An Analytical Model for the Gate C-V Characteristics of UTB III–V-on-insulator MIS Structure


Abstract—We propose a physics based analytical model for gate Capacitance-Voltage (C-V) characteristics of ultra-thin-body (UTB) III-V-on-insulator (XOI) MIS structure. The accuracy of the analytical model is verified by comparing with TCAD results. The model is general and is applicable to different III-V channel materials.

Keywords—Gate Capacitance; Compact model; XOI; III-V-on-insulator;

I. INTRODUCTION

Scaling of transistors improves cost, speed, and power per function with every new technology generation [1]. As Si CMOS technology approaches the physical limits of scaling, various alternatives are proposed. One of the potential candidates for future nanoscale devices is the so called XOI, compound semiconductor-on-insulator devices [2]. A number of experimental studies have reported excellent performance of XOI devices with only a few nanometer channel thickness[3] [4]. We have recently shown [5] that unlike other MOS devices, such as, bulk Si MOSFET, FINFET or SOI FET, the XOI devices exhibits completely unique C-V characteristics showing staircase like behavior.

C-V models are used for device parameter extraction of MOS devices. Analytical models are necessary for fast and accurate estimation of device characteristics in circuit simulations. Moreover analytical models provide insight into device response when device parameters or excitations are varied. Predictability is an important requirement in an analytical model. Quantum mechanical and other complex physical phenomena determine the characteristics of modern semiconductor devices owing to the nanoscale dimensions and bandgap engineering. Thus empirical models fail to predict the characteristics of such devices. The motivation of this work is to develop a physics based analytical model for the gate C-V characteristics of XOI devices with different channel materials. To demonstrate the generality and the accuracy of the model, we have alsocalculated the electrostatics of the device by self-consistently solving Schrodinger-Poisson equations using the TCAD tool Silvaco Atlas. Excellent match between analytical results and TCAD simulations have been obtained for two different channel materials. It is to be noted that the TCAD simulation for determining device electrostatics is considered acceptable even for most advanced nanoscale devices [6]-[8].

II. DEVICE STRUCTURE

We developed a general analytical model to express the CV characteristic of the device structure shown in Fig. 1(a). In order to validate the model against numerical calculation we took 10nm HfO$_2$ as Front Gate Oxide (FOX) and 50nm SiO$_2$ as Bottom Gate Oxide (BOX). In$_{0.7}$Ga$_{0.3}$Sb or InAs$_{0.7}$Sb$_{0.3}$ is taken as the channel material. Details of the numerical simulation procedure for the chosen dimensions are available in our previously published paper [5].

III. CV MODELING

The gate capacitance is expressed by the fundamental relationship

$$C_G = -\frac{dQ_{ch}^{QM}}{dV_G}$$  \hspace{1cm} (1)

Here $Q_{ch}^{QM}$ is the total charge in the channel considering quantum mechanical effects. We neglect the presence of any charge in the substrate region as the buried oxide is relatively thick and the substrate is undoped. For simplicity we assume that the channel charge may be represented by two sheet
charges located at FOX-channel interface and BOX-channel interface, respectively. Electron density in the \( i^{th} \) quantized state is given by \( [9] \)

\[
n_i = \frac{4\pi g_m^* kT}{h^2} \ln[1 + e^{(E_F-E_{min})/kT}] \tag{2}
\]

where \( g \) is the number of equivalent minima in conduction band, \( m^* \) is the effective mass, \( k \) is the Boltzmann constant, \( T \) is the Planck’s constant, \( E_F \) is the Fermi level, \( E_{min} \) is equal to \( E_F + E_i - q\psi_{ch} \) where \( \psi_{ch} \) is the channel potential, \( E_i \) is the \( i^{th} \) subband energy, and \( E_F \) is the conduction band minima. Therefore the total charge per unit area becomes

\[
Q_{ch}^{QM} = -q \frac{4\pi g_m^* kT}{h^2} \sum_i \ln[1 + e^{(E_F-E_{ch}+q\psi_{ch}-E_i)/kT}] \tag{4}
\]

