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# 2D Potential Analysis in Buried Oxide Layer of Nanoscale SOI MOSFET

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***Abstract***

*Proper incorporation of short channel effects in nanoscale SOI MOSFET modeling demands total two dimensional potential analysis through out the device as the field is truly two-dimensional (2D) in nature. 2D potential profile in the channel, based on Poisson's equation solution, have been extensively studied but similar in-depth analysis in the buried oxide layer is yet to be carried out. Miniaturization of device dimension makes 2D potential analysis in the buried layer indispensable as fringing field and substrate bias effect have huge impact on device performance, especially in nano regime. In this work, an analytical model of 2D potential profile in the buried oxide layer of SOI MOSFET has been developed by solving 2D Poisson's equation.*

***Indexing terms/Keywords:*** *Short Channel effects, Fringing field, SOI MOSFET, Analytical Modeling*

## INTRODUCTION

Performance improvement of VLSI circuits has been achieved by increasing the speed, decreasing the power consumption and miniaturizing the devices [1]. As scaling of planar CMOS has faced significant challenges, several nonconventional geometrical MOS structures have been proposed and studied experimentally as well as theoretically [1]. Among those structures, silicon-on-insulator (SOI) structure has attracted much attention of most of the researchers due to some of its inherent functional advantages and easier fabrication methodology [2]. SOI technology offers many advantages over its bulk counterpart like higher speed, lower power dissipation, higher radiation tolerance, lower parasitic capacitance, lower short channel effects, manufacturing compatibility with the existing bulk silicon CMOS technology [3]. Even though SOI shows superior performance over its bulk counterpart, there are unavoidable issues like short-channel effects (SCE) which arises with SOI devices in nano regime [4]. Further downscaling of SOI MOSFET can be realized with fully depleted and short-channel control which requires ultra-thin films and some specific technological solutions. Simulation based circuit analysis demands less complex analytical model which can be incorporated in circuit simulator to figure out its true functionality and advantages as a nanoscale MOS transistor [4].

In an ultra thin SOI structure, potential at the channel back interface significantly influences the 2D potential profile in the channel region. The potential at the back interface is influence by the substrate bias and the fringing field initiated by the drain-source bias. In order to analyze the channel back interface potential, a 2D potential model underneath the silicon film, is very much essential. 2D analysis of potential profile in the channel region has been studied extensively but a little attention is paid for potential analysis in the buried oxide (BOX) or buried layer

(BL) region [5, 6]. In the channel, considering a parabolic potential profile, Poisson's equation is solved with proper boundary conditions [7]. The true nature of the potential profile in the BOX is very complex and the solution of Poisson's equation is much more complex than the channel region. Poisson's equation needs proper boundary conditions to be solved and finding of proper boundary conditions in BOX region is also a difficult task. Using similar potential profile in the channel and BOX region [8] and very complex Green's function [9, 10] potential analysis in the BOX region has been carried out previously. Analyses using the idea of semiphysical approach [11], Laplace's serial development [11], empirical modeling [12] and conformal mapping [13] have also been proposed. However, there is still plenty of room for further improvement in 2D potential model in BOX region [13]. Solution of 2D Poisson's equation is the mostly accepted approach for potential profile analysis in the channel region. The Poisson's equation in BOX turns into Laplace's equation as buried oxide trap charge density is negligible. In the present work, 2D potential profile in the BOX region is analyzed with an analytical model developed by solving 2D Poisson's equation. Entire analysis has been intentionally restricted in the BOX region only.

**Theory**

A layered shallow source-drain SOI structure is shown in the Fig. 1. Let $t_f$, $t_{Si}$, $t_b$ and $t_{sub}$ be the thicknesses of gate oxide, silicon channel layer, buried oxide layer and substrate layer respectively and $L$ is the metallurgical channel length of the device.

