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Surface Potential and Threshold Voltage Model of Fully Depleted Narrow Channel SOI MOSFET Using Analytical Solution of 3D Poisson's Equation

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The present paper is about the modeling of surface potential and threshold voltage of Fully Depleted Silicon on Insulator MOSFET. The surface potential is calculated by solving the 3D Poisson's equation analytically. The appropriate boundary conditions are used in calculations. The effect of narrow channel width and short channel length for suppression of SCE is analyzed. The narrow channel width effect in the threshold voltage is analyzed for thin film Fully Depleted SOI MOSFET.

Keywords: SOI, Channel length, Threshold voltage, 3D modeling.

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1. INTRODUCTION

The scaling of the device now days reach to limit of regime the parasitic effect comes very badly. To avoid degradation of the device the SOI technology developed and results are positively approached .The Fully Depleted SOI MOSFET is a most versatile used in Modern electronics system .The SOI MOSFET's are advantageous over their bulk-silicon counterparts in terms of short channel-induced threshold voltage reduction [1]. Short Channel Effect and Drain induced Barrier Lowering, Hot electron Effect, Threshold roll off are some problems that to be addressed. The solution came in the form of various modeling developed in a process of Device Development. An analytical model for the surface potential and the threshold voltage of a silicon-on-insulator (SOI) MOSFET with electrically induced shallow source / drain (S / D) junctions was presented to investigate the short-channel effects (SCEs)[2]. The model was developed by using a two-dimensional (2-D) Poisson's equation, and considering the source / drain resistance and the self-heating effect [3]. Further a new complete short channel SOI MOSFET I-*V* model for circuit simulation developed. This unified model is applicable for Fully Depleted, Partially Depleted, and mixed-mode SOI MOSFET's [4]. The various methods to solve 1D, 2D analysis of SOI MOSFET were very interesting areas for work [5-11].

In present model, 3D Poisson's equation is solved by using separation of variable method.The narrow width effect and short channel effects are taken in account i.e. channel length scaled down up to 30 nm and width scaled down up to 40 nm. In Ultra-thin SOI MOSFET reduction in threshold voltage by decreasing silicon film thickness (t_s) up to 15 nm.

2. MODEL FORMULATION

The cross-sectional view of the fully depleted SOI MOSFET is shown in Figure 1.

The Source-channel junction is located at $y = 0$ and channel drain junction located at $y = L_{Eff}$. Here L_{Eff} is the effective length of channel. The interface of Si-SiO$_2$ are found in $x = 0$ and $x = t_s$ locations. Here the terms t_s, t_{oxf}, t_{oxb} represent the thickness of Si film, front and back gate oxide thickness. The potential applied on front gate oxide and back gate oxide denoted by V_{gf} and V_{gb} respectively.

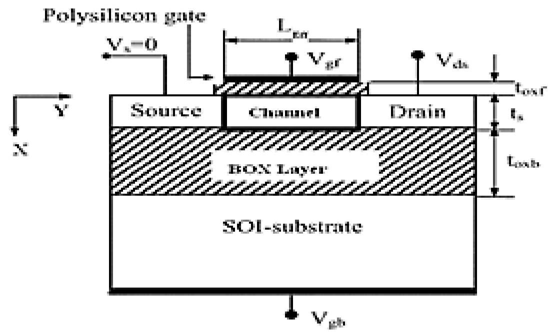

Fig. 1 – Crosssection view (*x*-*y*) of FDSOI MOSFET

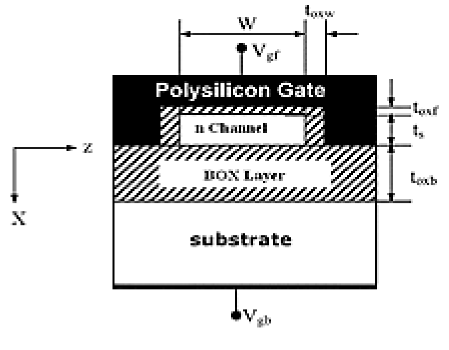

Fig. 2 – Cross-section view (*x*-*y*) of FD SOIMOSFET

Figure 2 shows the cross-sectional view(*x*-*z*) of the fully depleted SOI MOSFET, the channel width of the device is W. The side wall thickness is represented by t_{oxw} and its interface junction located at $z = 0$ and $z = W$.

The 3D Poisson's equation for FDSOI MOSFET is given by equation.