For our device, the depth of the channel quantum well is greater than 4eV. This can be considered as an infinite quantum well even for narrow channel thicknesses, as long as energies only up to the 2\(^{nd}\) eigen level are taken into consideration. Thus \( E_i \) is calculated using the well known solution for infinite rectangular quantum wells \( [10] \)

\[
E_i = \frac{n^2\pi^2\hbar^2}{m^* t_{ch}^2} \tag{5}
\]

To buildup the gate voltage dependent gate capacitance relationship, we have to find a correlation between the channel potential and gate voltage. Using Fig. 1(b), integrating the depletion mode Poisson’s equation over the channel in the range \( 0^+ \leq x \leq \xi_{ch} \) we have,

\[
\xi_{Bch} - \xi_{Fch} = \frac{q}{\varepsilon_{ch}} N_D t_{ch} \tag{6}
\]

Here \( N_D \) is the doping concentration, \( \xi_{ch} \) is the dielectric constant of the channel material, \( \xi_{Fch} \) and \( \xi_{Bch} \) are the electric fields of the channel at the FOX-channel interface and channel-BOX interface respectively. Integrating Poisson’s equation twice we get

\[
\psi_{sf} - \psi_{sb} = \frac{1}{2}(\xi_{Fch} + \xi_{Bch}) t_{ch} \tag{7}
\]

Here \( \psi_{sf} \) is the front surface potential and \( \psi_{sb} \) is the back surface potential of the channel. Combining (6) and (7) we express the two surface electric fields of the channel in terms of the two surface potentials,

\[
\xi_{Fch} = \frac{\psi_{sf} - \psi_{sb}}{t_{ch}} - \frac{q N_D}{2 \varepsilon_{ch}} t_{ch} \tag{8}
\]

Applying Gauss’s law at the oxide/channel interfaces, we can relate the electric field inside the FOX (\( \xi_{fox} \)) with \( \xi_{Fch} \) while taking the channel charge into consideration. Then using \( \xi_{fox} = (V_{FG} - \phi_{msf} - \psi_{sf})/t_{fox} \) in the continuity equation, we get

\[
\xi_{Fch} = \frac{\xi_{fox}}{\xi_{ch}} (V_{FG} - \phi_{msf} - \psi_{sf}) + \frac{Q_{ch}^{QM}}{\xi_{ch}} \tag{9}
\]

where \( C_{fox} = \frac{E_{fox}}{\xi_{fox}} \). Here \( V_{FG} \) is the front gate voltage, \( \phi_{msf} \) and \( C_{fox} \) are the front gate potential, front gate flat band potential and FOX capacitance, respectively. Similarly, the back surface electric field can be written as

\[
\xi_{Bch} = \frac{C_{Box}}{\xi_{ch}} (\psi_{sb} - V_{BG} + \phi_{msb}) - \frac{Q_{ch}^{QM}}{\xi_{ch}} \tag{10}
\]

where \( C_{Box} = \frac{E_{Box}}{t_{Box}} \). Here \( V_{BG} \) and \( \phi_{msb} \) are the back gate voltage, back gate flat band potential and BOX capacitance, respectively. \( V_{FG} \) maybe expressed as

\[
V_{FG} = \phi_{msf} + \psi_{sf} + \frac{\xi_{ch} (\psi_{sf} - \psi_{sb})}{C_{Fox} t_{ch}} - \frac{Q_{ch}^{QM}}{C_{Box} t_{ch}} - \frac{q N_D}{2 C_{Box} t_{ch}} \tag{11}
\]

Similarly, the back gate voltage \( V_{BG} \) is given by

\[
V_{BG} = \phi_{msb} + \psi_{sb} - \frac{\xi_{ch} (\psi_{sf} - \psi_{sb})}{C_{Box} t_{ch}} - \frac{Q_{ch}^{QM}}{C_{Box} t_{ch}} - \frac{q N_D}{2 C_{Box} t_{ch}} \tag{12}
\]

