firstly we observe the electron quantization effect by reducing the electron effective mass and observe the C-V curve. Secondly we find the hole quantization effect by reducing the holes effective mass. And finally we reduce the channel thickness for two different effective mass of electron and hole to observe the quantization effect on C-V.

1.2 Literature review

Vimala and Balamurugan [1] derived the solution for quantum mechanical compact modeling of symmetric double-gate MOSFETs using variation approach such as electric potential and inversion-layer charge. In that paper solving the poisson and schrödinger equations simultaneously reveals quantum mechanical effects (QME) that influence the performance of double gate MOSFETs. The inversion charge and electrical potential distributions perpendicular to the channel are expressed in closed forms. The effect of silicon thickness variation in inversion-layer charge and potentials are quantitatively defined. The influence of space quantization effect on the threshold voltage, inversion layer, and total gate capacitance in scaled Si-MOSFETs is discussed by Vasileska and Ferry [2]. Explicit analytical models of charge and capacitance of undoped double-gate MOSFETs are developed by Moldovan [3]. Throughout the paper, the drain current and charge and capacitances are written as continuous explicit functions of the applied bias. It obtains very good agreement between the calculated capacitance characteristics and 2-D numerical device simulations, for different silicon film thicknesses. A comprehensive analysis of the impact of oxide thickness on the gate capacitance of MOSFET, nanowire FET, and CNTFET devices is done by Sinha and Chaudhury [4]. They compare and analyze the effect of variation of oxide thickness on gate capacitance for double gate MOSFET, silicon nanowire FET, and CNTFET deices through an exhaustive simulation. Impact of quantum-mechanical effects on the double gate MOSFET characteristics is executed by Dauge, Jomaah and Ghibaudo [5]. They work on the behavior of double gate MOS structure using numerical simulation and solve the carrier distribution and several technology parameters such as silicon film thickness, film doping or oxide material. A compact double-gate MOSFET model comprising quantum-mechanical and non static effects is developed by Baccarani [6]. Vasileska [7] derived the influence of space-quantization effects and poly-gate depletion on the threshold voltage, inversion layer and total gate capacitance on scaled Si-MOSFETs. They investigate the total gate capacitance that uses classical charge description and takes into account the depletion of the poly-silicon gates and their simulation results suggest that poly-gate depletion influence more the magnitude of C_{out} than the quantum-mechanical charge description. Islam and Mithun [8] observe the effect of non-uniform doping on gate C-V characteristics of MOSFETs. They claim that non-uniform doping has great influence in C-V characteristic of MOSFETs in weak accumulation and depletion regime.

1.3 Thesis outline

- In chapter 1, MOSFET background is first introduced. Also we introduce the MOSFET capacitance and how quantization effect arises in double gate MOSFET. After introducing the double gate MOSFET background and capacitance, objectives are presented. The rest of the thesis is organized as follows.

- Chapter 2 begins with the 2-D schrödinger and poisson solver, including different models and method parameters for solving equations using silvaco simulation tool.

- The quantization effects by varying electron and hole effective mass and the channel thickness are described in chapter 3. Quantization effects on C-V curve, eigen values, wave functions, and the carrier concentration are shown in tables and figures by varying the effective masses of electron and hole. The channel body thickness effects on the C-V curves are also analyzed in this chapter.

- Conclusions of the thesis are painted in chapter 4.

Chapter 2: Simulation Model and Methodology

For simulation of quantum effects on the gate C-V of a double gate MOSFET, we use SILVACO simulation package. This package has self-consistent poisson- schrödinger model that we use. The details are described below.

2.1 Schrodinger's equation

Two dimensional schrödinger equation for isotropic effective mass is

$$-\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\psi+V(x,y)\psi=E\psi \text{ -------------------(2.1)}$$

Here, m^* is the mass of electron/hole, ψ is the wave function, V is the potential energy and E is the energy. Our MOSFET structure is 2D and silvaco solves this equation at each slice along the channel. The different parameters for setting up schrödinger solver are described below.

N.SCHRO: This parameter is used in the model statement and it enables schrödinger solver for electron.

P.SCHRO: This parameter is used in the model statement and it enables schrödinger solver for hole.

OX.SCHRO: This parameter specifies the band edges of insulators which included in the solution of schrodinger's equation.

EIGEN: This parameter is used in the model statement to specify the number of eigen states to be solved by the schrödinger solver. If eigen=6 then it will solve for the 6 eigen states.

Although we use the name silicon as the channel material, we use an isotropic effective mass schrödinger solver for both electrons and holes with a single effective mass. For this thesis the following statements are used.

NUM.DIRECT is used in the model statement and it defines the number of electron band and anisotropy of effective mass.

If NUM.DIRECT=1, the conduction bands shift for isotropic electron band and I-valley with isotropic effective mass m_c (on the material statement) is obtained.

If NUM.DIRECT=3, a solution for three double-degenerate X-valleys with anisotropy effective mass is obtained.

If NUM.DIRECT=4, a solution for four L-valleys with anisotropy effective mass is obtained. We used NUM.DIRECT=1 with variable m_c.

NUM.BAND is used in the model statement to specify the number of hole band.

If NUM.BAND=1, the valance band shift for isotropic hole band and at that time solution for only one valance band with effective mass m_v(on the material statement) is obtained.

If NUM.BAND=2, a solution for only heavy holes and light holes.

If NUM.BAND=3, a solution for only heavy holes, light holes, and split off holes is obtained.

In our simulation, we used num.band=1 with variable m_v.

QMINCONC is used the model statement. We can refine the carrier concentrations by setting a minimum carrier concentration using the qminconc parameter on the models statement. The model statement that we used in silvaco written below

```
Model n.schro p.schro eigens=8 num.direct=1 num.band=1
qminconc=1.0e15 ox.schro print
```

2.2 Poisson's equation

The two dimensional poisson's equation is

$$\frac{\partial}{\partial x}\left(\epsilon_r \frac{\partial V}{\partial x}\right)+\frac{\partial}{\partial y}\left(\epsilon_r \frac{\partial V}{\partial y}\right)=-\frac{\rho}{\epsilon_o} \text{-----------------(2.2)}$$

Silvaco automatically solves Poisson's equation and we just need to specify the boundary condition. The voltage is fixed at the electrodes and zero field boundary condition is used in other boundary. For this we use the following command

```
Contact name=source reflect
Contact name=drain   reflect
```