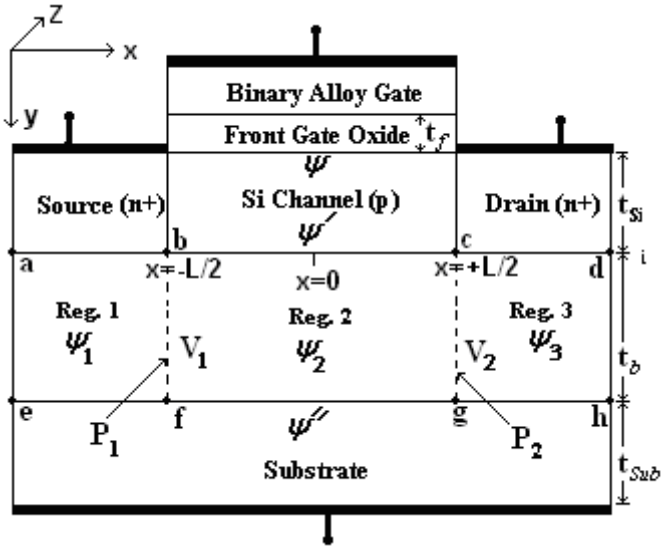


***Fig. 1:*** *Cross sectional view of SSDS SOI MOSFET.*

Let ψ, ψ′ and ψ′′ be the interface potentials at the front gate oxide - channel, channel-BOX and BOX-substrate, respectively. Horizontal direction is represented with x coordinate and x is considered to be zero at the middle of the channel. The BOX region is initially divided into three regions, Reg.1, Reg. 2 and Reg.3 respectively as shown in Fig.1. Two virtual vertical planes, $P_1$ (at $x=-L/2$) and $P_2$ (at $x=+L/2$), extended along the width of the device (z –coordinate) are assumed. Interestingly, the potential on these planes are function of 'y' but independent of 'z' and 'x' positions. Planes $P_1$ and $P_2$ are assigned potentials $V_1$

and $V_2$, respectively. Vertical direction is represented by 'y' coordinate with y=0 at front gate oxide-channel interface, $y=t_{Si}$ at channel-BOX interface and $y=t_{Si}+t_b$ at BOX-substrate interface

**Analytical Model**

Considering free charge density in the BOX region to be zero, two dimensional Poisson's equation is transformed into a 2-D Laplace's equation and is written as;

$$\frac{\partial \psi(x,y)}{\partial x}+\frac{\partial \psi(x,y)}{\partial y}=0 \quad (1)$$

where $\psi(x,y)$ is the 2D potential in the buried oxide layer. Solution of similar type of equation is discussed in the book of electrostatics by D. J. Grifith [14] and potential profile in the BOX region can be represented in a generalized form as a product of two independent functions [14];

$$\psi(x,y)=X(x)Y(y) \quad (2)$$

Putting eqn. 2 in eqn. 1; forming partial differential equation through separation of variables; converting partial differential equation into an ordinary differential equation; solving the ordinary differential equation, the general solution of potential function can be written in the form [14]

$$\psi(x,y)=(A\exp(kx)+B\exp(-kx))(C\sin(ky)+D\cos(ky)) \quad (3)$$

The constants A, B, C and D are the amplitudes of the potential function and all of them are to be computed from boundary conditions and 'k' is a function of integer. As the solution is a generalized solution for BOX region, it is applicable to all the three regions with different constant values and with same 'k' factor.

**Region 1;**

In region Reg.1, 2-D potential function is denoted by $\psi_1(x,y)$ and the solution can be written as

$$\psi_1(x,y)=(A_1\exp(kx)+B_1\exp(-kx))(C_1\sin(ky)+D_1\cos(ky)) \quad (4)$$

The constants $A_1$, $B_1$, $C_1$ and $D_1$ can be determined from the following boundary conditions:

(a) $\psi_1=0$ at (x=-∞,y), since at infinity potential is zero.

(b) $\psi_1=0$ at (x, $y=t_{Si}$ ), since source is at zero bias.

(c) $\psi_1=\psi''$ at (x,$y=t_{box}+t_{Si}$), since potential at BOX-substrate interface is ψ".

(d) $\psi_1=V_1$ at (x=-L/2, y), since potential at the virtual plane $P_1$ is $V_1$.

Since there is no accumulation, depletion or inversion of charge in the substrate, the p-type substrate is assumed to act like a contact. For high doping, thick substrate and low substrate bias this assumption is valid and is important to avoid the extension of present 2D analysis in the substrate region. The BOX-substrate interface potential is taken to be equal to $\psi''=\frac{rV_{sub}}{t_{Sub}}$ where $V_{sub}$ is the substrate bias and 'r' is fitting parameter representing the resistance effect of the substrate.