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$$\frac{\partial^2\varphi(x,y,z)}{\partial x^2}+\frac{\partial^2\varphi(x,y,z)}{\partial y^2}+\frac{\partial^2\varphi(x,y,z)}{\partial z^2}=\frac{qN_A}{\varepsilon_{si}} \quad (1)$$

Here N_A represents the doping concentration and $\varphi(x, y, z)$ is the surface potential at (x, y, z) point. The required boundary conditions to solve the Poisson's equations are given below as

$$\varphi\ 0,y,z\ -\frac{t_{oxf}}{\varepsilon_{ox}}\ \varepsilon_{si}\frac{\partial\varphi\ x,y,z}{\partial x}|_{x=0}-Q_{it}^{f}\ =V_{gf}-V_{fb}^{f} \quad (2)$$

$$\varphi\ \mathrm{t_{si}},y,z\ +\frac{t_{oxf}}{\varepsilon_{ox}}\ \varepsilon_{si}\frac{\partial\varphi\ x,y,z}{\partial x}|_{x=tsi}+Q_{it}^{b}\ =V_{gf}-V_{fb}^{b} \quad (3)$$

$$\varphi\ x,0,z\ =V_{bi} \quad (4)$$

$$\varphi\ x,L_{Eff},z\ =V_{bi}+V_{ds} \quad (5)$$

$$\varphi\ x,y,0\ -\frac{t_{oxw}}{\varepsilon_{ox}}\ \varepsilon_{si}\frac{\partial\varphi\ x,y,z}{\partial x}|_{z=0}-Q_{it}^{f}\ =V_{gf}-V_{fb}^{f} \quad (6)$$

$$\varphi\ x,y,w\ +\frac{t_{oxw}}{\varepsilon_{ox}}\ \varepsilon_{si}\frac{\partial\varphi\ x,y,z}{\partial x}|_{z=w}+Q_{it}^{f}\ =V_{gf}-V_{fb}^{f} \quad (7)$$

The above boundary conditions will be useful in finding the solution of the Poisson's equation of MOSFET. There are various methods to solve the Poisson's equation like Green Function technique. We are using separation of variable method to solve 3D Poisson's equation.

$$\frac{d^2\ \varphi l\ x}{dx^2}=\frac{qN_A x}{\varepsilon_{si}} \quad (8)$$

$$\frac{d^2\varphi\prime\ x,y}{dx^2}+\frac{d^2\varphi\prime\ x,y}{dy^2}=0 \quad (9)$$

$$\frac{d^2\varphi\prime\prime\ x,y,z}{dx^2}+\frac{d^2\varphi\prime\prime\ x,y,z}{dy^2}+\frac{d^2\varphi\prime\prime\ x,y,z}{dy^2}=0 \quad (10)$$

The 1-D Poisson's equation is represented by equation (8) and (9), (10) represents the 2-D and 3D Laplace equation. Here $\varphi_l(x)$, $\varphi'(x, y)$, $\varphi''(x, y, z)$ are the solution of 1D Poisson's equation, 2D, 3D Laplace equation respectively. The solution of 3D Poisson's equation is obtained by sum of the solution of equation (8), (9), (10).

$$\varphi\ x,y,z\ =\varphi l\ x\ +\varphi'\ x,y\ +\varphi''\ x,y,z \quad (11)$$

3. SOLUTION OF ΦL X

The solution of equation (8) with help of Boundary condition given as

$$\varphi l\ x\ -\frac{t_{oxf}}{\varepsilon_{ox}}\ \varepsilon_{si}\frac{d\varphi l\ x}{dx}|_{x=0}-Q_{it}^{f}\ =V_{gf}-V_{fb}^{f} \quad (12)$$

$$\varphi l\ \mathrm{t_s}\ +\frac{t_{oxf}}{\varepsilon_{ox}}\ \varepsilon_{si}\frac{d\varphi l\ x}{dx}|_{x=ts}+Q_{it}^{b}\ =V_{gf}-V_{fb}^{b} \quad (13)$$

After solving the above equation, solution can be written as

$$\varphi_l(x)=\varphi_{sb}+E_{sb}\ (t_s-x)+\frac{qN_A}{2\varepsilon_{si}}\ t_s-x \quad (14)$$

Here $\varphi_{sb}=\varphi_l(t_s)$ and $E_{sb}=-(\frac{\partial\varphi l\ x}{\partial x}|_{x=0})$

