A Surface Potential Model for Bulk MOSFET which Accurately Reflects Channel Doping Profile Expelling Fitting Parameters

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***Abstract*— A surface potential model for bulk MOSFET which accurately reflects channel doping profile is proposed. Only physical parameters such as device structures and doping profiles are used in the proposed model. For the vertical direction to channel, the model consistently integrates both surface potential and arbitral channel doping profiles in Poisson equation by using HiSIM2 [1] framework. For channel direction, the model improves Pang's quasi-2D Gaussian box model [2] by taking the effect of source/drain junction depth into account. To accurately reflect the effect of the doping profile, drain current is evaluated by numerical integration using the calculated surface potential. The dependence of both short channel effect (SCE) and the reverse short channel effect (RSCE) on Vds, Vbs, channel length, junction depth and channel doping profiles, are expressed accurately without using any fitting parameters.**

***Keywords-component;* Surface potential model, MOSFET, Poisson equation, channel doping profile, short channel effect, reverse short channel effect .**

I. INTRODUCTION

Compact models for bulk MOSFET have many fitting parameters to fulfill a stringent demand for high fitting accuracy. This is true even for advanced surface potential models such as HiSIM2 [1]. Moreover, the channel doping profile is quite simplified to achieve fast calculation. However, this kind of compact models cannot be used for inverse modeling of channel doping profile, process variation analysis and characteristics prediction for process condition change. Although TCAD can be used for these purposes, it takes long calculation time and the results are less accurate because of the uncertainty of the simulated impurity profiles based on dubious process models. Therefore, a micro-TCAD, i.e. a fast and light compact transistor model which has the almost same accuracy as TCAD is most desirable for the purposes described above. To realize this request, we developed a compact model for sub-threshold characteristics calculation of bulk MOSFET which accurately accounts for channel doping profile and is expressed by process and structural parameters only.

II. MODEL

A. Vertical direction

In a non-inversion region ($V_{FB} < V_{gs} < V_{th}$) where the carrier density can be ignored as charge, the potential can be written by the differential equation

$$\varepsilon_s \frac{d^2\phi(W_D,z)}{dz^2} = q \cdot N(z),$$

where $N(z)$ is channel doping profile, W_D is depletion layer width and z is depth from Si-SiO2 interface, respectively. The equation is analytically solved and the surface potential ϕ_s is defined with $\phi_s = \phi(W_D, 0)$, and then can be written as

$$\phi_s = \frac{q}{\varepsilon_s}\int_0^{W_D} N(z)z \cdot dz + V_{bs} + \frac{1}{\beta}.$$

Poisson equation and effective channel concentration N_{sub} are written:

$$C_{ox}\left(V_{gs} - V_{FB} - \phi_s\right) = \sqrt{\frac{2\varepsilon_s q}{\beta}} \left(N_{sub}(W_D)\cdot\left(\beta(\phi_s - V_{bs}) - 1 + \exp(-\beta(\phi_s - V_{bs}))\right) + \frac{{n_i}^2}{N_{sub}(0)}\left(\exp\left(\beta\left(\phi_s - \phi_f\right)\right) - \exp\left(\beta\left(V_{bs} - \phi_f\right)\right)\right)\right)^{\frac{1}{2}}$$

$$N_{sub}(W_D) = \frac{\left(\int_0^{W_D} N(z)dz\right)^2}{2\int_0^{W_D} N(z)z \cdot dz}$$

In a non-inversion region, the right-hand side of the Poisson equation above is nearly equal to the substrate charge $q\int_0^{W_D} N(z)dz$.

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The Poisson equation above is reconstructed by using W_D as a variable, and then solved by using numerical iteration method embedded in the HiSIM2 framework. Thus, surface potential which reflects the channel doping profile can be obtained.