Applying the first boundary condition, we get

$$(B_1\exp^{k\infty})(C_1\sin(ky)+D_1\cos(ky))=0 \quad (5)$$

The second multiplying term can not be zero hence $B_1=0$.

Eqn. 4 can now be written as

$$\psi_1(x,y)=(\exp(kx))(C_{11}\sin(ky)+D_{11}\cos(ky)) \quad (6)$$

where $C_{11}=A_1C_1$ and $D_{11}=A_1D_1$.

Applying the second boundary condition, we get

$$\exp(kx)(C_{11}\sin(kt_{Si})+D_{11}\cos(kt_{Si}))=0 \quad (7)$$

Applying the third boundary condition in eqn.6, we get

$$\exp(kx)\{C_{11}\sin(k(t_{Si}+t_{box}))+D_{11}\cos(k(t_{Si}+t_{box}))\}=\psi'' \quad (8)$$

Multiplying eqn. 7 with $\sin(k(t_{Si}+t_{box}))$ and eqn. 8 with $\sin(kt_{Si})$, we obtain

$$D_{11} = \frac{-\exp(kx)\psi'' \sin(kt_{Si})}{\sin(kt_{box})}$$

(9)

Substituting this value in eqn. 7 we get

$$C_{11} = \frac{\exp(-kx)\psi'' \cos(kt_{Si})}{\sin(kt_{box})}$$

(10)

Applying the fourth boundary condition in eqn. 6, we get

$$V_1 = \frac{\psi'' \sin(ky - kt_{Si})}{Sin(kt_{box})}$$

(11)

**Region 3;**

In region Reg.3, 2-D potential profile is denoted by $\psi_3(x,y)$ and the solution can be written as

$$\psi_3(x,y) = (A_3 \exp(kx) + B_3 \exp(-kx))(C_3 \sin(ky) + D_3 \cos(ky))$$

(12)

The constants $A_3$, $B_3$, $C_3$ and $D_3$ can be determined from the following boundary conditions:

(a) $\psi_3=0$ at $(x=+\infty,y)$, since at infinity potential is zero.

(b) $\psi_3=V_{ds}$ at $(x,y=t_{Si})$, $V_{ds}$ is drain bias.

(c) $\psi_3=\psi''$ at $(x,y=t_{box}+t_{Si})$, since potential at substrate and oxide interface is $\psi''$.

(d) $\psi_3=V_2$ at $(x=+L/2, y)$, since potential at the virtual plane $P_2$ is $V_2$.

Adopting similar approach as in Reg. 1, potential at the virtual interface $P_2$ can be written as

$$V_2 = \left[ \begin{array}{l} \left\{ \dfrac{V_{ds}\sin(kt_{box}) - V_{ds}\sin(kt_{Si}+kt_{box})\cos(kt_{Si}) + \psi''\sin(kt_{Si})\cos(kt_{Si})}{\sin(kt_{box})} \right\} \sin(ky) \\ + \left\{ \dfrac{V_{ds}\sin(kt_{Si}+kt_{box}) - \psi''\sin(kt_{Si})}{\sin(kt_{box})} \right\} \cos(ky) \end{array} \right] \quad (13)$$

**Region 2;**

In region Reg.2, 2-D potential profile is denoted by $\psi_2(x,y)$ and the solution can be written as

$$\psi_2(x,y) = (A_2 \exp(kx) + B_2 \exp(-kx))(C_2 \sin(ky) + D_2 \cos(ky)) \quad (14)$$

The constants $A_2$, $B_2$, $C_2$ and $D_2$ can be solved from the following boundary conditions:

(a) $\psi_2= V_1$ at $(x=-L/2,y)$, since potential at the virtual plane $P_1$ is $V_1$.

(b) $\psi_2=\psi'$ at $(x,y=t_{Si})$, since potential at channel and buried oxide interface is $\psi'$.

(c) $\psi_3=V_2$ at $(x=+L/2, y)$, since potential at the virtual plane $P_2$ is $V_2$.

(d) $\psi_3=\psi''$ at $(x,y=t_{box}+t_{Si})$, since potential at substrate and buried oxide interface is $\psi''$.