4. SOLUTION OF φ′ x, y

The solution of equation (9) with the help of Boundary condition which are given as

$$\varphi'\ x,y\ -\frac{t_{oxf}}{\varepsilon_{ox}}\ \varepsilon_{si}\frac{d\varphi\prime\ x,y}{dx}|_{x=0}\ =0 \quad (15)$$

$$\varphi'\ {}^{x,y}\ +\frac{t_{oxb}}{\varepsilon_{ox}}\ \varepsilon_{si}\frac{d\varphi'\ x,y}{dx}|_{x=ts}\ =0 \quad (16)$$

$$\varphi'\ x,0\ =V_{bi}-\varphi_l(x) \quad (17)$$

$$\varphi'\ x,L_{Eff}\ =V_{bi}-\varphi\mathrm{l}(x)+V_{ds} \quad (18)$$

$$\varphi'\ x,y\ =\frac{1}{\sinh\gamma L_{Eff}}\times[V'\sinh\gamma_r y+V\sinh\ \ \gamma_r L_{Eff}-y\ \ ]\times\ \sin\ \gamma_r x\ +\frac{\varepsilon_{si}}{\varepsilon_{ox}}t_{oxf}\gamma\cos\ x\gamma_r \quad (19)$$

Here the V' and V will be described as given below

$$V=\frac{i_{num1}+\frac{\varepsilon_{si}}{\varepsilon_{ox}}t_{oxf}\gamma_r i_{num2}}{i_{Dnum}} \quad (19a)$$

$$V'\ =V+\frac{V_{ds}\frac{1}{\gamma_r}\ \ 1-\cos(\gamma_r t_s\ \ +\frac{\varepsilon_{si}}{\varepsilon_{ox}}t_{oxf}\sin\ \gamma_r t_s}{i_{Dnum}} \quad (19b)$$

$$i_{Dnum}=[\frac{1}{4\gamma_r}[2\beta_r t_s-\sin(2\gamma_r t_s)]+(\frac{\varepsilon_{si}}{\varepsilon_{ox}}t_{oxf}\gamma_r)^2\frac{1}{4\gamma_r}\times[2\gamma_r t_s-\sin(2\gamma_r t_s)]+\frac{\varepsilon_{si}t_{oxf}}{2\varepsilon_{ox}}[1-\cos\ 2\gamma_r t_s\ ] \quad (19c)$$

$$i_{num1}\ =\frac{qN_A}{\varepsilon_{si}\gamma_r^3}\ [1-\cos\ \gamma_r t_{si}\ ]+\ E_{sb}\frac{\sin\ \gamma_r t_s}{\gamma_r^2}+[\ V_{bi}-\psi_{sb}-E_{sb}t_s-\frac{q}{2\varepsilon_{si}}N_A t_s^2]\frac{1}{\gamma_r}-[V_{bi}-\psi_{sb}]\ \frac{\cos\ \gamma_r t_s}{\gamma_r^2} \quad (19d)$$

$$i_{num2}\ =\frac{qN_A}{\varepsilon_{si}\gamma_r^3}\sin\ \gamma_r t_s\ +\ E_{sb}\frac{\cos\ \gamma_r t_s}{\gamma_r^2}-[E_{sb}-\frac{qN_A t_s}{\varepsilon_{si}}]\frac{1}{\gamma_r^2}+\ [\ V_{bi}-\psi_{sb}]\ \frac{\sin\ \gamma_r t_s}{\gamma_r^2} \quad (19e)$$

5. SOLUTION OF $\varphi''\ x,y,z$

The solution of 3D Laplace equation is obtained by using following Boundary conditions.

$$\varphi''\ {}^{x,y,z}\ -\frac{t_{oxf}}{\varepsilon_{ox}}\ \varepsilon_{si}\frac{\partial\varphi'\prime\ x,y,z}{\partial x}|_{x=0}\ =0 \quad (20)$$

$$\varphi''\ x,y,z\ +\frac{t_{oxb}}{\varepsilon_{ox}}\ \varepsilon_{si}\frac{\partial\varphi\prime\prime\ x,y,z}{\partial x}|_{x=ts}\ =0 \quad (21)$$

$$\varphi''\ {}^{x,0,z}\ =0 \quad (22)$$

$$\varphi''\ {}^{x,L_{Eff},z}\ =0 \quad (23)$$

$$\varphi''\ {}^{x,y,0}\ -\frac{t_{oxw}}{\varepsilon_{ox}}\ \varepsilon_{si}\frac{\partial\varphi\ x,y,z}{\partial x}|_{z=0}-Q_{it}^{f}\ =V_{gf}-V_{fb}^{f}-\varphi l\ x\ -\varphi'\ x,y \quad (24)$$

$$\varphi''\ {}^{x,y,w}\ +\frac{t_{oxw}}{\varepsilon_{ox}}\ \varepsilon_{si}\frac{\partial\varphi\ x,y,z}{\partial x}|_{z=W}+Q_{it}^{f}\ =V_{gf}-V_{fb}^{f}-\varphi l\ x\ -\varphi'\ x,y \quad (25)$$