B. Channel Direction

A surface potential model which divides channel region to three regions -- two pocket implantation regions and center region -- according to channel concentration was proposed by Pang et al. [2]. In their model, first, surface potential is calculated in each region, and the correction term for channel direction is calculated by using quasi-2D Gaussian box approximation in order to express modulation of surface potential by SCE and RSCE.

In the proposed model, first, effect of source/drain junction depth X_j is introduced in Pang's model (Fig.1) by taking the geometrical charge sharing effect into account. The regions of right isosceles triangles which contact the source/drain edge are defined, and the charge of this region is ignored when solving Poisson equations. For example, the effective channel concentration $N_{sub}(x)$ for each region in figure 1 when solving the Poisson equation is shown as the following.

$$0 \le x \le W_{D(p)}, L - W_{D(p)} \le x \le L:$$

$$N_{sub}(x) = \frac{1}{2} N_p$$

$$W_{D(p)} \le x \le L_p, L - L_p \le x \le L - W_{D(p)}:$$

$$N_{sub}(x) = N_p$$

$$L_p \le x \le \frac{X_j}{2} - W_{D(p)}, L - \frac{X_j}{2} + W_{D(p)} \le x \le L - L_p:$$

$$N_{sub}(x) = \left(1 - \frac{1}{W_{D(c)}}\left(\frac{X_j}{2} - W_{D(p)}\right)\right) N_c$$

$$\frac{X_j}{2} - W_{D(p)} \le x \le L - \frac{X_j}{2} + W_{D(p)}:$$

$$N_{sub}(x) = N_c$$

Next, the carrier density $N_I(x)$ and those derivative are approximated by the following equation using calculated surface potential (Fig.2 and 3) in subthreshold region ($V_g < V_{th}$).

$$N_I(x) \cong \left(\frac{{n_i}^2}{N_{sub}(x)}\right)\left(\frac{L_D(x)^2}{W_D(x)}\right)\exp\left(\beta\left(\phi_s(x) - \phi_f(x)\right)\right)$$

$$\frac{dN_I(x)}{dx} \cong \beta \cdot N_I(x)\left(\frac{d\phi_s(x)}{dx} - \frac{d\phi_f(x)}{dx}\right)$$

$$W_D(x) = L_D(x)\sqrt{2}\sqrt{\beta\left(\phi_s(x) - V_{bs}\right) - 1}$$

$$L_D(x) = \sqrt{\frac{\varepsilon_s q N_{sub}(x)}{\beta}}$$

The drain current I_D is written by using the carrier density and quasi-Fermi potential $\phi_f(x)$ as

$$I_D = q \cdot \mu \cdot \left(N_I(x) \cdot \frac{d\phi_s(x)}{dx} - \frac{1}{\beta}\frac{dN_I(x)}{dx}\right)$$

$$= q \cdot \mu \cdot N_I(x) \cdot \frac{d\phi_f(x)}{dx}$$

This equation is integrated from source to drain, and then the following expression is obtained [3]. In our model, drain current is evaluated using numerical integration method in order to accurately reflect the effect of the doping profile (Fig.4).

$$I_D = \frac{q \cdot \mu \cdot \left(1 - \exp(-\beta V_{ds})\right)}{\beta \int_0^L \left(\frac{N_{sub}(x)}{{n_i}^2}\right)\left(\frac{W_D(x)}{L_D(x)^2}\right)\exp\left(-\beta\phi_s(x)\right)dx}$$

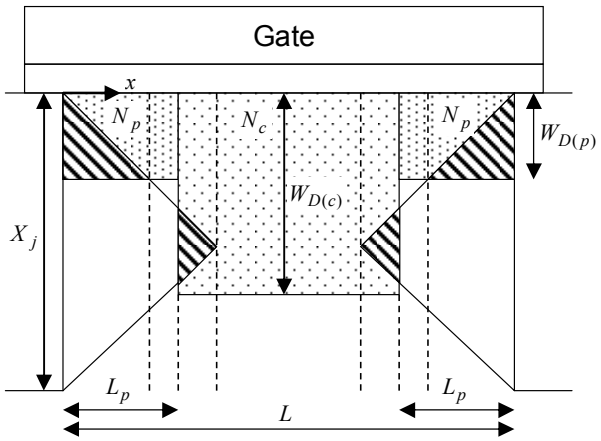

Figure 1: Division of channel region (by dot lines)
In regions painted by oblique lines, the charge is ignored when solving Poisson equations.