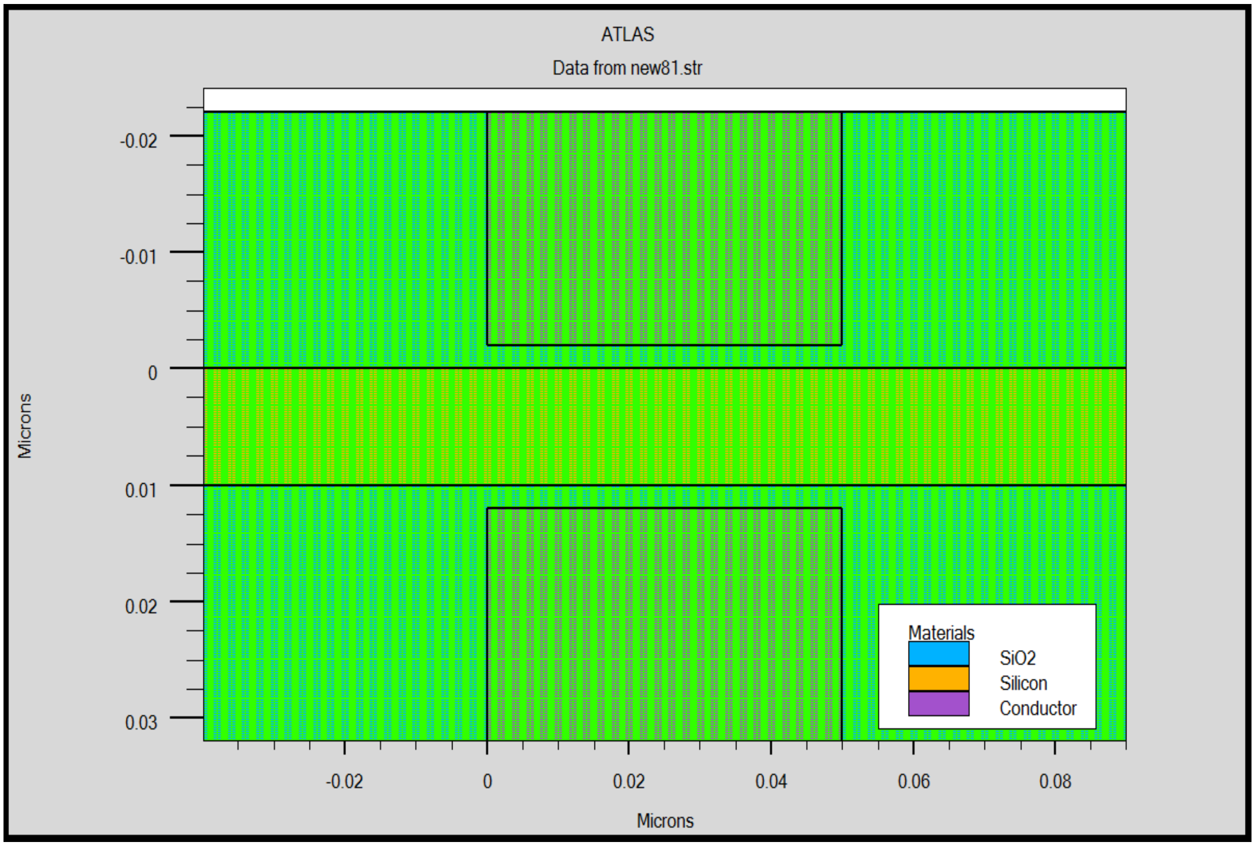

Figure 2.1: Mesh specification of a 50 nm channel length double gate MOSFET.

2.3 Methods

To solve the quantum effect on the gate capacitance we use the beneath commend in atlas.

```
method itlim=20 carriers=0
```

Itlim controls how many iteration can occur for the equation we want to solve. Here, itlim=20, that means the maximum iteration number is 20.

Carriers: Specifies the numbers of carrier continuity equation that will be solved. Valid values are 1 and 2. Carriers=0 implies that only poisson's equation will be obtained. Carriers=1 implies that only one carrier solution will be obtain. When this is specified, also specify either holes or electrons. Carriers=2 implies that solution will be obtained for both electrons and holes. In our work we did not solve any drift-diffusion equation, rather we solve schrödinger's equation for charge density. So, we set carrriers=0.

Chapter 3: Results & Discussion

We study the quantization effects on the gate capacitance of a double gate MOSFET. The structure from tonyplot of SILVACO is shown in figure 3.1. Gate oxide is a 2 nm SiO_2 we set channel thickness to 10 nm, gate length to 50 nm, and source and drain extension to 40 nm each. We set the doping density of source and drain to $1 \times 10^{19}\ /cm^3$. A gate metal thickness of 20 nm is used.

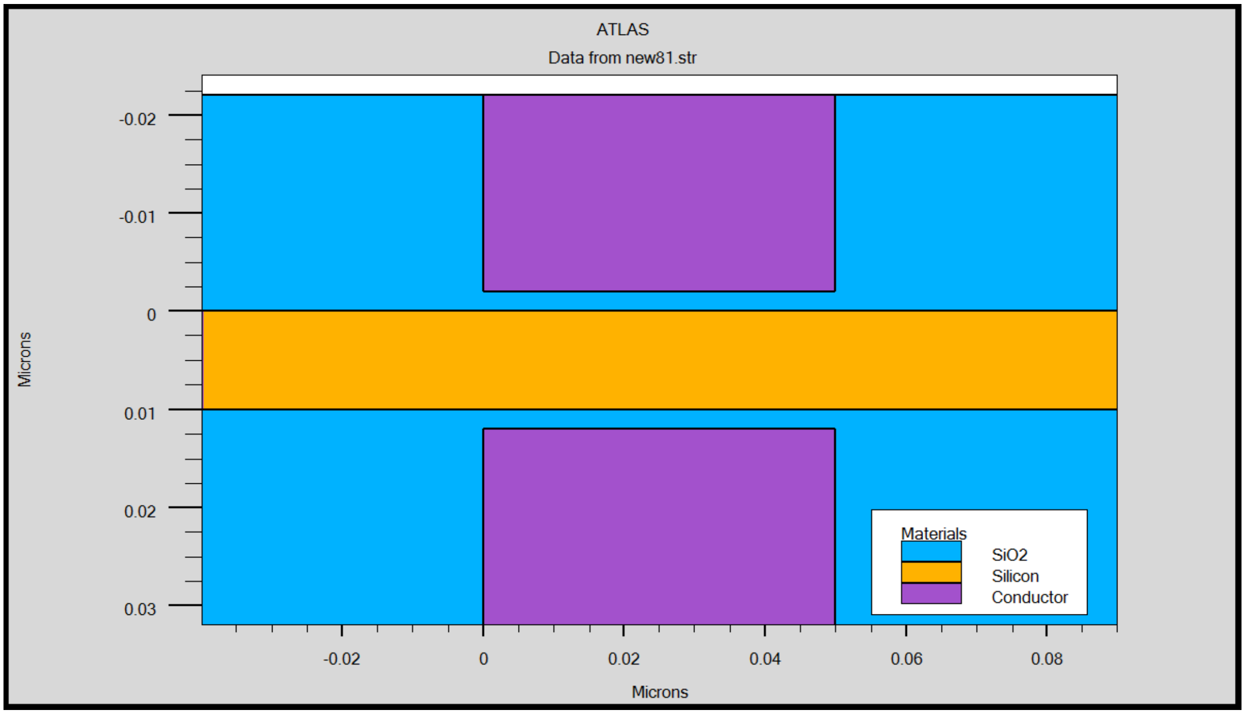

Figure 3.1: Device structure of a double gate MOSFET.

As our focus is to find the quantization effect on capacitance, we try to solve the device with fine mesh. In atlas normally the grid values are shown in micron throughout the device. In our case, though we define uniform mesh over the whole stricture it takes a reasonable time. The mesh is shown in figure 3.2; We set a grid spacing of 2 nm for both x and y-axis.