Four equations can be formulated on the basis of four boundary conditions stated above.

$$(A_2 \exp(-kL/2) + B_2 \exp(kL/2))(C_2 \sin(ky) + D_2 \cos(ky)) = V_1 \quad (15)$$

$$(A_2 \exp(kx) + B_2 \exp(-kx))(C_2 \sin(kt_{Si}) + D_2 \cos(kt_{Si})) = \psi' \quad (16)$$

$$(A_2 \exp(kL/2) + B_2 \exp(-kL/2))(C_2 \sin(ky) + D_2 \cos(ky)) = V_2 \quad (17)$$

$$(A_2 \exp(kx) + B_2 \exp(-kx))(C_2 \sin(k(t_{Si}+t_{box})) + D_2 \cos(k(t_{Si}+t_{box}))) = \psi'' \quad (18)$$

There are six unknowns ($A_2$,$B_2$,$C_2$,$D_2$,$\psi'$ and k) ; therefore we need another two boundary conditions to formulate a set of six equations. To derive the two boundary conditions we used the following idea from Gauss theorem [14]

$$E_{above} - E_{bellow} = \frac{\sigma_s}{\varepsilon_m} \quad (19)$$

where, $E_{above}$ and $E_{bellow}$ are the electric field just bellow and above a plane or surface, $\sigma_s$ is the charge density on that surface and $\varepsilon_m$ is the dielectric constant of the medium below the surface. Applying this on the planes $P_1$ and $P_2$, the following two boundary conditions are obtained

$$-\left\{\frac{\partial\psi_1(x,y)}{\partial x}\right\}-\left\{-\frac{\partial\psi_2(x,y)}{\partial x}\right\}=\frac{\psi_2(x=-\frac{L}{2},y)}{\varepsilon_{SiO2}} \quad at \quad P_1 \tag{20}$$

$$-\left\{\frac{\partial\psi_3(x,y)}{\partial x}\right\}-\left\{-\frac{\partial\psi_2(x,y)}{\partial x}\right\}=\frac{\psi_2(x=+\frac{L}{2},y)}{\varepsilon_{SiO2}} \quad at \quad P_2 \tag{21}$$

Using equations 15, 16, 17, 18, 20 and 21, the 2-D potential profile in the BOX region as well as the value of 'k' are derived as;

$$\psi_2(x,y)=\frac{V_2\sinh(k(2x+L)/2)-V_1\sinh(k(2x-L)/2)}{\sinh(kL)} \tag{22}$$

$$k=\frac{\varepsilon_{SiO_2}V_2}{V_1L^{2n}\left\{\frac{\varepsilon_{SiO_2}}{2n!}-\frac{L}{(2n+1)!}\right\}} \quad [n=0,1,2,3....\infty] \tag{23}$$

The final expression of the potential profile in the BOX region is given as

$$\psi_2(x,y)=\sum_{K(n=0,1,2,.....,\infty)}\frac{V_2(k)\sinh(k(2x+L)/2)-V_1(k)\sinh(k(2x-L)/2)}{\sinh(kL)} \tag{24}$$

Back interface potential $\psi'$ can be calculated from Eq. 24 with $y=t_{Si}$ and electric field can be computed by taking the derivative of $\psi'$ with respective to x.

## RESULTS AND DISCUSSION

In the present work two-dimensional potential profile in the buried oxide region has been extensively studied for SOI MOSFET structure. We have considered a fully depleted SOI MOSFET structure with negligible buried oxide trap charge density, zero source bias and a highly doped substrate region. Material parameters used for simulation are given in the Table. 1. Through out the simulation channel length is considered to be 50nm.

***Table 1:*** *Parameter values used for simulation*

| Parameters | Value |
|---|---|
| $N_A$ | $10^{21}$ m$^{-3}$ |
| $N_{SUB}$ | $10^{21}$m$^{-3}$ |
| $N_{S-D}$ | $10^{26}$m$^{-3}$ |
| $t_{Si}$ | 20nm |
| $t_f$ | 5nm |
| $t_{box}$ | 100nm |
| $t_{sub}$ | 200nm |