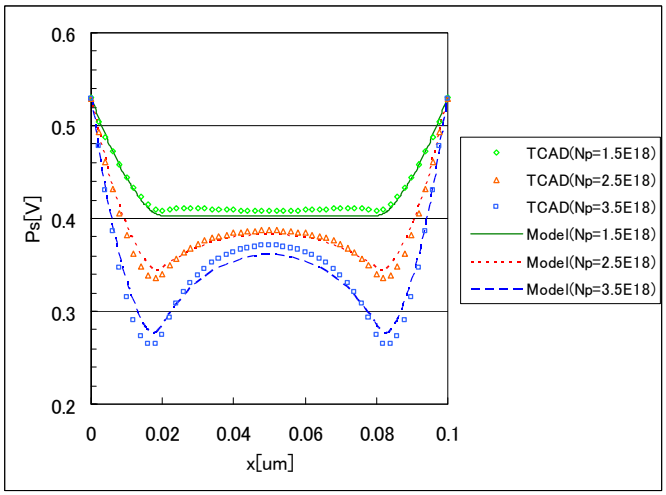

Figure 2: Surface potential by TCAD and our model for $N_c = 5E17[\mathrm{cm}^{-3}]$, $N_p = 1.5E18, 2.5E18, 3.5E18[\mathrm{cm}^{-3}]$, $L = 0.1[\mu\mathrm{m}]$, $L_p = 0.02[\mu\mathrm{m}]$, $X_j = 30[\mathrm{nm}]$, $V_{ds} = 0[V]$, $V_{gs} = 0.2[V]$

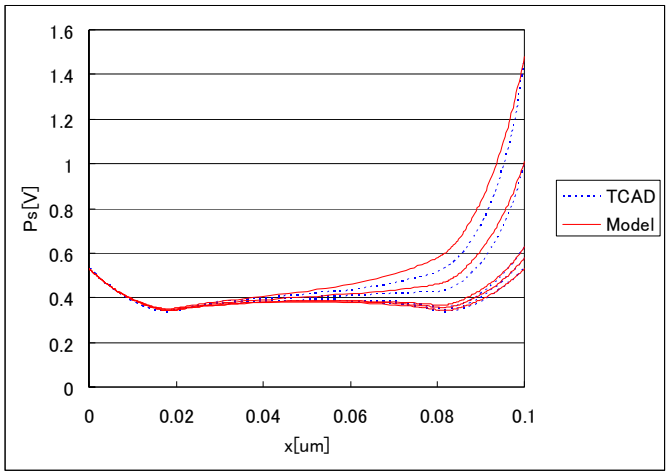

Figure 3: Surface potential by TCAD and our model for $N_c = 5E17[\mathrm{cm}^{-3}]$, $N_p = 2.5E18[\mathrm{cm}^{-3}]$, $L = 0.1[\mu\mathrm{m}]$, $L_p = 0.02[\mu\mathrm{m}]$, $X_j = 30[\mathrm{nm}]$, $V_{ds} = 0,0.05,0.1,0.5,1[V]$, $V_{gs} = 0.2[V]$

