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Justifying threshold voltage definition for undoped body transistors through "crossover point" concept

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ABSTRACT

Two different definitions, one is potential based and the other is charge based, are used in the literatures to define the threshold voltage of undoped body symmetric double gate transistors. This paper, by introducing a novel concept of crossover point, proves that the charge based definition is more accurate than the potential based definition. It is shown that for a given channel length the potential based definition predicts anomalous change in threshold voltage with body thickness variation while the charge based definition results in monotonous change. The threshold voltage is then extracted from drain current versus gate voltage characteristics using linear extrapolation, transconductance and match-point methods. In all the three cases it is found that trend of threshold voltage variation support the charge based definition.

1. Introduction

As the conventional single gate bulk Metal Oxide Semiconductor Field Effect Transistor (MOSFET) scaling is approaching the limit imposed by short channel effects, double gate (DG) MOSFET is becoming attractive candidate for future VLSI due to its better gate control over the channel [1]. In DG MOSFET the short channel effect is controlled by the device geometry and hence undoped (or lightly doped) body is used to sustain the channel. Undoped body also helps to alleviate several other problems related to nano-scale CMOS, e.g., mobility degradation, random dopant fluctuations, compatibility with mid-gap metal gate, etc. However, there is a sharp distinction between the electrostatics of traditional bulk transistors and undoped body devices. In bulk transistor, where the substrate is sufficiently doped, the inversion charges are located close to the surface and hence the surface potential solely controls the electrostatic integrity of the device. However, in undoped body devices, gate electric field penetrates the body center and inversion charge exists throughout the body. Therefore, the definition of threshold voltage needs to be reconsidered for undoped body devices.

Till now two definitions for threshold voltage calculation in short channel undoped DG MOSFETs have been proposed. The first one is surface potential based [2], which is similar to the definition of the threshold voltage of bulk devices. The second one is based on the amount of charge per unit area of the body [3,4]. It is argued that the charge based definition is more accurate than the surface potential based definition as in undoped body devices charge exists throughout the body [5]. However, no proof is found behind this claim. In this paper we introduced the concept of "crossover point" to solve this dilemma.

We demonstrate that the body potential versus gate voltage characteristics for DG MOSFETs having equal channel lengths but different body thickness pass through a single common point, which we term a "crossover point". Using the concept of "crossover point" it is shown that in case of surface potential based definition the threshold voltage changes anomalously with body thickness variation, whereas in case of charge based definition the threshold voltage increases monotonously with decreasing body thickness. It is also found that the threshold voltage actually increases monotonously with decreasing body thickness if it is extracted from I_D–V_G characteristics using different methodologies (linear extrapolation method, transconductance method and match-point method). We therefore justify that the charge based definition is more appropriate than surface potential for threshold voltage calculation of undoped body multi-gate transistors.

2. Results and discussion

2.1. Calculation of threshold voltage

So far two definitions for threshold voltage (V_{TH}) calculation are used for short channel undoped body multi-gate transistors: (i) surface potential based definition [2], which is similar to the

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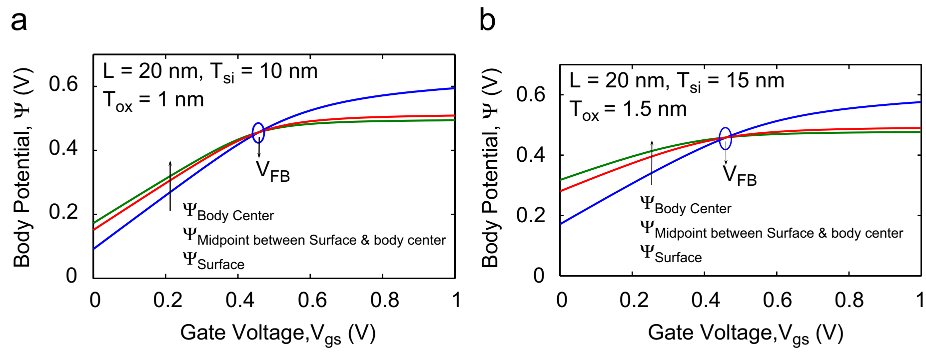

Fig. 1. Body potential versus gate voltage characteristics for: (a) $L = 20\,\text{nm}$, $T_{si} = 10\,\text{nm}$ and $T_{ox} = 1\,\text{nm}$; (b) $L = 20\,\text{nm}$, $T_{si} = 15\,\text{nm}$ and $T_{ox} = 1.5\,\text{nm}$ at body surface $(L/2, T_{si}/2)$, center $(L/2, 0)$ and midpoint between them $(L/2, T_{si}/4)$. Here, we have used mid-gap metal gate.