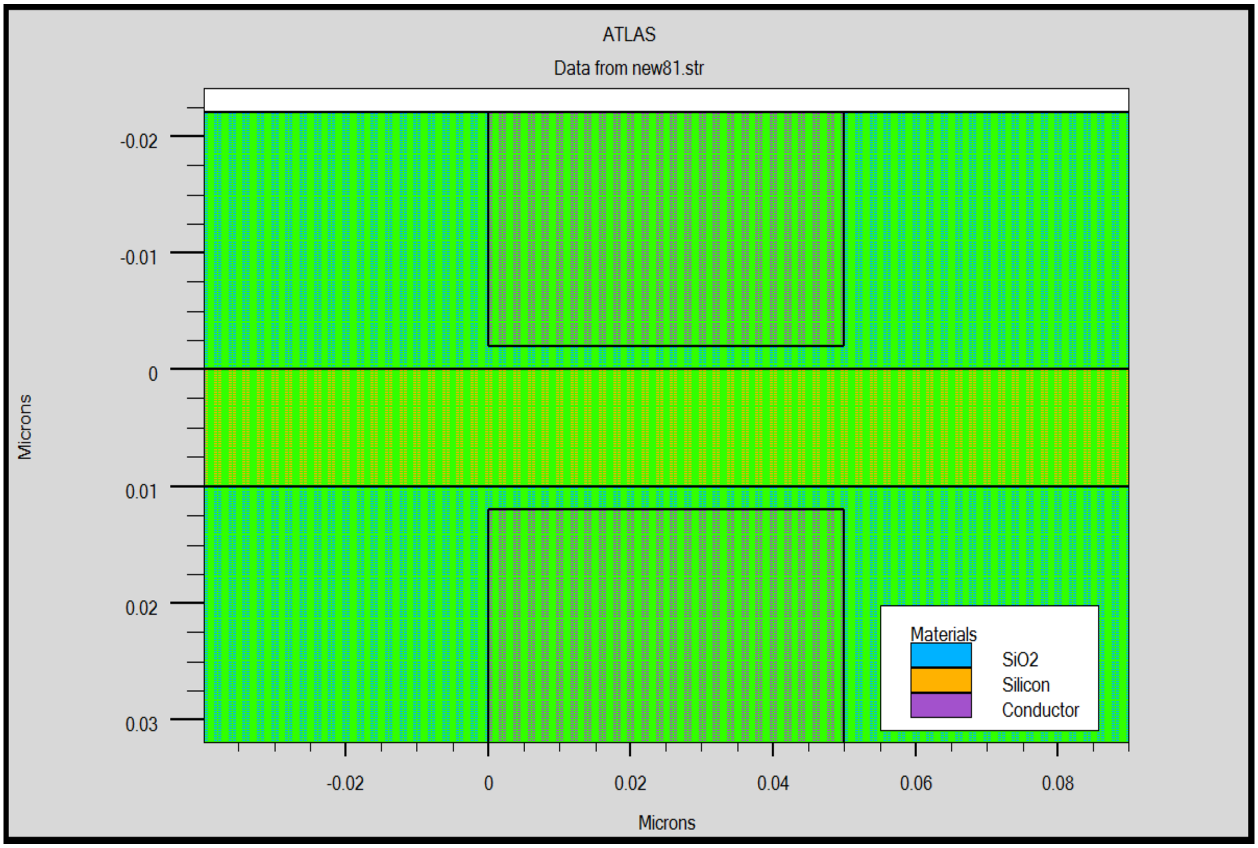

Figure 3.2: Mesh specification of a 50 nm channel length double gate MOSFET.

In models statement we use n.schro for solving the electron quantum effect, p.schro for holes and ox.schro for oxide penetration of wave function. We use num.driect to choose the number of direction in k space and use num.band to choose the number of valence band. We also use carriers=0 in methods statement so that silvaco does not solve drift-diffusion equations. In simulation, we consider one conduction band with isotropic effective mass m_c and one valance band with effective mass m_v. In simulation, we set V_{DS}=0, and zero field boundary condition on the source and drain for solving poisson’s equation.

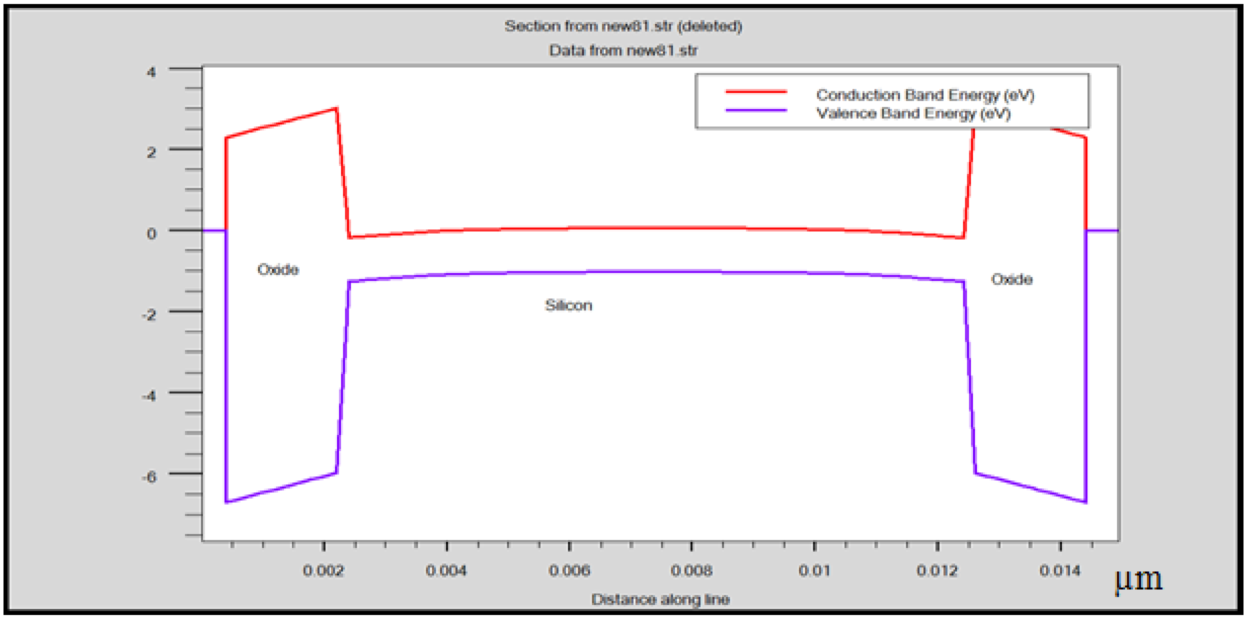

Figure 3.3: The band diagram of a double gate MOSFET along top to bottom gate for V_{gs}=1.5V.

Figure 3.3 shows the conduction and valence band diagram along the vertical line of the structure at the middle of the gate at V_{gs}=1.5V. This device uses a T_{si}=10 nm and $m_c = m_v = .5m_o$.

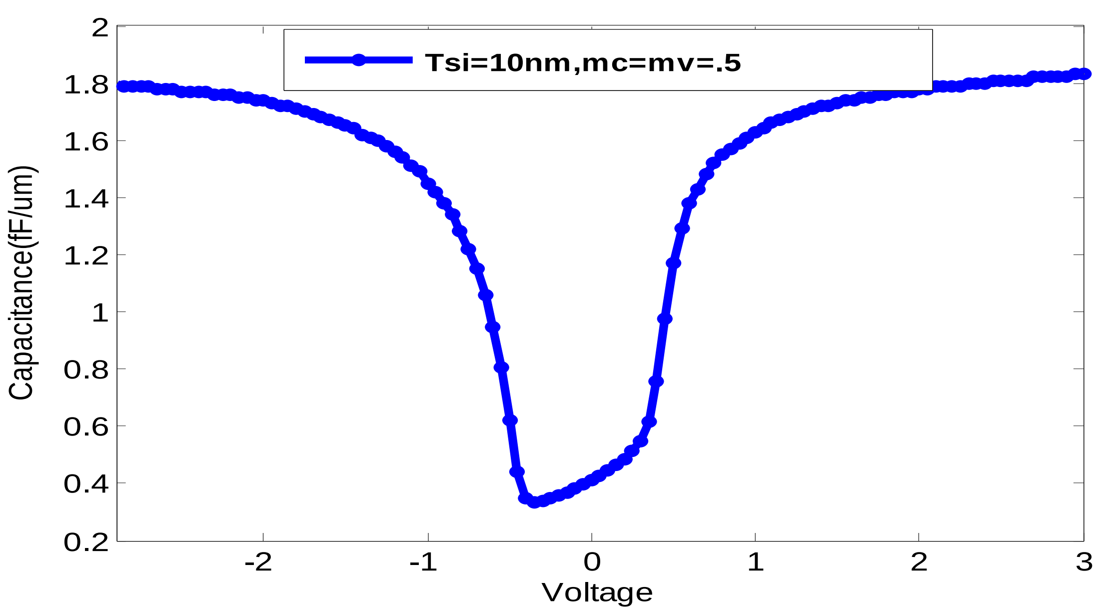

Figure 3.4: Double gate MOS capacitance for a gate bias swing from -3V to 3V.