After solving the above equations the solution of 3D Poisson's equation in form of

$$\varphi''\ x,y,z\ =M_{sr}[\sinh\{(\chi_{sr}w-z)\}+\sinh(\chi_{sr}z)]\times\frac{\sin(\ \alpha_s y-L_{Eff}\ )}{\cos(\alpha_s L_{Eff})}[\sin(x\beta_r)+\frac{t_{oxf}}{\varepsilon_{ox}}\varepsilon_{si}\cos\beta_r\ x] \quad (26)$$

Here α_s, β_r, χ_{sr}, M_{sr} are described as given below

$$\sum_{s=1}^{\infty}\sum_{r=1}^{\infty}\left[M_{sr} - \frac{\varepsilon_{si}}{\varepsilon_{ox}} t_{oxw}\chi_{sr}N_{sr}\right]\frac{\sin\left(\alpha_s\left(y - L_{Eff}\right)\right)}{\cos(\alpha_s L_{Eff})}\sin(\beta_r x) + \frac{\varepsilon_{si}}{\varepsilon_{ox}} t_{oxf}\beta_r\cos(\beta_r x) = V_{gf} - V_{fb}^{f} - \varphi_l(x) - \varphi_s(x,y)$$

$$M_{sr} = \frac{i_{num}^{3d}}{i_{Dnum}^{3d}} + \frac{\varepsilon_{si}}{\varepsilon_{ox}} t_{oxw}\chi_{sr}N_{sr}$$

$$i_{Dnum}^{3d} = \frac{1}{4\beta_r}\left(2\beta_r t_s - \sin(\beta_r t_s)\right) + \left(\frac{\varepsilon_{si}}{\varepsilon_{ox}} t_{oxf}\beta_r\right)^2 \frac{1}{4\beta_r} \times \left(2\beta_r t_s - \sin(\beta_r t_s)\right) + \frac{\varepsilon_{si}t_{oxf}}{2\varepsilon_{ox}}\left(1 - \cos(2\beta_r t_s)\right) \times \frac{1}{2\cos^2(\alpha_s L_{eff})}\left(L_{eff} - \frac{\sin(2\alpha_s L_{Eff})}{2\alpha_s}\right)$$

$$i_{num}^{3d} = \frac{(\cos(\alpha_s L_{Eff})) - 1}{\alpha_s\cos(\alpha_s L_{Eff})} i_1 + \frac{\varepsilon_{si}}{\varepsilon_{ox}} t_{oxf}\beta_r i_2 - \frac{1}{\cos(\alpha_s L_{Eff})} \times \sum_{r=1}^{\infty}\frac{i_3}{\sinh(\beta_r L_{Eff})}\left[V_r^{l} i_4 + V_r i_5\right] i_1 = \frac{qN_A}{\varepsilon_{si}\beta_r^3}\left[1 - \cos(\beta_r t_s)\right] + E_{sb}\frac{\sin(\beta_r t_s)}{\beta_r^2} + \left[V_{gf} - V_{fb}^{f} - \varphi_{sb} - E_{sb}t_s - \frac{q}{2\varepsilon_{si}}N_A t_s^2\right]\frac{1}{\beta_r} - \left[V_{gf} - V_{fb}^{f} - \varphi_{sb}\right]\frac{\cos(\beta_r t_s)}{\beta_r^2}$$

$$i_2 = \frac{qN_A}{\varepsilon_{si}\beta_r^3}\sin(\beta_r t_s) + E_{sb}\frac{\cos(\beta_r t_s)}{\beta_r^2} - \left(E_{sb} - \frac{qN_A t_s}{\varepsilon_s}\right)\frac{1}{\beta_r^2} - \left[V_{gf} - V_{fb}^{f} - \psi_{sb}\right]\frac{\sin(\beta_r t_s)}{\beta_r^2}$$