Equations (4), (11) and (12) are coupled to each other though the channel charge. Therefore, these equations cannot be solved exactly independent of one another. At this stage we neglect this coupling for the time being. When \( V_{BG} = 0V \), putting \( Q_{ch}^{QM} = 0 \) and using (12) we get,

\[
\psi_{sb} = \frac{\xi_{fox} + q N_D}{C_{Box} t_{ch}} + \frac{Q_{ch}^{QM}}{C_{Box} t_{ch}} \tag{13}
\]

Putting this value into (11) we get

\[
V_g = V_{FG} = \phi_{msf} + \psi_{sf} + \frac{\xi_{ch} (\psi_{sf} - \psi_{sb})}{C_{Box} t_{ch}} + \frac{q N_D}{2 C_{Box} t_{ch}} - \frac{\xi_{ch}}{C_{Box} t_{ch}} \tag{14}
\]

Note that a self-consistent potential \( \psi_{SCF} = \alpha Q_{ch}^{QM}/C_{ch} \) is added on the right hand side of (14), to balance the two sides by offsetting the error induced due to neglecting the coupling of potential equations with the channel charges. Here \( C_{ch} = \xi_{ch}/t_{ch} \) and \( \alpha \) is a self-consistent parameter. Value of \( \alpha \) is determined from a comparison between results obtained from analytical calculation and numerical simulation using Silvaco Atlas simulator. As the value depends on the channel material as well as on the thickness of the channel, \( \alpha \) must be calibrated for each particular device technology by comparing with either TCAD or experimental results. Note that its value does not have any dependency on the doping concentration. Fig. 2 shows the value of \( \alpha \) for InGaSb and InAsSb at different channel thicknesses.

For a particular gate voltage, as all other parameters of (14) are known, we can solve for \( \psi_{sf} \) iteratively. As \( V_{BG} \) is set to 0V, we can write \( \psi_{ch} = \psi_{sf} \). Then using (4), we have calculated the channel charge considering two subbands. The capacitance is then calculated by differentiating the charge equation with respect to gate voltage.

Fig. 3(a) shows the variation of channel charge with the channel potential in both linear and logarithmic scale. At increased channel potential, higher eigen states start to populate which in turn increases the slope. The change in channel potential with gate voltage – flatband voltage is also shown in Fig. 3(b).
Fig. 2: Variation of the self-consistent parameter, $\alpha$, as a function of channel thickness.

Fig. 3. (a) Channel charge versus channel potential and (b) Channel potential versus gate voltage–flatband voltage curve of 7nm In$_{0.3}$Ga$_{0.7}$Sb-on-Insulator FET.

IV. VALIDATION OF MODEL

Results obtained from the analytical model are compared with the TCAD (Silvaco Atlas) results for a single gate In$_{0.3}$Ga$_{0.7}$Sb-on-Insulator FET. The back gate potential, $V_{BG}$ is set to 0V and $\psi_{ch} = \psi_{sf}$. Differentiating (4) and (14), the gate capacitance can be expressed as...
In order to confirm the generality of the model, it is verified for a device with InAs$_{0.7}$Sb$_{0.3}$ channel material. We found excellent match as shown in Fig. 4(b) for all four channel thicknesses. The result between InGaSb and InAsSb varied due to difference in effective masses, permittivities and the eigen energies of the channel material. Also, the bandgap, intrinsic carrier concentration and composition of the materials are also responsible for such variations. The model is also validated for different doping concentrations of 7nm In$_{0.3}$Ga$_{0.7}$Sb-on-Insulator FET and 10nm InAs$_{0.7}$Sb$_{0.3}$-on-Insulator FET which is shown in Fig. 5(a) and 5(b), respectively. The numerical and analytical results are found to be in an excellent agreement.

V. CONCLUSION

We have presented a physics based analytical model for gate C-V characteristics of ultra-scaled XOI FET. To investigate the accuracy of the model, we have compared analytical results with numerical calculations from Silvaco Atlas for two different channel materials with a variety of channel thicknesses and doping concentrations. Except for the channel thicknesses greater than 15 nm with the InGaSb channel, the quantitative agreement between the model and the TCAD results are excellent.

VI. REFERENCES