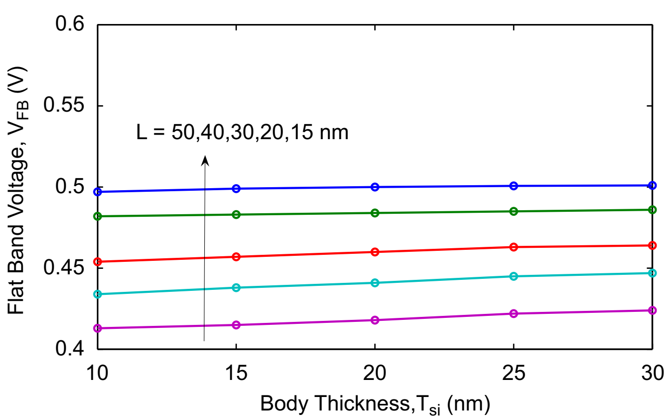

Fig. 2. Curve showing constant V_{FB} at different body thickness for different L's at $T_{ox} = 1\,\text{nm}$.

threshold voltage definition of bulk devices and (ii) charge based definition [3,4], which is based on the amount of charge per unit area of the body. As in undoped body transistors charge exists throughout the body, the second definition is argued to be more accurate, where the threshold voltage is defined as the gate voltage at which the charge per unit area (Q) at the virtual cathode becomes equal to some critical threshold charge (Q_{TH}), and Q is defined as

$$Q = qn_i \int_0^{T_{si}/2} e^{\Psi(X_c,y)/U_T} dy \tag{1}$$

Here, q is the electronic charge, n_i is the intrinsic carrier concentration of body, $\Psi(x,y)$ is the body potential, T_{si} is the body thickness, L is the channel length, U_T is the thermal voltage, x and y are the directions parallel and perpendicular to the Si/SiO_2 interface and $(L/2, 0)$ denotes body center, X_c is the position of virtual cathode ($d\Psi/dx|_{x=X_c} = 0$), which is approximately equal to $L/2$ for low V_{ds}. Now, as $\Psi(X_c, y)$ is a very complicated function of y, the above integration cannot be evaluated analytically. So in common practice the integration is approximated as

$$Q \approx qn_i \frac{T_{si}}{2} e^{\Psi(X_c,T_{si}/4)/U_T} \tag{2}$$

Therefore, the threshold criteria $Q = Q_{TH}$ can be expressed in terms of potential as

$$\Psi(X_c, T_{si}/4)_{TH} = U_T \ln\left(\frac{2Q_{TH}}{qn_i T_{si}}\right) \tag{3}$$

In surface potential based definition the threshold voltage is defined as the gate voltage when the surface potential Ψ_s at virtual cathode becomes equal to some constant critical value Ψ_{crit}. Taur [2] has taken the value of Ψ_{crit} as $E_g/2$, where E_g is silicon bandgap. Since V_{DD} for future technology nodes will take values less than 1 V [6], $\Psi_{crit} = E_g/2$ appears to be impractical as it results in threshold voltage of the order of 0.8 V. $\Psi_{crit} = E_g/2$ condition actually denotes the onset of strong inversion. As future devices will be operating in moderate inversion region, $\Psi_{crit} = E_g/2 - 4U_T = 0.45\,\text{V}$ appears to be more practical definition for threshold voltage.