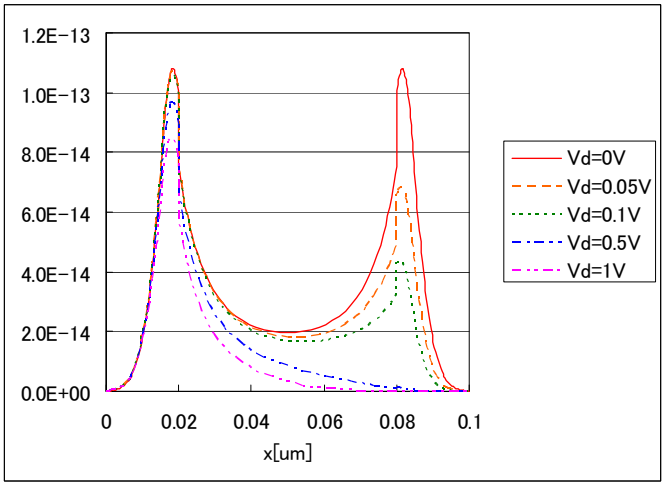

Figure 4: $\left(\frac{N_{sub}(x)}{{n_i}^2}\right)\left(\frac{W_D(x)}{{L_D(x)}^2}\right)\exp(-\beta\phi_s(x))$ by our model for $N_c = 5E17[\mathrm{cm}^{-3}]$, $N_p = 2.5E18[\mathrm{cm}^{-3}]$, $L = 0.1[\mu\mathrm{m}]$, $L_p = 0.02[\mu\mathrm{m}]$, $X_j = 30[\mathrm{nm}]$, $V_{ds} = 0,0.05,0.1,0.5,1[V]$, $V_{gs} = 0.2[V]$

III. RESULTS

The channel doping profile of TCAD simulation was fed into the proposed model, and then, the profile was re-extracted from the $C_{gg} - V_{gs}$ and the $V_{th} - V_{bs}$ characteristics calculated by the proposed mode. The following equations are used for the re-extraction.

From $C_{gg} - V_{gs}$:

$$W_D = \varepsilon_s\left(\frac{1}{C_{gg}} - \frac{1}{C_{ox}}\right)$$

$$N(W_D) = \frac{C_{gg}}{q\varepsilon_s}\left(\frac{d}{dV_{gs}}\left(\frac{1}{C_{gg}}\right)\right)^{-1}$$

From $V_{th} - V_{bs}$:

$$W_D = -\frac{\varepsilon_s}{C_{ox}}\left(\frac{dV_{th}}{dV_{bs}}\right)^{-1}$$

$$N(W_D) = -\frac{{C_{ox}}^2}{q\varepsilon_s}\left(\frac{dV_{th}}{dV_{bs}}\right)\left(\frac{d}{dV_{bs}}\left(\frac{dV_{th}}{dV_{bs}}\right)^{-1}\right)^{-1}$$

The re-extracted profiles exactly overlap with the original one as shown in the figure 5, and this result means the proposed vertical profile model is very precise.

Threshold voltage for various gate lengths calculated with TCAD and the proposed model is shown in the figures 6, 7, and 8. Here, the definition of threshold voltage is $V_{th} = V_{gs}\,@\,I_D = 10^{-9}[A]\cdot W/L$. The dependence of V_{ds}, V_{bs}, and junction depth X_j of the proposed model traces TCAD results very accurately. The model parameters are doping concentration in pocket region N_p, doping concentration in center region of channel N_c, width of pocket region L_p, and source/drain junction depth. All are the process parameters and their values are the same with TCAD simulations. The expellant of fitting parameter is realized by adopting the geometrical charge sharing model described in Section II B. This is the most significant advantage of this model compared with the original Pang's model which ignores the charge sharing effect in spite of assuming deep source/drain junction depth or Yu's model [4] used in BSIM3/4 which introduces fitting parameter η to handle various source/drain junction depths. Finally, figure 9 shows threshold voltage by TCAD simulations and the proposed model for channel doping of various combinations of N_p, N_c, and L_p. Good scalability within 20mV error was achieved without any fitting parameters. Although it takes about 1 hour if TCAD is used for generating the data necessary for drawing fig. 7, the proposed model can reproduce the almost same results within a second. Therefore, this model can be easily used as a micro-TCAD for inverse modeling of channel doping profile, process variation analysis and characteristics prediction for process condition change.