The simulated C-V curve over the entire operation region (accumulation, depletion and inversion) is shown figure 3.4 for the same device. In this curve, we do not observe any quantization effect since we took a reasonable value of effective mass and channel thickness. At these values, the eigen energies are closely spaced and therefore, there is no step like behavior in charge density and hence on the C-V. The bound energy states are shown in figure 3.5 and 3.6 for electron and hole respectively and values are also shown in table 3.1 and 3.2.

Table 3.1: Eigen values for electron when $m_c = m_v = 0.5m_o$, T_{si}=10 nm at V_g=1.5V.

n	E_n(eV)
1	.0324
2	.0342
3	.0872

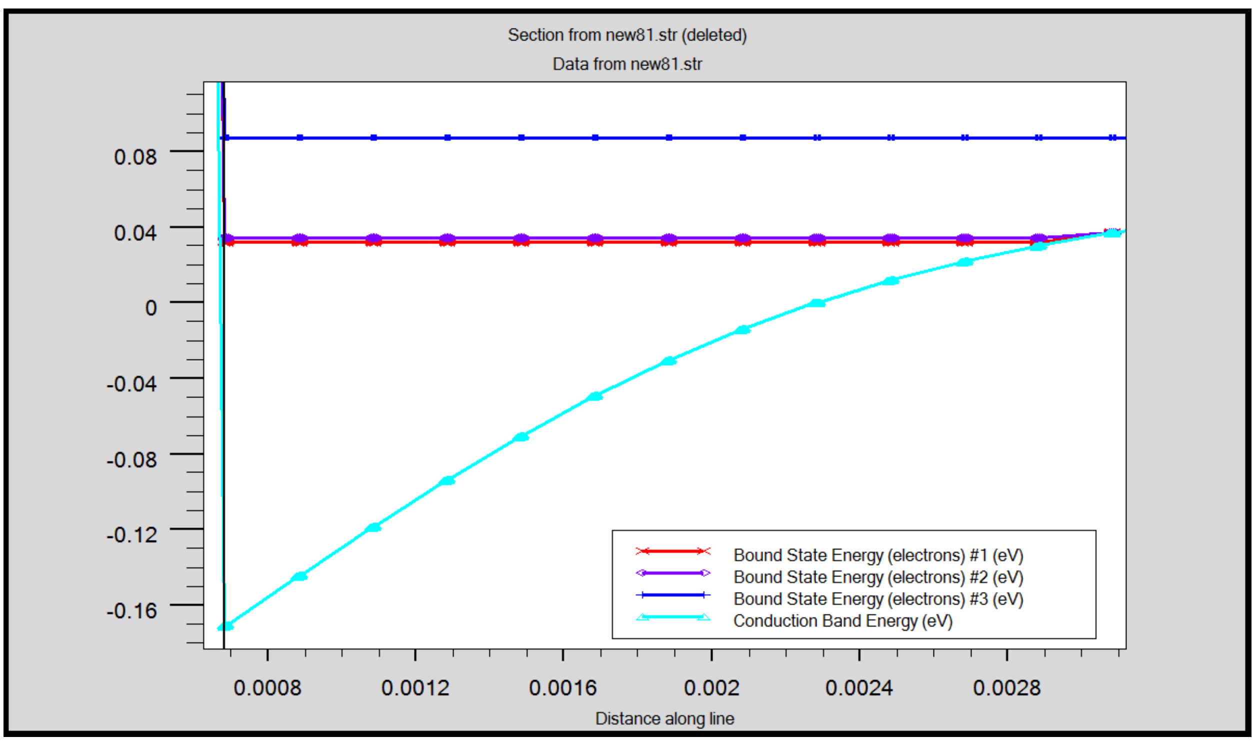

Figure 3.5: Bound state energy/eigen energy for electron at V_{gs}=1.5V when T_{si}=10 nm, $m_c = m_v$= 0.5 m_o.

Table 3.2: Eigen values for hole when $m_c = m_v = 0.5m_o$, T_{si}=10 nm at V_g= -1.5V.

n	E_h(eV)
1	0.0276
2	0.0265
3	-0.0279

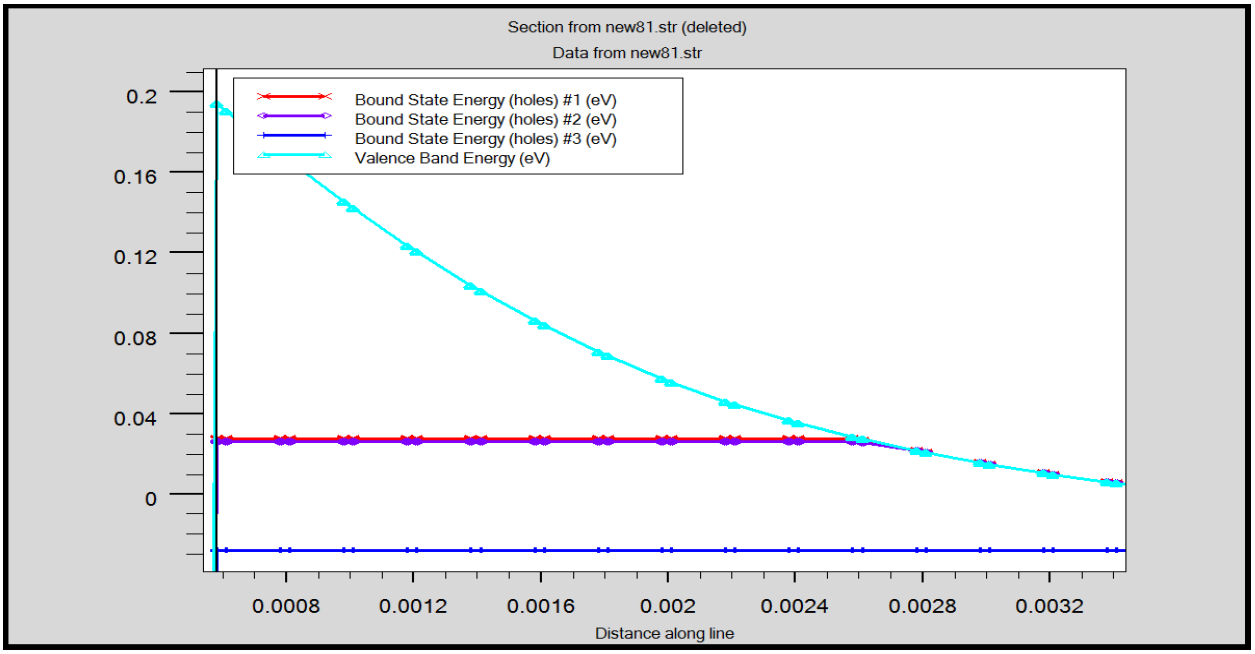

Figure 3.6: Bound state energy/eigen energy for hole at V_g= -1.5V when T_{si}=10 nm and $m_c = m_v$= $0.5m_o$.