$$i_3 = \frac{1}{4\beta_r}\left[2\beta_r t_s - \sin(\beta_r t_s)\right] + \left(\frac{\varepsilon_{si}}{\varepsilon_{ox}} t_{oxf}\beta_r\right)^2 \frac{1}{4\beta_r} \times \left[2\beta_r t_{si} + \sin(\beta_r t_s)\right] + \frac{\varepsilon_{si}t_{oxf}}{2\varepsilon_{ox}}\left[1 - \cos(2\beta_r t_s)\right]$$

$$i_4 = \frac{\frac{\sin(2\alpha_s L_{Eff})}{2\alpha_s} - \frac{\alpha_s}{\beta_r^2}\sinh(\beta_r L_{Eff})}{1 + \left(\frac{\alpha_s}{\beta_r}\right)^2}$$

$$i_5 = \frac{\frac{\alpha_s}{\beta_r^2}\cosh(\alpha_s L_{Eff})\sinh(\beta_r L_{Eff}) - \sin(\alpha_s L_{Eff})\cos(\beta_r L_{Eff})}{1 + \left(\frac{\alpha_s}{\beta_r}\right)^2}$$

$$N_{sr} = \frac{\frac{i_{num}^{3d}}{i_{Dnum}^{3d}}\left(1 - \cosh(\chi_{sr}W)\right) - \frac{\varepsilon_{si}}{\varepsilon_{ox}} t_{oxf}\chi_{sr}\sinh(\chi_{sr}W)}{\sinh(\chi_{sr}W) + 2\frac{\varepsilon_{si}}{\varepsilon_{ox}} t_{oxf}\chi_{sr}\cosh(\chi_{sr}W) + \left(\frac{\varepsilon_{si}}{\varepsilon_{ox}} t_{oxf}\chi_{sr}\right)^2\sinh(\chi_{sr}W)}$$

$$M_{sr} = \frac{N_{sr}\sinh(\chi_{sr}W)}{1 - \cosh(\chi_{sr}W)}$$

$$P_{sr} = \frac{N_{sr}}{1 - \cosh(\chi_{sr}W)}$$

Now the solution of equation (8), (9), (10) gives the potential at point (x, y, z). The potential variation at the interface i.e. $x = 0$ of uniformly doped SOI MOSFET for various channel length is shown in Figure 3.The surface potential calculated for SOI MOSFET. The potential plot gives the information about potential distribution in channel in front surface, middle in channel and lower surface in channel. The V_{gf} and V_{gb} can be expressed to represent the external voltages

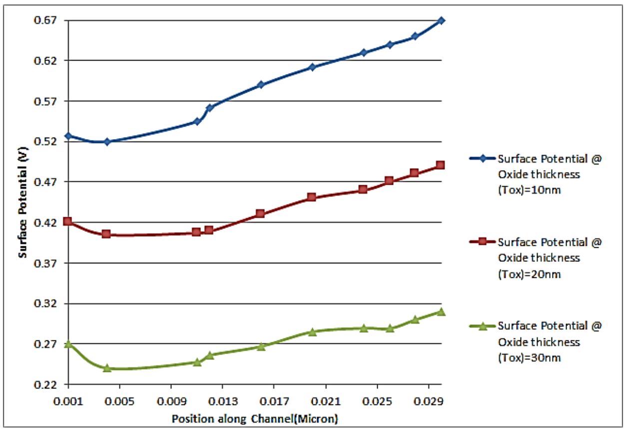

Fig. 3 – Channel potential variation with normalized position along the channel length at $V_{ds} = 0.5$ V

Figure 3 shows the variation of the surface potential along the channel length for different values of oxide thickness. On increasing the value of oxide thickness t_{ox} at both ends Gate lose control over the channel there by increasing the Drain Induced Barrier Lowering (DIBL).However continued decrease in the oxide thickness definitely reduces the DIBL.

