Analytic Threshold Voltage Model of Recessed Channel MOSFETs

Yongmin Kwon, Yeonsung Kang, Sanghoon Lee, Byung-Gook Park, and Hyungcheol Shin

***Abstract*—Threshold voltage is one of the most important factors in a device modeling. In this paper, analytical method to calculate threshold voltage for recessed channel (RC) MOSFETs is studied. If we know the fundamental parameter of device, such as radius, oxide thickness and doping concentration, threshold voltage can be obtained easily by using this model. The model predicts the threshold voltage which is the result of 2D numerical device simulation.**

***Index Terms*—Threshold voltage, recessed channel MOSFETs, concave, analytic model, depletion width**

I. INTRODUCTION

The classical planar MOSFET is approaching its scaling limit due to tunneling current through the ultrathin gate oxide. To improve the scalability of CMOS technology, several non-classical MOSFETs have been proposed. Among them, recess channel (RC) MOSFETs have advantages in terms of short channel effects because the bottom corner effect in the recessed region acts against the DIBL effects [1]. Due to the interest in this device, modeling and application of RC MOSFETs is studied by other groups [2-5]. Although threshold voltage is a fundamental parameter to predict the I-V characteristics of devices, a compact and analytic threshold model has not been reported.

Threshold voltage for recessed channel MOSFETs can be obtained in a similar method of planar MOSFETs. Using charge sheet approximation and gradual channel approximation, I-V equation can be derived. Typically, we expand equations in V_{DS} into a power series when we derive threshold voltage. In case of RC MOSFETs, however, it is very complicated to calculate analytically because the depletion charge is distributed in concave silicon region.

In this paper, we propose a new analytic model of threshold voltage of RC MOSFETs for the first time. We compare the results of approximated analytic method with those of numerical simulation. Accuracy of the derived model is validated by ATLAS simulator [6].

II. RESULT AND DISCUSSION

A cross-sectional view of recess channel (RC) MOSFET is shown in Fig. 1. R, r_d, N_A, t_{ox}, and r’ are radius including gate and oxide thickness, depletion width of RC MOSFETs, doping concentration, oxide thickness and radial direction, respectively.

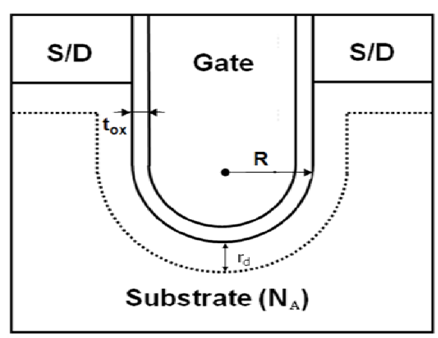

Fig. 1. A cross-sectional view of RC MOSFETs.

By solving cylindrical Poisson’s equation, the potential distribution in the silicon region can be derived.

$$\frac{1}{r'}\frac{\partial}{\partial r'}\left(r'\frac{\partial\psi}{\partial r'}\right)=\frac{qN_A}{\varepsilon_{si}}\qquad\left(R<r'<R+r_d\right)\qquad(1)$$

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Assuming that there's no charge in $r' > R + r_d$, we can obtain the solution of Eq. (1) by integrating from R to $R + r_d$.

$$\psi(r) = \frac{qN_A}{2\varepsilon_s}\left(\frac{1}{2}r^2 + (R + r_d)^2 \ln\frac{R + r_d}{r\sqrt{e}}\right) \tag{2}$$

At strong inversion, we can relate Eq. (2) to planar MOSFETs. The depletion width of planar MOSFETs (x_d) is :

$$x_d = \sqrt{\frac{2\varepsilon_s(2\phi_F + V)}{qN_A}} \tag{3}$$

$$\psi_s = 2\phi_F + V = \frac{qN_A}{2\varepsilon_s}\left(\frac{1}{2}R^2 + (R + r_d)^2 \ln\frac{R + r_d}{R\sqrt{e}}\right) \tag{4}$$

$$x_d = \sqrt{\frac{1}{2}R^2 + (R + r_d)^2 \ln\frac{R + r_d}{R\sqrt{e}}} \tag{5}$$

With Eq. (5) we can obtain depletion width of RC MOSFETs numerically. For example, the device with $N_A = 1X10^{17}$ cm^{-3}, V= 0 V and R= 22.5 nm has $x_d = 30.4$ nm and $r_d = 26.5$ nm.