From now we try to find out the quantization effect by varying the

1. Elector effective mass
2. Hole effective mass
3. Channel thickness

3.1 Electron Quantization effect on C-V by varying m_c

We observe the electron quantization effects on C-V by varying electron effective mass m_c. For infinite quantum well, we know that the eigen energies are

$$E_n = \frac{h^2 \pi^2 n^2}{8 m^* a^2} \quad \text{---------------------------(3.1)}$$

Where a is the well width. In case of double gate MOSFET, quantum wells are also formed at the two oxide/semiconductor interfaces. So, if we start to reduce the m_c, then the separation between eigen energies will also increase. This will eventually make the charge profile look like step. The consequence will certainly be seen in the C-V curve as well.

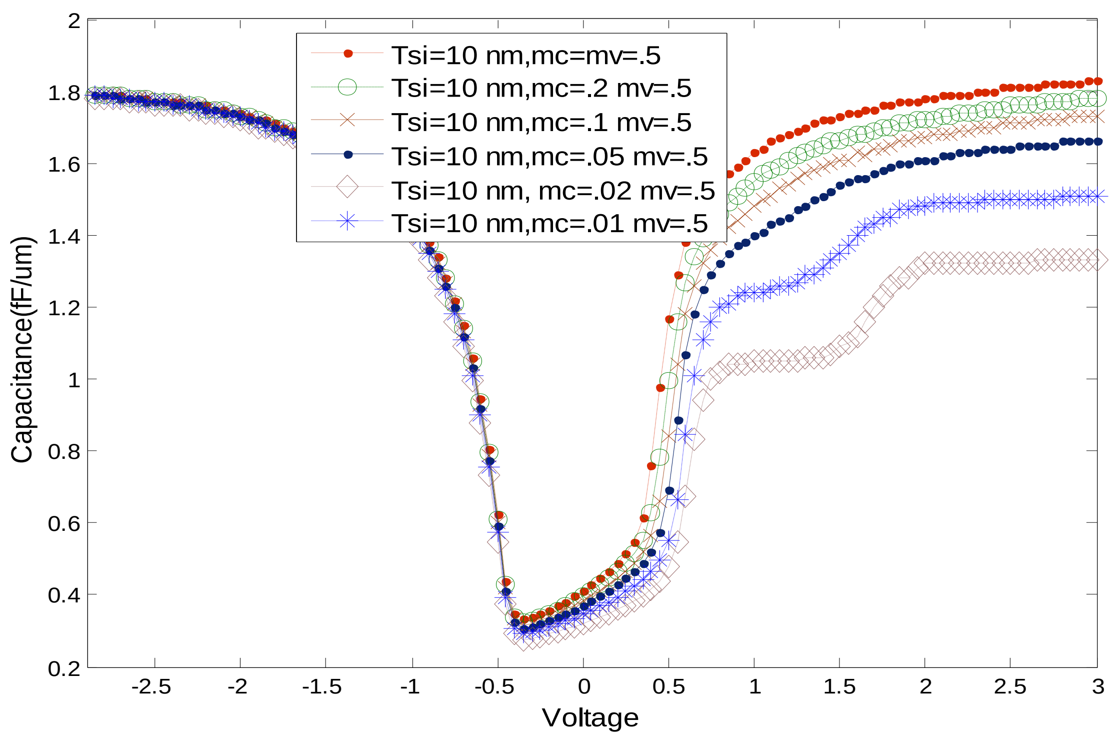

Figure 3.7: C-V curve for electron quantization effect.

The C-V curves for 5 different values of m_c are shown in figure 3.7. From the figure, we see that the quantization effects become noticeable when m_c is less than $0.1m_o$ ($m_c<0.1m_o$), the eigen energy spacing increases significantly that makes the C-V curve look like step. So, quantization effect not only makes the C-V curve look like step, but it also reduces the capacitance value. The wave functions of two lowest states and the electron density profiles for two different values of m_c are shown in figs. 3.8-3.10. The lowest three eigen energies are also tabulated in table 3.3 and 3.4. Clearly, for relatively large effective mass, the first wave function and the electron density profile have their peaks close to the two oxide/semiconductor interfaces, so called surface inversion. However at low effective mass, the electron density is almost flat over the entire channel body, so called the volume inversion. So, with reduced effective mass, in addition to quantization in C-V curve, the channel inversion switches from surface inversion to volume inversion.

Table 3.3: Eigen values for electron when m_c=0.2m_o, m_v=0.5m_o, T_{si}=10 nm at V_g=1.5V.

n	E_n(eV)
1	-0.00172
2	0.0135
3	0.105

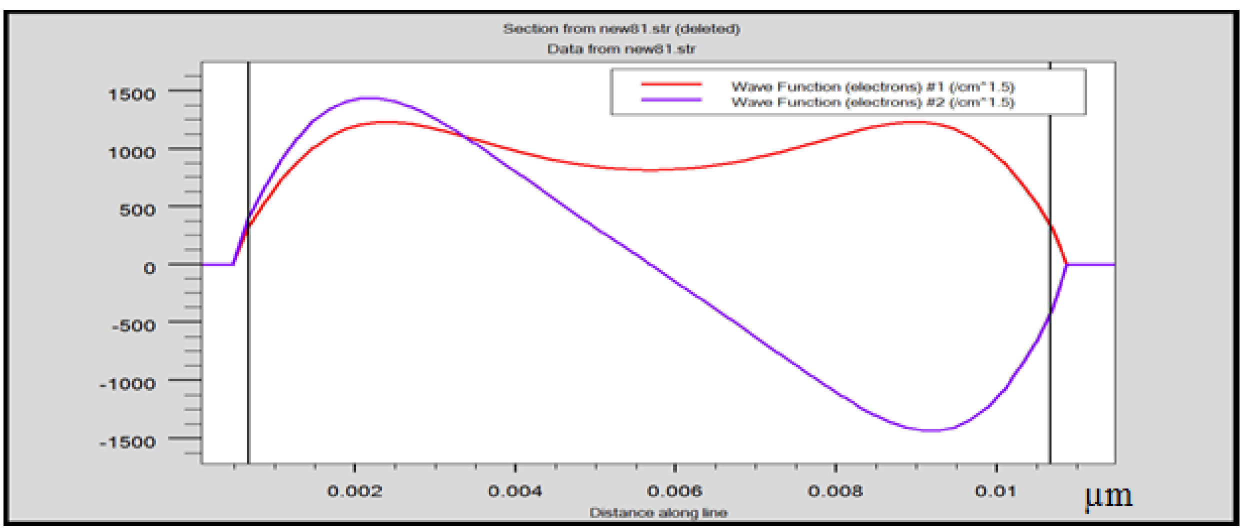

Figure 3.8: Wave function for electron, m_c=0.2m_o and m_v=0.5m_o and T_{si}=10 nm at V_g=1.5V.