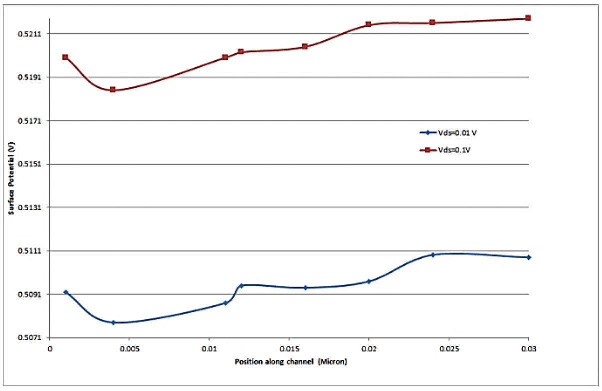

Fig. 4 – Channel potential variation with normalized position along the channel

Figure 4 shows the variation of surface potential along the channel for different values of V_{ds} For FDSOI MOSFET, the variation in surface potential along the channel for *n*-channel Fully Depleted SOI MOSFET with two different drain source voltage (V_{ds}) i.e. $V_{ds} = 0.1$ and $V_{ds} = 0.01$. The position of the minimum surface potential lies near by the source region of the gate due to the step function profile of surface potential. Also there is not much charge in the minimum surface potential for higher values of V_{ds}. Hence the area near source region is screened from the change in V_{ds}. However, there is enhancement in the values of surface potential near drain for increasing values of V_{ds}.

6. MODEL OF THRESHOLD VOLTAGE FOR NARROW CHANNEL FULLY DEPLETED SOI MOSFET

In this section modeling of threshold voltage is presented for narrow width FD SOI MOSFET .The front gate Threshold voltage (V_{TF1}) of narrow width SOI MOSFET is defined as $V_{TF1} = V_{gf}$, when $\varphi(0, y^f_{min}, W/2) = 2\,\emptyset_b$ here y^f_{min} is the position of surface potential in lateral direction. By differentiating the equation (11) with respect to y at $x = 0$ and $z = W/2$. Solving the equation, the solution came in form.

The Bisection method is used to calculate

$$y^f_{min}\cdot\frac{\partial\varphi(x,y,z)}{\partial y}\Big|_{x=0,\ y=y^f_{min},\ z=\frac{W}{2}} = 0 \qquad (27)$$

On solving the equation (11) and (14),(19) and (26), V_{TF}can be calculated as

$$V_{TF} = V_{TFO} - \Delta V_{TF1} - \Delta V_{TFW} \qquad (28)$$

Where

$$V_{TFO} = V^f_{FB} + 2\Phi b + \frac{Q^f_{it}}{C_{oxf}} + \frac{\varepsilon_{si}}{C_{oxf}}\frac{d\varphi l(x)}{dx}\Big|_{x=0}$$

$$= V^f_{FB} + \left(1 + \frac{C_s + C^f_{it}}{coxf}\right)2\Phi b - \frac{C_s}{C_{oxf}}\varphi_{sb} + \frac{qN_A t_s}{2C_{oxf}} \qquad (29)$$

$$\Delta_{TF1} = \frac{\varepsilon_{si}}{C_{oxf}}\frac{\partial\varphi s(x,y)}{\partial x}\Big|_{x=0,y=y^f_{min}}$$

$$= \frac{\varepsilon_{si}}{C_{oxf}}\sum_{r=1}^{\infty}\frac{\gamma^r}{\sinh\gamma^r L_{Eff}}\times\left(V_r'\sinh(\gamma^r y^f_{min}) + V_r\sinh(\gamma^r (L_{Eff}-y^f_{min}))\right) \qquad (30)$$

$$\Delta V_{TFW} = \frac{\varepsilon_{si}}{C_{oxf}}\frac{\partial\varphi_v(x,y,z)}{\partial x}\Big|_{x=0,\ y=y^f_{min},\ z=\frac{W}{2}}$$

$$= \frac{2\varepsilon_{si}}{C_{oxf}}\sum_{s=1}^{\infty}\sum_{r=1}^{\infty}P_{sr}\sinh\left(\frac{\chi_{srW}}{2}\right)\times\frac{\sin(\alpha_s(y^f_{min}-L_{Eff}))}{\cos(\alpha_s L_{Eff})}\times\beta_r \qquad (31)$$

From above equations we can find some conclusions like V_{TFO} is not dependent on channel length and width. So it represents the threshold voltage of long and wide SOI MOSFET. V_{TF1} is varying with L_{Eff} and V_{ds} but independent from channel width i.e. threshold voltage reduction due to the shot channel effect. V_{TFW} is the threshold voltage reduction due to narrow width effect.