Using charge-sheet approximation and gradual channel approximation(GCA), I-V equation can be derived.

$$Q_d = -qN_a r_d' = -qN_a\left(r_d + \frac{r_d^{\ 2}}{2R}\right) \tag{6}$$

$$Q_s = -C_{ox}\left(V_g - V_{fb} - 2\varphi_F - V\right) \tag{7}$$

$$Q_i = -C_{ox}\left(V_g - V_{fb} - 2\varphi_F - V\right) + qN_a\left(r_d + \frac{r_d^{\ 2}}{2R}\right) \tag{8}$$

$$I_{ds} = \mu_{eff} C_{ox}\frac{W}{L}\left[\left(V_g - V_{fb} - 2\varphi_F - \frac{V_{ds}}{2}\right)V_{ds} - \frac{qN_a}{C_{ox}}\int_0^{V_{ds}}\left(r_d + \frac{r_d^{\ 2}}{2R}\right)dV\right] \tag{9}$$

Q_d, Q_s and Q_i are depletion charge, induced charge and inversion charge, respectively. Because extracting r_d from x_d in Eq. (5) needs numerical process, it is difficult to integrate the second term in Eq. (9). If r_d can be obtained in an analytical way, it will be more simple and easy to derive I-V equation. To simplify the step, approximated analytic r_d is used [2]:

$$r_d \approx x_d\left(1 - \frac{x_d}{6R}\right) \tag{10}$$

It is shown that approximated r_d matches well with r_d by numerical method in Fig. 2. Substituting Eq. (10) into Eq. (9),

$$\begin{aligned}\int_0^{V_{ds}}\left(r_d + \frac{r_d^{\ 2}}{2R}\right)dV &= \int_0^{V_{ds}}\left(x_d + \frac{x_d^{\ 2}}{3R} - \frac{x_d^{\ 3}}{6R^2} + \frac{x_d^{\ 4}}{72R^3}\right)dV \\ &= \left[\sqrt{\frac{2\varepsilon}{qN_a}}\frac{2}{3}(V + 2\phi_F)^{3/2} + \frac{2\varepsilon}{qN_a}\frac{(V + 2\phi_F)^2}{6R} - \left(\frac{2\varepsilon}{qN_a}\right)^{3/2}\frac{(V + 2\phi_F)^{5/2}}{15R^2} + \left(\frac{2\varepsilon}{qN_a}\right)^2\frac{(V + 2\phi_F)^3}{216R^3}\right]_{V=0}^{V=V_{DS}}\end{aligned} \tag{11}$$

The first and third terms in the right equation can be written in an expanded form :

$$\sqrt{\frac{2\varepsilon}{qN_a}}\frac{2}{3}(V + 2\phi_F)^{3/2}\Bigg|_{V=0}^{V=V_{DS}} \approx \sqrt{\frac{2\varepsilon}{qN_a}}(2\phi_F)^{1/2}V_{DS} \tag{12-a}$$

$$\left(\frac{2\varepsilon}{qN_a}\right)^{3/2}\frac{(V + 2\phi_F)^{5/2}}{15R^2}\Bigg|_{V=0}^{V=V_{DS}} \approx \left(\frac{2\varepsilon}{qN_a}\right)^{3/2}\frac{1}{6R^2}(2\phi_F)^{3/2}V_{DS} \tag{12-b}$$