Table 3.4: Eigen values for electron when m_c=0.02m_o, m_v=0.5m_o, T_{si}=10 nm at V_g=1.5V.

n	E_n(eV)
1	-0.212
2	0.0261
3	0.618

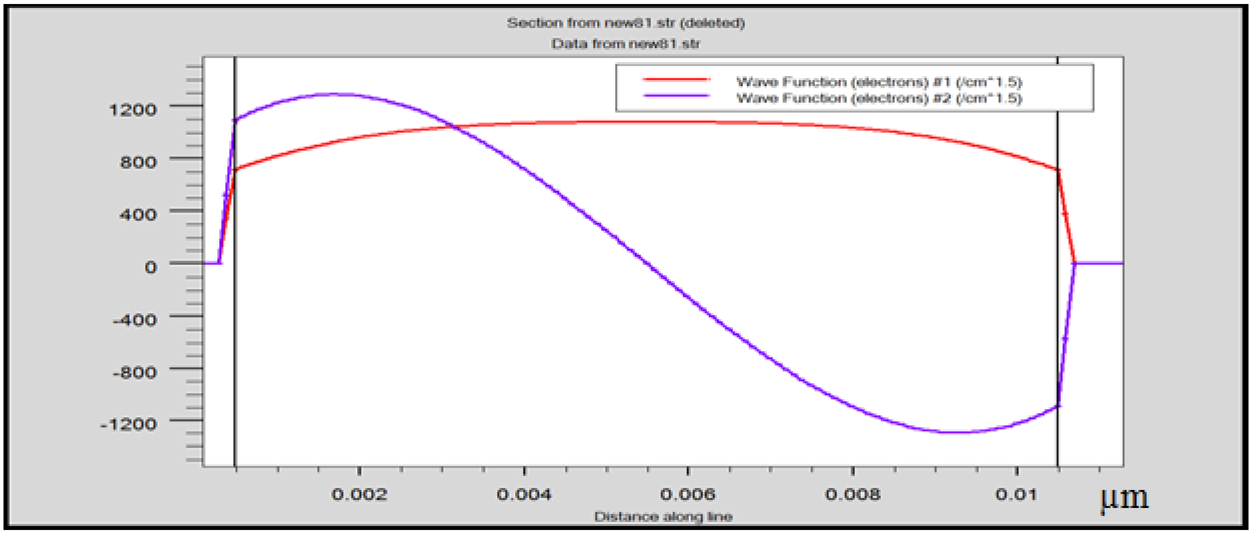

Figure 3.9: Wave function for electron at m_c=0.02m_o, m_v=0.5m_o, and T_{si}=10 nm for V_g=1.5V.

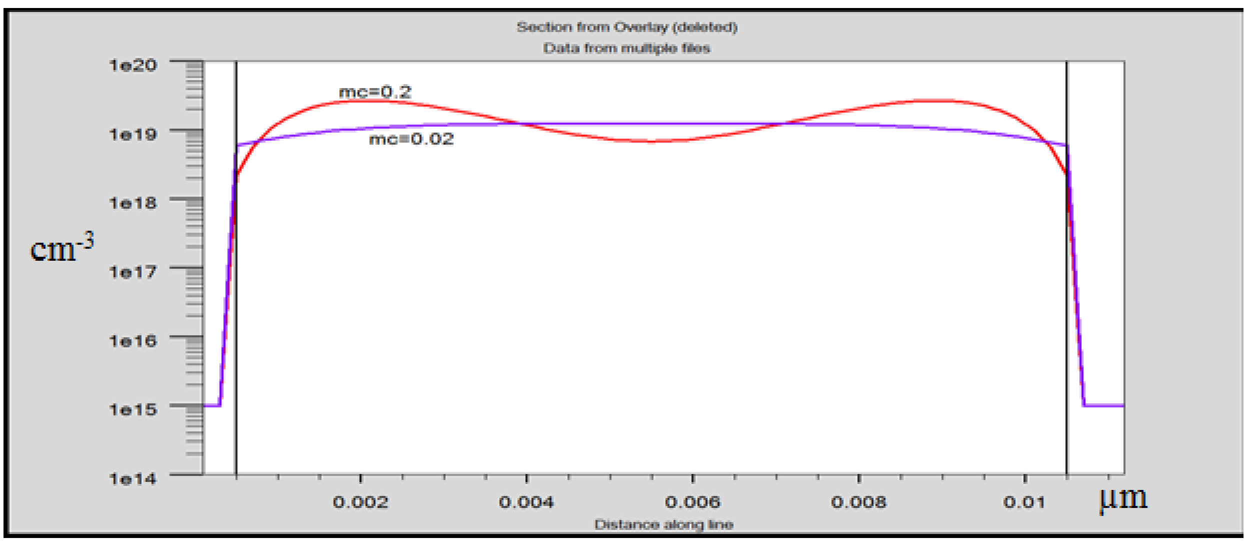

Figure 3.10: Electron concentration for m_c=0.2m_o and 0.02m_o at V_g =1.5V.

3.2 Hole quantization effect on C-V by varying m_v

We observe the hole quantization effects on C-V by varying hole effective mass m_v.

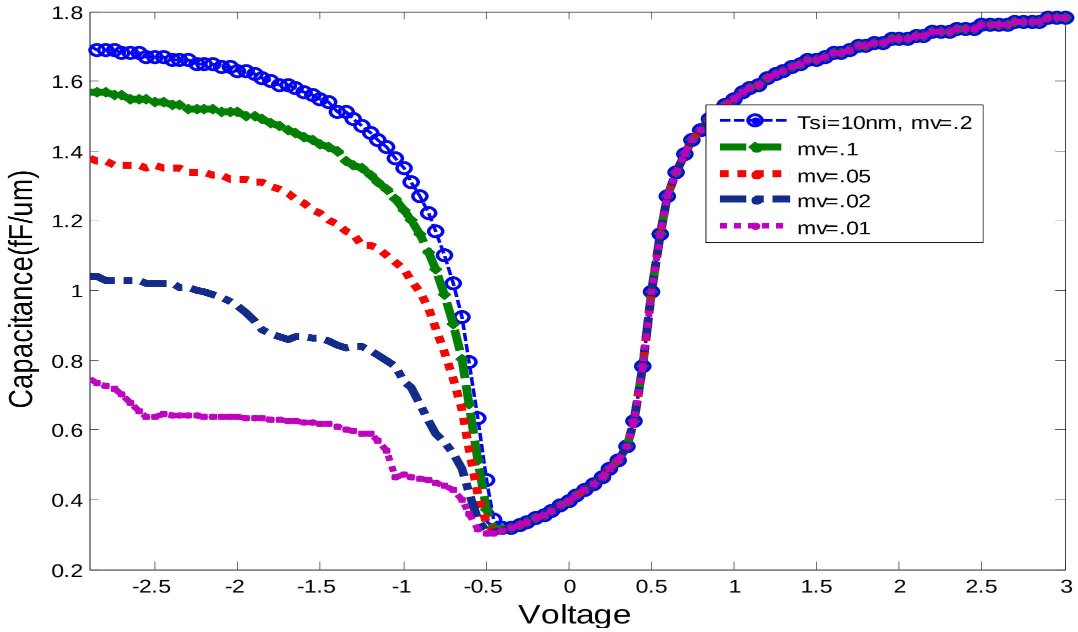

Figure 3.11: C-V curve for hole quantization effect.

The C-V curves for 5 different values of m_v are shown in figure 3.11. From the figure, we see that the quantization effects become noticeable when m_v is less than $0.1m_o$. When $m_v<0.1m_o$, the eigen energy spacing increases significantly that makes the C-V curve look like step. Also the inversion region capacitance reduces significantly with reducing the m_v. So, quantization effect not only makes the C-V curve look like step, but it also reduces the capacitance value.