7. RESULT AND DISCUSSION

Figure 5 and 7shows the variation of threshold voltage with channel length and drain to source voltage. The threshold voltage rolls down with decreasing the channel length because of increasing portion of the larger work function gate as the channel length reduces. This is a unique feature which gives FDSOI structure and added advantage when the device dimensions are continuously shrinking. The total calculated

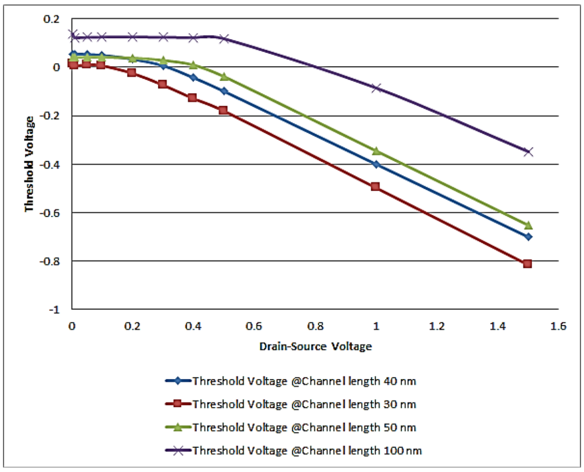

Fig. 5 – Threshold Voltage variation for varying channel length L_{Eff} = 30 nm, 40 nm, 50 nm, 100 nm

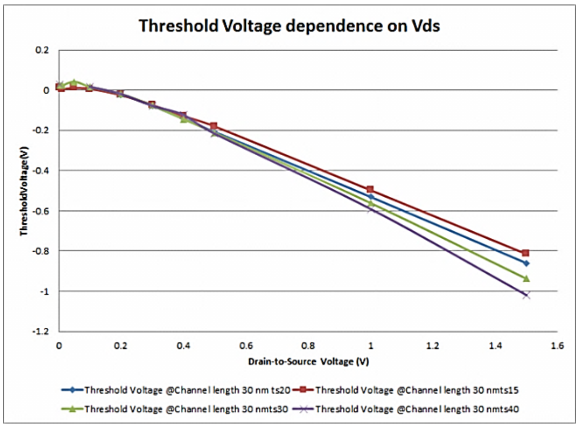

Fig. 6 – Threshold Voltage Dependence on thickness of Si film for effective channel Length 30 nm and t_s = 15, 20, 30, 40 nm

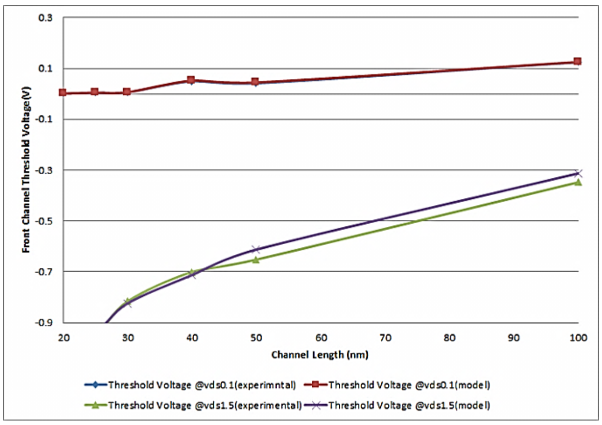

Fig. 7 – Threshold Dependence on variation of drain-source voltages

threshold voltage is in close agreement with the same computed using device simulator ATLAS 3D.

Figure 6 shows that the thickness of the silicon film also plays a key role in reduction of threshold voltage .When the device is on then the screen gate shields the region under the gate from any drain voltage variations and this way, screen gate absorbs any additional drain to source voltage beyond saturation .This in turn leads to reduction in threshold voltage.

8. CONCLUSION

The analytical model developed has been verified by the results obtained by ATLAS 3-D device simulator. Devices with gate length 30 nm have been simulated keeping all other parameters same. The device parameters used are as follows: $t_s = 15$ nm, $t_{ox} = 3$ nm, $N_A = 1 \times 18$ cm^3, $W = 40$ nm. Based on the analytical model and the ATLAS-3D simulation results the variation of channel potential with the normalized channel position (y / L_{Eff}) for channel length 30 nm and $V_{ds} = 0.5$. It can be seen that for the drain bias, $V_{ds} = 0.5$, the minimum channel potential increases as the channel length decreases because of the SCEs and hence the channel barrier is reduced. The effect of varying channel width in suppression of SCE in device. The threshold voltage reduced as the channel length of the reduced at Nano scale i.e. $L_{Eff} = 30$ nm. The thickness of the silicon film also plays a key role in reduction of threshold voltage.

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