2.2. Crossover point and pseudo-flatband condition

From numerical device simulation [7] it is observed that if the body potential of an undoped DG MOSFET is plotted against gate voltage at $y = 0$ (body center), $y = T_{si}/2$ (body surface), $T_{si}/4$ (midpoint of surface and body center) all characteristics pass through a common point for a particular gate voltage (V_{FB}) (Fig. 1(a) and (b)). This implies that at V_{FB} there is no potential drop along the radial direction from body center to the surface. This is precisely the flatband condition. But we attribute this situation as "pseudo-flatband condition" as there exists potential variation along the lateral direction. Interestingly, it is also observed that V_{FB} is *almost* independent of the variation of body thickness when channel length is constant (Fig. 2), or in other words, devices having same L but different T_{si}'s hold same value of V_{FB}. Hence, for a given L and different T_{si}'s, if we plot potential as a function of V_{gs} at a particular radial point $(X_c, T_{si} \cdot m)$, where $|m|(\leqslant\frac{1}{2})$ is a constant, all the characteristics should pass through the common "flatband" point, which we termed as "crossover point" (Fig. 3(a)–(c)). The body potential related to this point is denoted by Ψ_{cross}. Another observation made in this work is that the value of Ψ_{cross} increases with decreasing channel length as shown in Fig. 4. This is due to the fact that for long channel devices surface potential is always greater than body center for positive gate voltages. Hence for long channel devices $V_{FB} \approx 0$ (or more precisely equal to the difference between gate and body work function). However, for short channel devices, due to the lateral electric field from drain-to-source body center potential could be higher than surface (Fig. 1(a) and (b)) for positive V_{gs}. Hence, in order to bring the surface potential equal to body center one needs higher gate voltage. As a result Ψ_{cross} increases with decreasing L. This phenomena is used to justify the definition of threshold voltage as discussed in the next section. Fig. 4 also shows that the gate oxide thickness (T_{ox}) variation does not have much effect on Ψ_{cross} versus L characteristics.

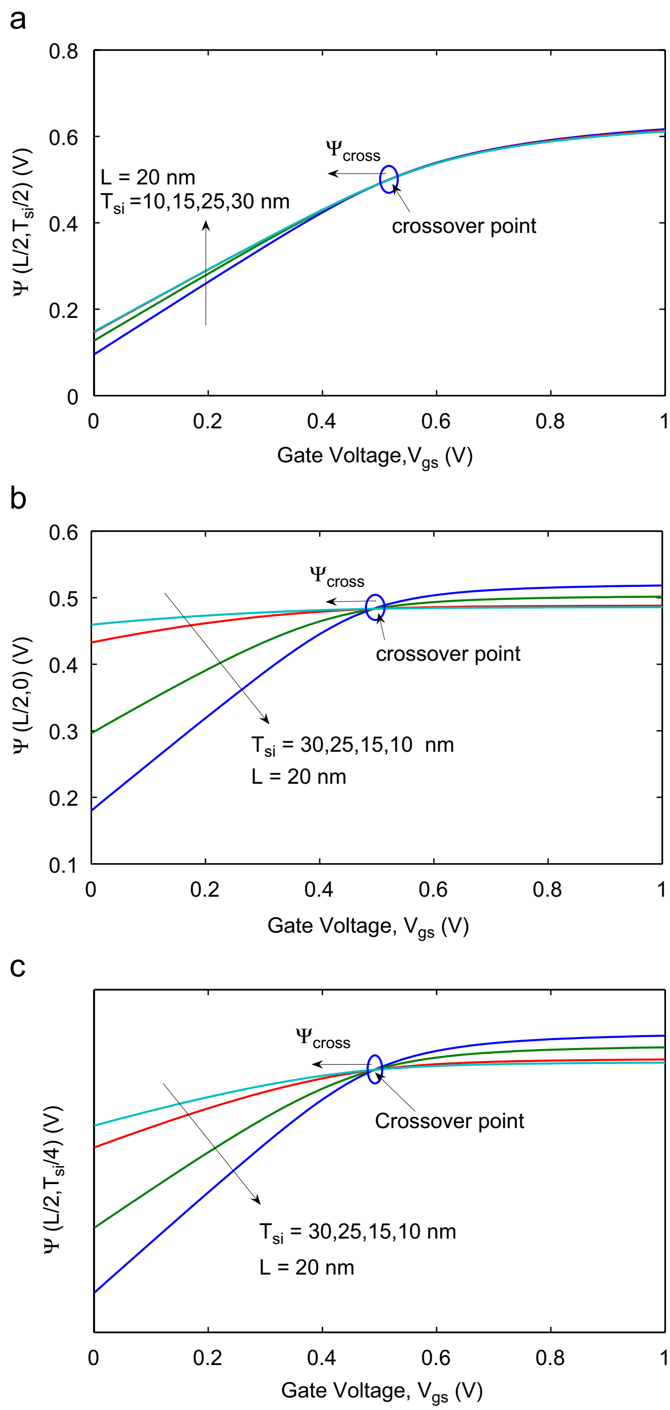

Fig. 3. Body potential versus gate voltage characteristics for channel length $L=20\,\text{nm}$ at body surface $(L/2, T_{si}/2)$, center $(L/2, 0)$ and midpoint between them $(L/2, T_{si}/4)$ for $T_{ox}=1\,\text{nm}$.