The bound state energies, for $m_v=0.2m_o$ and $m_v=0.02m_o$ are shown in Table 3.5 and 3.6 respectively. The wave functions of 2 lowest bound states are shown in figure 3.12 and 3.13. Figure 3.14 shows the hole concentration for $m_v=0.2m_o$ and $0.02m_o$ and we see that the hole concentration reduces when reducing the effective mass of hole. Also, similar to electron, we notice that inversion switches from surface inversion to volume inversion at reduced hole mass.

Table 3.5: Eigen values for holes when m_c=0.2m_o, m_v=0.2m_o, T_{si}=10 nm at V_g= -1.5V.

h	E_h(eV)
1	0.0868
2	0.0773
3	-0.0067

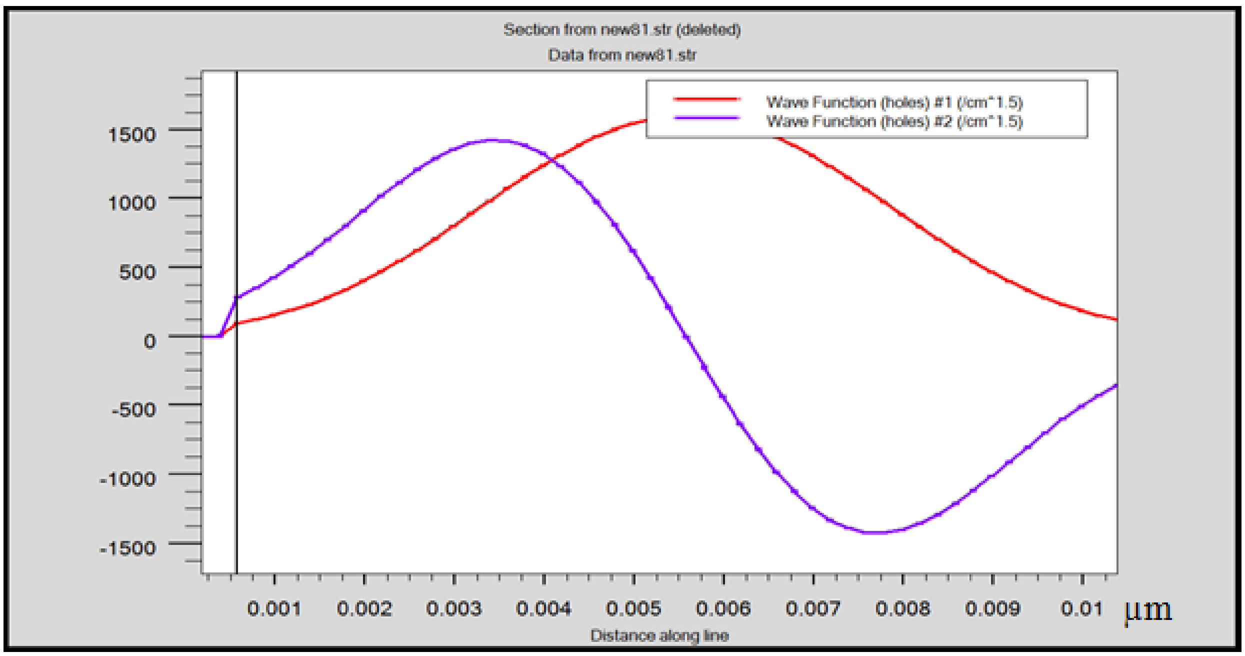

Figure 3.12: Wave function for holes when m_c = m_v = 0.2m_o and T_{si}=10 nm at V_g= -1.5V.

Table 3.6: Eigen values for holes when m_c=0.2m_o, m_v=0.02m_o, T_{si}=10 nm at V_g = -1.5V.

h	E_h(eV)
1	0.514
2	0.325
3	-0.325

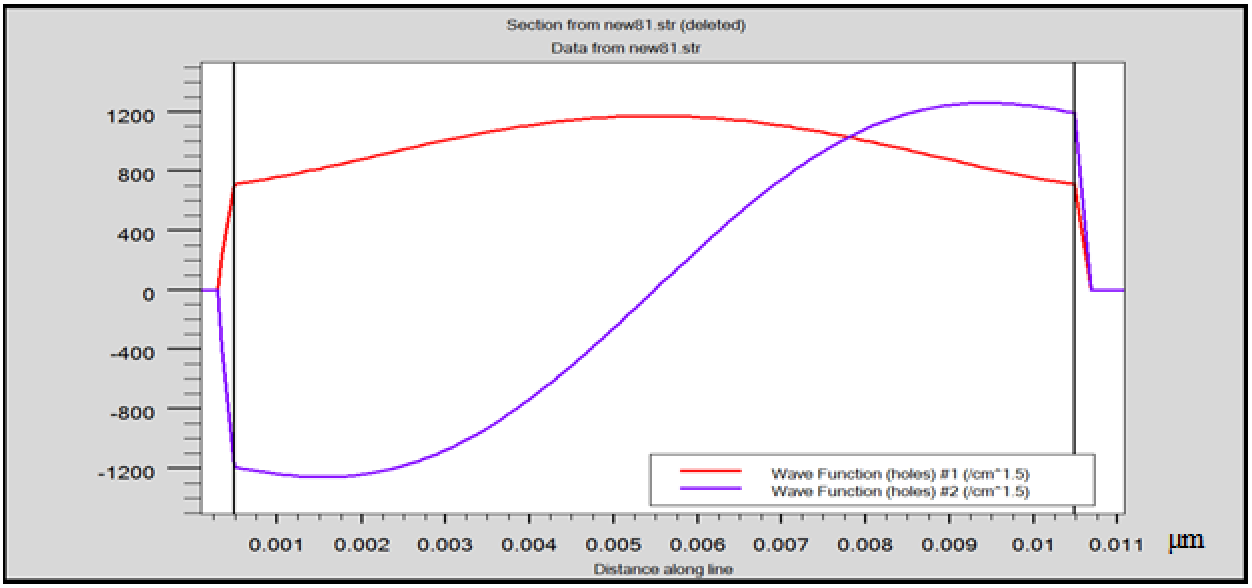

Figure 3.13: Wave function for holes when m_c=0.2m_o, m_v=0.02m_o and T_{si}=10 nm at V_g= -1.5V.