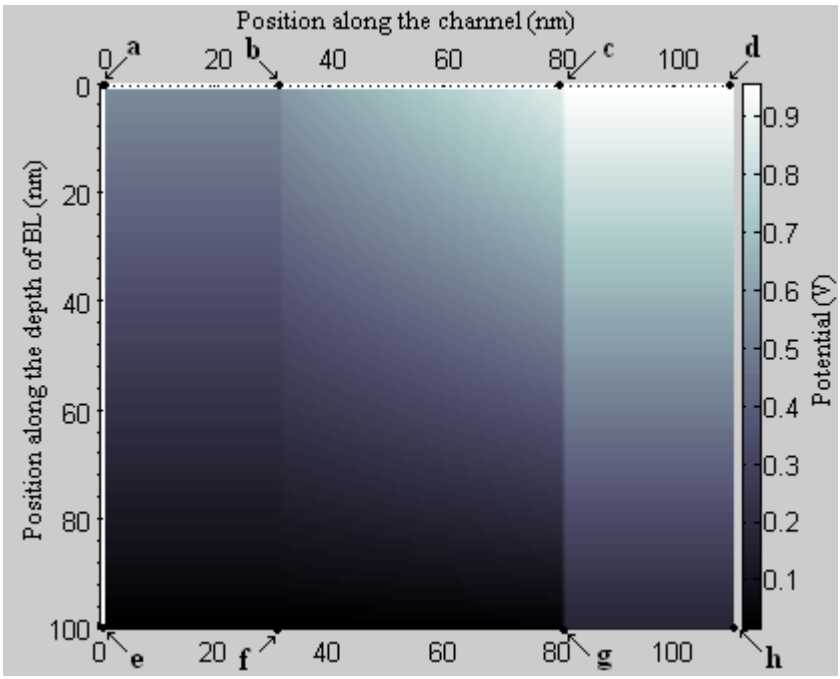


***Fig. 2.*** *Two-dimensional potential profile in the BL region for $V_{sub}$ = 1V and $V_{ds}$= 1V. Symbols a, b, c, d, e, f, g and h are boundary positions of BL region as shown in the Fig. 1.*

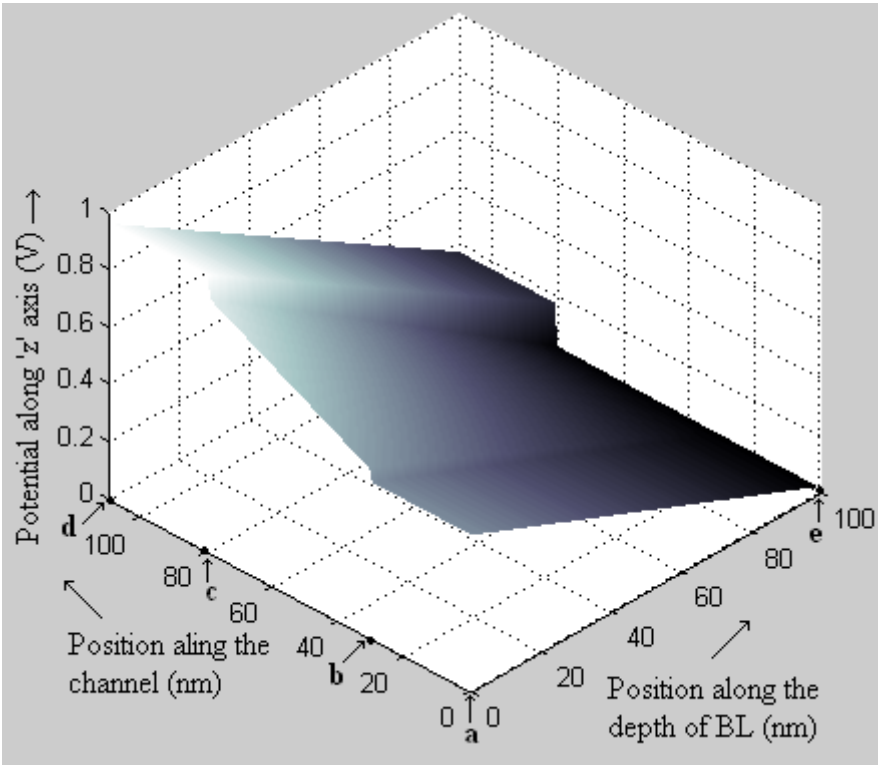


***Fig. 3:*** *Three-dimensional view of the potential surface in the BL region. Channel is from 30nm to 80nm (point b to c) along the x coordinate and BL is from 0 to 100nm along y coordinate (point a to e).*