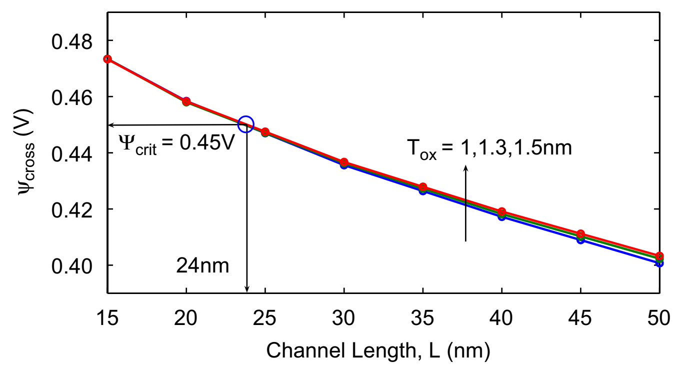

Fig. 4. Variation of "crossover point" potential (Ψ_{cross}) as a function of channel length for different T_{ox}'s.

2.3. *Effect of body thickness on threshold voltage*

The relative value between Ψ_{crit} and Ψ_{cross} dictates how the V_{TH} will change with T_{si} for a given channel length if one uses surface potential based definition. If $\Psi_{crit} > \Psi_{cross}$, the threshold voltage will decrease with T_{si}. However, the opposite trend is observed for devices having $\Psi_{crit} < \Psi_{cross}$. As Ψ_{cross} increases with decreasing L (Fig. 4), it is expected that for small channel lengths ($<24\,\text{nm}$), V_{TH} should increase with T_{si} and for large L ($>24\,\text{nm}$) it should exhibit the opposite trend. Therefore, surface potential based definition results in anomalous change in threshold voltage for body thickness variation for any given channel length as shown in Fig. 5(a).

Using charge based definition, the threshold voltage variation with body thickness is found to follow monotonous trend for any given channel length (Fig. 5(b)). In this work we have used potential at $(X_c, T_{si}/4)$ and $Q_{TH} = 8\times10^{-4}\,\text{C/m}^2$ to compute threshold voltage from Eq. (3). The trend of V_{TH} versus T_{si} characteristics remain unchanged if other values of Q_{TH} are used.

In order to justify which definition is correct, we have extracted threshold voltage from $I_D - V_G$ characteristics using three different methods. First, we use linear extrapolation method. Here, V_{TH} is extracted by linearly extrapolating the I_{ds} versus V_{gs} characteristics at low drain voltage from the point of maximum g_m $(= \mathrm{d}I_d/\mathrm{d}V_{gs})$. Second, we use transconductance method, where V_{TH} is extracted the point of maximum $\partial g_m/\partial V_{gs}$. Third, we use match-point method. Here, V_{TH} is extracted from the V_{gs} at which $\log(I_{ds})$ versus V_{gs} characteristics deviates 5% from the linear sub-threshold behavior. The extracted V_{TH} are plotted as a function of body thickness in Fig. 6(a)–(c). For all three cases monotonous trend is observed which is similar to charged based definition (Fig. 5(b)). Therefore, we conclude that for undoped multi-gate devices charge based model for threshold voltage calculation is more accurate than surface potential model.

It is worth nothing that similar argument is equally valid for gate-all-around (GAA) cylindrical transistors, as "crossover points" are also observed in those devices [5].

3. Conclusion

In this work it is demonstrated that the body potential versus gate voltage characteristics for undoped body symmetric DG MOSFETs having equal channel lengths but different body thickness pass through a common point termed a "crossover point". Using the concept of "crossover point" it is demonstrated that for a given channel length the potential based threshold voltage definition predicts anomalous change in threshold voltage as a function of body thickness while the charge based definition results in monotonous change. When the threshold voltage is extracted from drain current versus gate voltage characteristics using linear extrapolation, transconductance and match-point methods it is found that in all three cases trend of threshold voltage variation support the charge based definition. It is