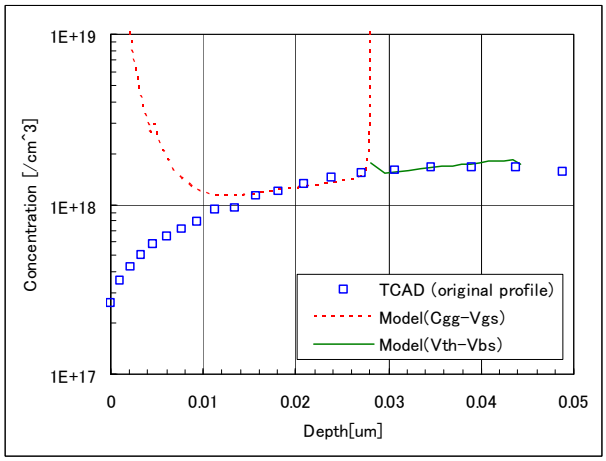

Figure 5: The original profile of TCAD simulation and channel profiles transformed from $C_{gg} - V_{gs}$ and $V_{th} - V_{bs}$ by our model for

$N(z) = 8\times10^{17}[\mathrm{cm}^{-3}] + 2.4\times10^{19}[\mathrm{cm}^{-3}/\mu\mathrm{m}]\cdot z[\mu\mathrm{m}]$.

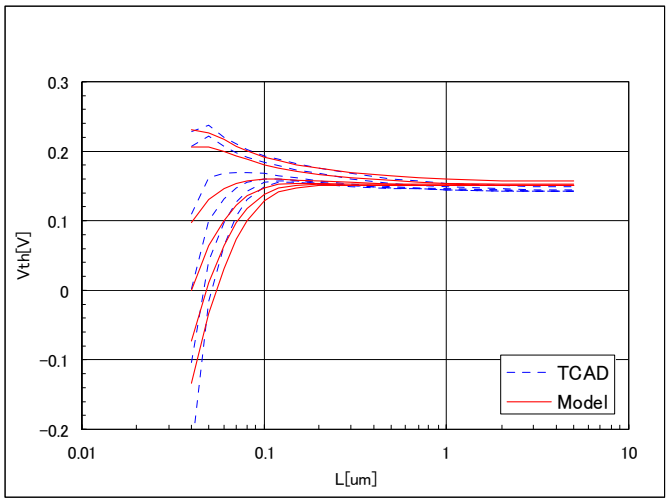

Figure 6: Threshold voltage by TCAD and our model for $N_c = 5E17[\mathrm{cm}^{-3}]$, $N_p = 2.5E18[\mathrm{cm}^{-3}]$, $L_p = 0.02[\mu\mathrm{m}]$, $X_j = 30[\mathrm{nm}]$, $V_{ds} = 0,0.05,0.1,0.5,1[V]$

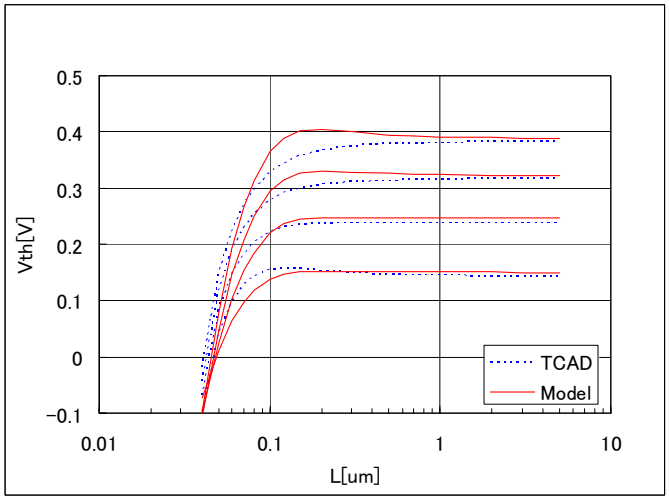

Figure 7: Threshold voltage by TCAD and our model for $N_c = 5E17[\mathrm{cm}^{-3}]$, $N_p = 2.5E18[\mathrm{cm}^{-3}]$, $L_p = 0.02[\mu\mathrm{m}]$, $X_j = 30[\mathrm{nm}]$, $V_{bs} = 0,-0.5,-1,-1.5[V]$, $V_{ds} = 1[V]$