The two-dimensional potential profile in the BL region for $V_{sub}$ = 1V and $V_{ds}$= 1V is shown in Fig. 2. The three-dimensional view of the potential profile in the BL region which is obtained by rotating the two-dimensional potential profile is shown

in Fig. 3. It is clear from Fig.2 that potential has its maximum value at point 'd' (right topmost corner) and its minimum value at point 'e' (left bottom most corner) and in other region the value of potential changes according to the combined influence of drain and substrate biases. The potential decreases as we go from channel-BOX interface to BOX-substrate interface and also from the drain to source side. This potential variation represented as a three-dimensional plane is shown in Fig. 3. The value of potential at a specific position depends on combined effect of fringing field initiated from drain bias and the substrate field.

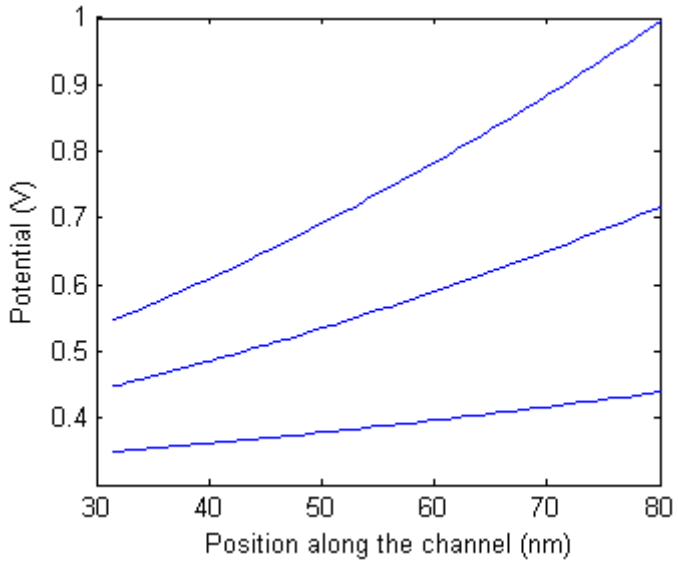


***Fig. 4.*** *Potential along the channel back interface (at $y=t_{Si}$) for $V_{sub}$ = 1V and $V_{ds}$:0.5V, 1V and 1.5V respectively (↑).*

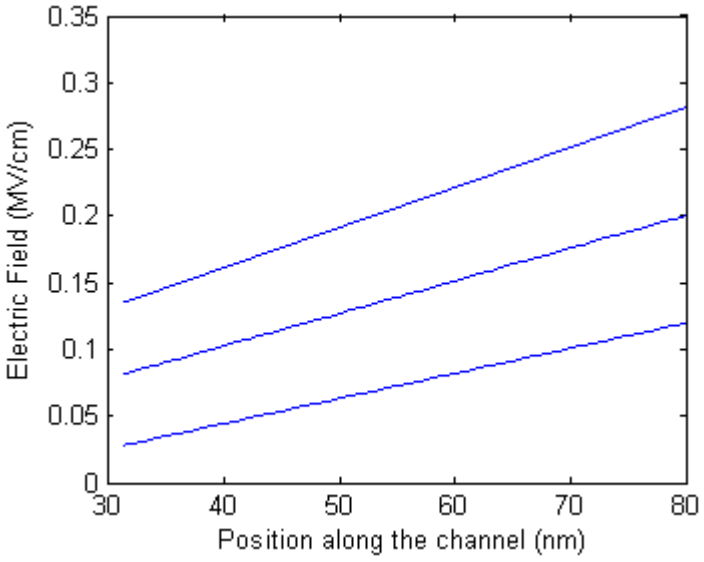


***Fig. 5.*** *Electric field along the channel back interface. Symbols and parameters are the same as in Fig. 4.*

The potential and the electric field at the channel back interface are shown in Figs. 4 and 5, respectively. The potential and the field due to the substrate bias are same

throughout the channel back interface but higher fringing field effect at the vicinity of the drain region is responsible for upward shift of the potential and electric field as we proceed from the source to the drain side.