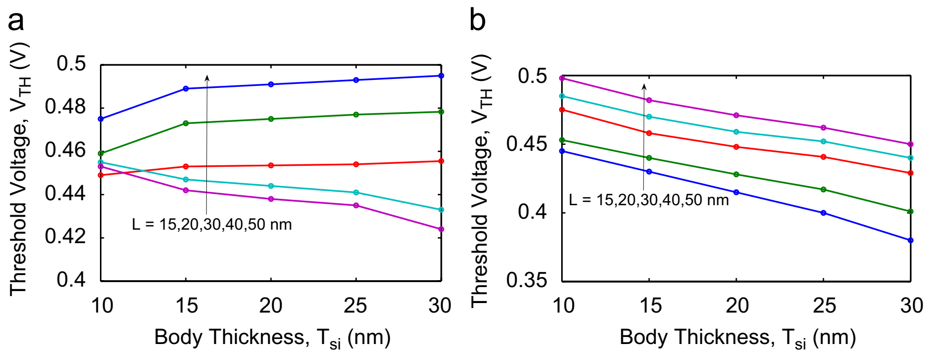

Fig. 5. (a) V_{TH} calculated from surface potential based definition. (b) V_{TH} calculated from charge based definition for $T_{ox} = 1$ nm.

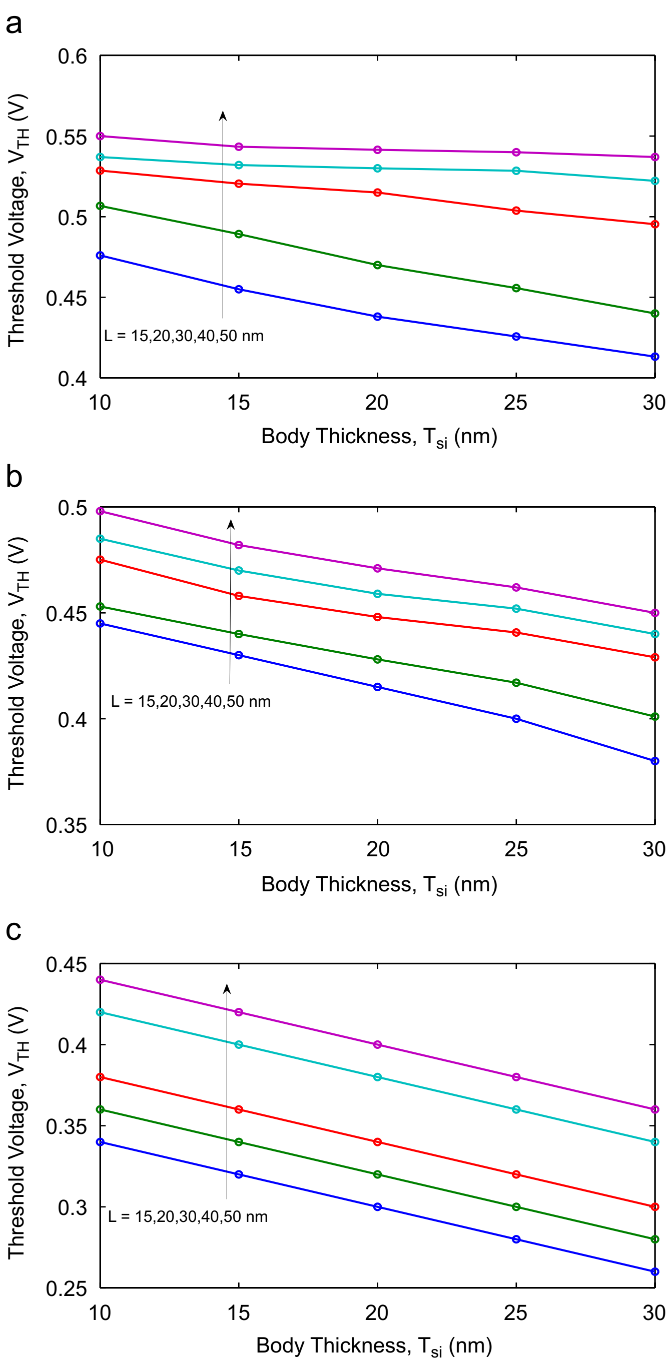

Fig. 6. V_{TH} versus T_{si} characteristics as extracted from: (a) linear extrapolation method, (b) transconduction method and (c) match-point method for $T_{ox} = 1$ nm.

therefore concluded that charge based definition is more accurate than potential based definition.

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