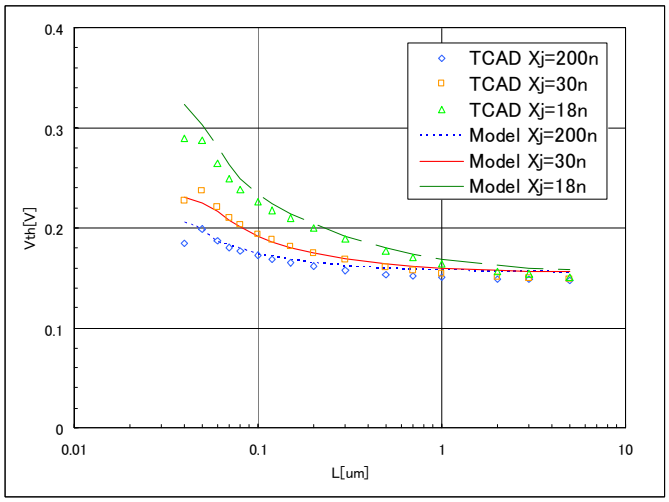

Figure 8: Threshold voltage by TCAD and our model for $N_c = 5E17[\mathrm{cm}^{-3}]$, $N_p = 2.5E18[\mathrm{cm}^{-3}]$, $L_p = 0.02[\mu\mathrm{m}]$, $X_j = 18,30,200[\mathrm{nm}]$, $V_{ds} = 0.05[V]$

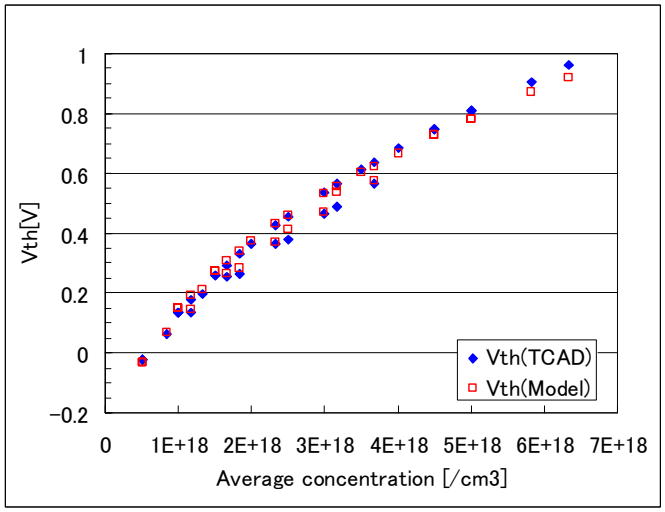

Figure 9: Threshold voltage by TCAD and our model for channel concentration of various combinations of $N_c, N_p L_p$, $L = 0.06[\mu\mathrm{m}]$, $X_j = 18[\mathrm{nm}]$, $V_{ds} = 0.05[V]$

IV. Conclusion

A new compact transistor model for bulk MOSFET has been developed based on the surface potential model framework embedded in HiSIM2. By adopting a new geometrical charge sharing model, the model can predict the threshold voltage dependence on Vds, Vbs, channel length, junction depth and channel doping profile within 20mV accuracy without using any fitting parameter. The model can be used as a micro-TCAD for threshold voltage calculation which has over 1000 times calculation efficiency compared with conventional TCAD.

Acknowledgment

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