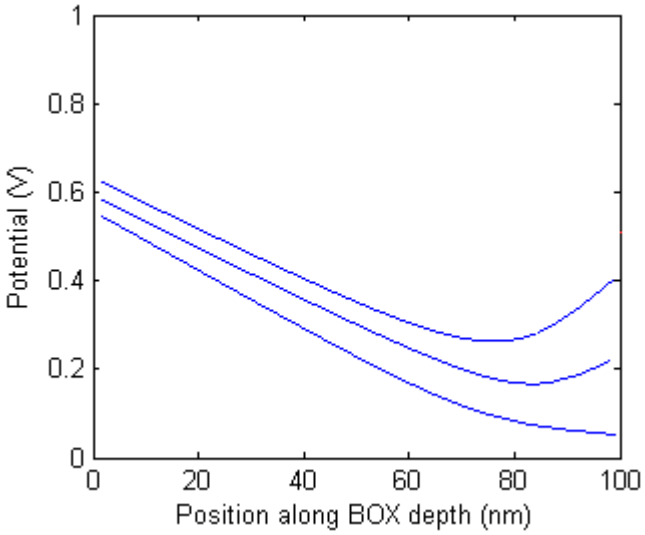


***Fig. 6.*** *Potential along y-axis in the buried layer at the middle of the channel (x=0) for $V_{ds}$ of 1V and $V_{sub}$:1V, 3V and 6V respectively (↑).*

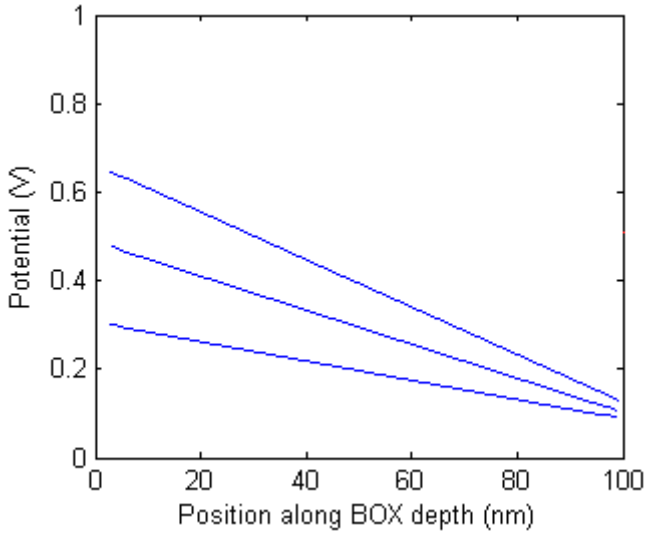


***Fig. 7.*** *Potential along y-axis in the buried layer at the middle of the channel (x=0) for $V_{sub}$ of 1V and $V_{ds}$: 0.5V, 1V and 1.5V respectively (↑).*

Potential along y-axis in the buried layer at the middle of the channel for different substrate and drain biases are plotted in Figs. 8 and 9, respectively. With the increase of the substrate bias, BOX-substrate interface potential ($\psi''$) increases as a result channel back interface potential ($\psi'$) also increases. Enhanced $\psi''$ due to higher $V_{sub}$ is responsible for initiating a parabolic nature in the potential profile shown in Fig. 8. Enhanced drain bias is responsible for higher channel back interface potential due to increased fringing field effect as shown in Fig. 9. It is also clear from these plots that fringing field effect on channel back interface potential is much more pronounced than

the substrate field effect in such low dimension.

## CONCLUSION

An analytical model of 2D potential profile in the buried oxide layer of SOI MOSFET has been developed by solving 2D Poisson's equation. Enhanced channel-back interface potential is responsible for initiating higher short channel effect and our model was able to effectively analyze the channel back interface potential. Higher substrate and drain biases enhance the potentials at the channel-back interface or the top region of the buried layer thereby increasing the short channel effects. The proposed model is a generalized model and it can be adopted for other similar MOS. Although the present analytical model was intentionally restricted to potential analysis in the buried layer, this analytical model can be used with well established 2D analytical model in the channel region to develop a complete 2D potential model throughout the device. Total 2D potential model can be used for performance analysis of short channel SOI MOSFET for future applications.

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