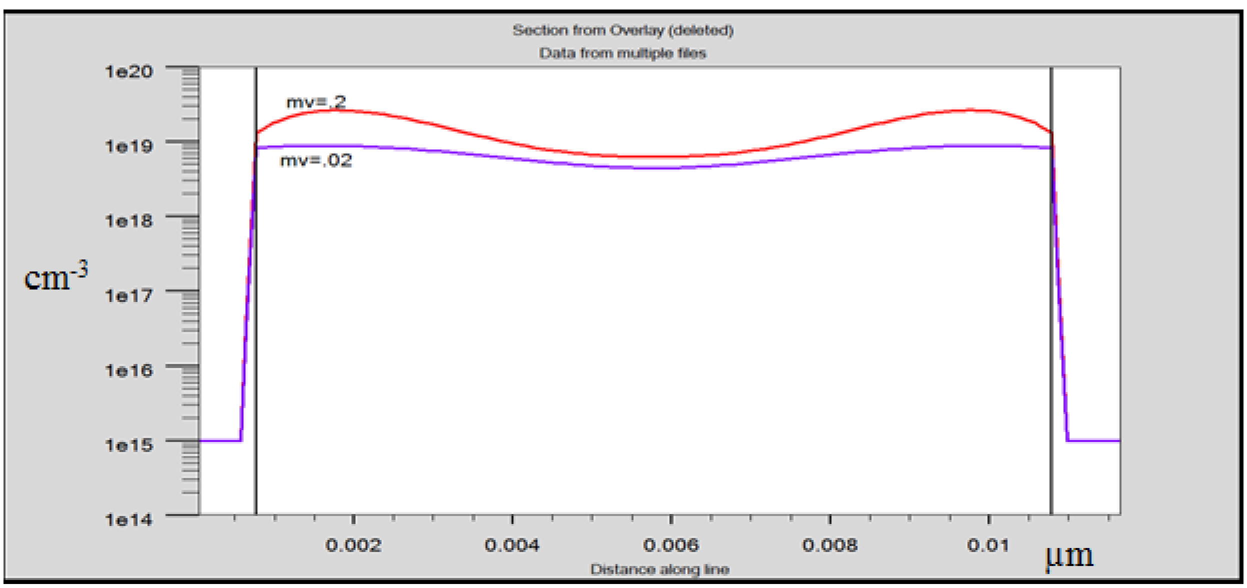

Figure 3.14: Hole concentration for m_v=0.2m_o and 0.02m_o at V_g= -1.5V.

3.3 Quantization effect on C-V by varying T_{ch}

Now, we observe the quantization effects on C-V by varying the channel thickness. For infinite quantum well, equation (3.1), if we reduce the well width a then the separation between eigen energies will increase.

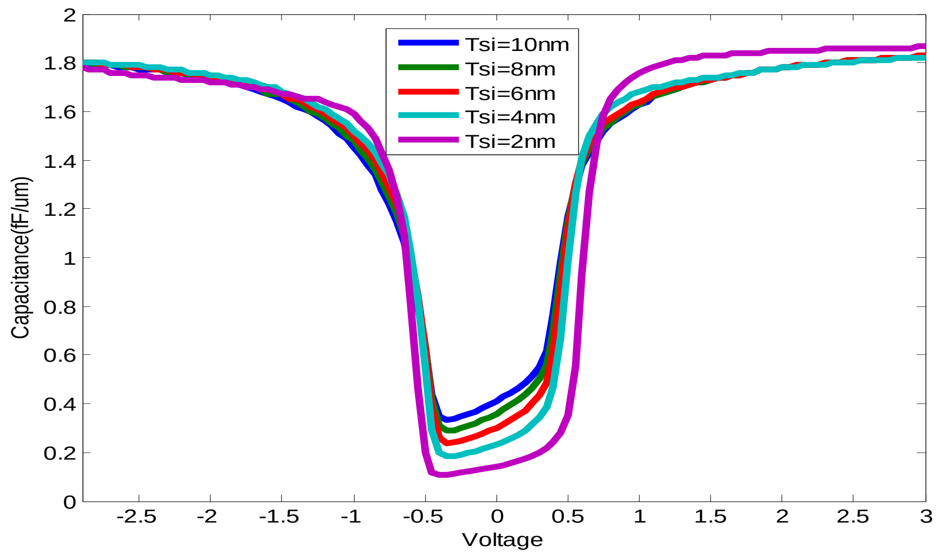

Figure 3.15: C-V curves for different channel thickness when $m_c = m_v = 0.5m_o$.

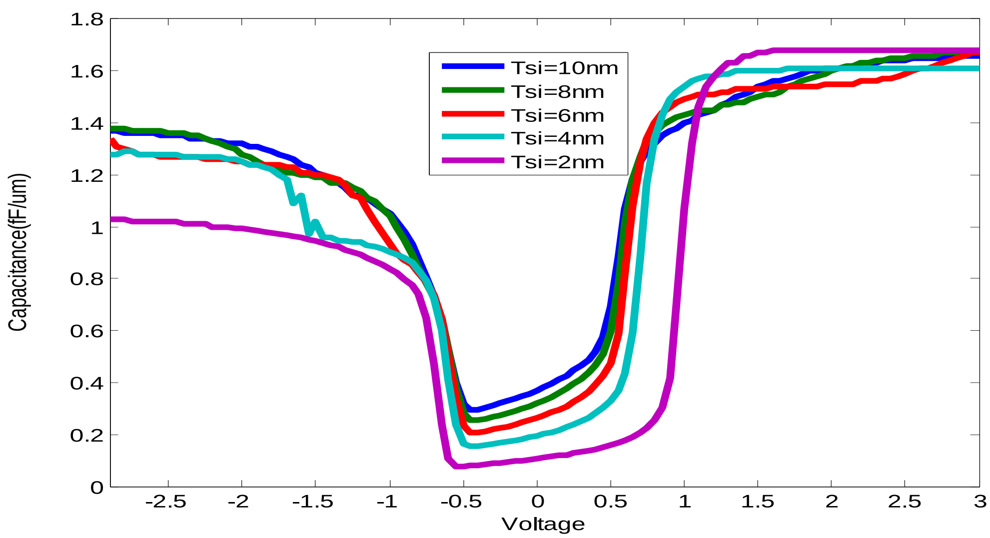

Figure 3.16: C-V curves for different channel thickness when $m_c = m_v = 0.05m_o$.

The C-V curves for 5 different values of T_{si} are shown in figure 3.15 and 3.16. For figure 3.15 $m_c = m_v = 0.5m_o$ and in figure 3.16 $m_c = m_v = 0.05m_o$. Here we don't see any step in C-V curve but we see a different phenomenon of quantization effective that strongly deals with the minimum part of C-V curve. When we put $m_c = m_v = 0.5m_o$ and change the channel thickness from 10 nm to 2 nm, the minimum capacitance is reduced and the minimum points shifts toward left in the voltage axis. But when we put $m_c = m_v = 0.05m_o$ and change the channel thickness from 10 nm to 2 nm the minimum point shifts to the left and the capacitance values in accumulation and inversion are also changed.

Chapter 4: Conclusions

We have investigated the quantization effects on the gate capacitance of a double gate MOSFET. Here we take a 130 nm material wafer and it has 50 nm gate length, source and drain extension is 40 nm each, 2 nm gate oxide and 10 nm channel thickness with a doping density of 1×10^{19} $/cm^3$. Firstly we observe the electron quantization effect by reducing the electron effective mass from a nominal value and we see that when $m_c<0.1m_o$ the quantization effect become noticeable. We find that the eigen energy separation becomes high. Because of this high energy separation the capacitance of MOSFET decreases significantly. We also show the electron concentration for different effective mass of electron and we find that electron concentration decrease when we reduce the electron effective mass and that's phenomena reduce the capacitance which we observe in C-V curve. The channel inversion also switches from surface inversion to volume inversion with reduced effective mass. The results imply that channel materials with low electron effective mass will have significantly high quantization with low inversion capacitance. Secondly we find the hole quantization effect by reducing the holes effective mass. For hole when we reduce the effective mass lower than $m_v<0.1$, quantization effect becomes noticeable and the eigen energy spacing increases significantly which decrease the hole concentration and decrease the total capacitance. And finally we reduce the channel thickness for two different effective mass of electron and hole. Though we don't see any step in C-V curve but we see a different phenomenon of quantization effective that's deals with the minimum part of C-V curve. When we put $m_c = m_v = 0.5m_o$ and change the channel thickness from 10 nm to 2 nm the lowest position of the C-V curve shift left with a small step also reduce the capacitance. But when we put $m_c = m_v = 0.05m_o$ and change the channel thickness from 10 nm to 2 nm the minimum point shift to left and the accumulation and inversion capacitance are changed.

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