Then, we can write Eq.(9) as follows :

$$I_{ds} = \mu_{eff} C_{ox}\frac{W}{L}\left[\left(V_g - V_{fb} - 2\varphi_F - \frac{V_{ds}}{2}\right)V_{ds} - \frac{qN_a}{C_{ox}}f(V_{DS})\right] \tag{13}$$

$$f(V_{DS}) = \left[\begin{aligned}&\sqrt{\frac{2\varepsilon}{qN_a}}(2\phi_F)^{1/2}V_{DS} + \frac{2\varepsilon}{qN_a}\frac{V_{DS}^{\ 2} + 4V_{DS}\phi_F}{6R} \\ &-\left(\frac{2\varepsilon}{qN_a}\right)^{3/2}\frac{1}{6R^2}(2\phi_F)^{3/2}V_{DS} + \left(\frac{2\varepsilon}{qN_a}\right)^2\frac{V_{DS}^{\ 3} + 6V_{DS}^{\ 2}2\phi_F + 12V_{DS}\phi_F^{\ 2}}{36R^3}\end{aligned}\right]$$

To extract threshold voltage, V_{DS}^2 and V_{DS}^3 can be neglected for small V_{DS} in Eq. (13). (see Fig. 3) Finally, we obtain the analytic I-V equation after removing higher order terms.

$$I_{ds} = \mu_{eff} C_{ox}\frac{W}{L}\left[\left(V_g - V_{fb} - 2\phi_F - g(2\phi_F) - \frac{V_{ds}}{2}\right)V_{ds}\right] \tag{14}$$

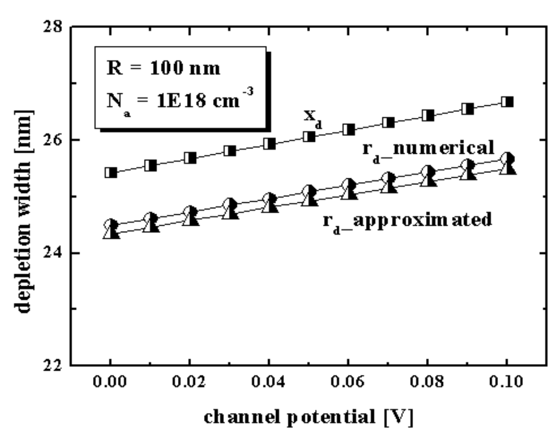

Fig. 2. depletion width(r_d) as a function of channel potential.

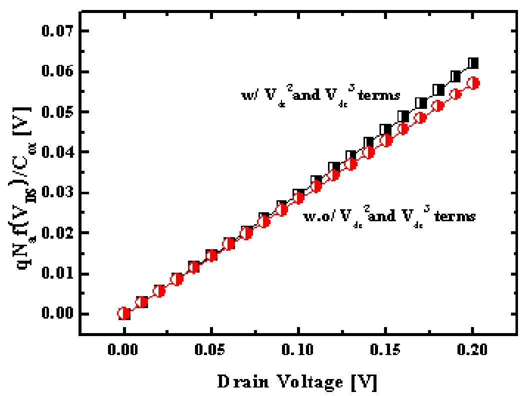

Fig. 3. effect of higher order terms in $f(V_{DS})$ with respect to V_{DS}.

$$g(2\phi_F)=\frac{\sqrt{2qN_a\varepsilon}}{C_{ox}}\sqrt{2\phi_F}\left(1-\frac{\varepsilon}{qN_a}\frac{2\phi_F}{3R^2}\right)+\frac{2\varepsilon}{C_{ox}}\frac{2\phi_F}{3R}\left(1+\frac{\varepsilon}{qN_a}\frac{2\phi_F}{2R^2}\right)$$

$$V_{th}=V_{fb}+2\phi_F+\frac{\sqrt{2qN_a\varepsilon}}{C_{ox}}\sqrt{2\phi_F}\left(1-\frac{\varepsilon}{qN_a}\frac{2\phi_F}{3R^2}\right)+\frac{2\varepsilon}{C_{ox}}\frac{2\phi_F}{3R}\left(1+\frac{\varepsilon}{qN_a}\frac{2\phi_F}{2R^2}\right) \quad (15)$$

Comparing to the 2-D simulation result, we can verify Eq. (15) in Fig. 4 and Fig. 5 which are under the condition with N_A = 7E17 cm^{-3} and R = 30 nm. According to the result, the threshold voltage increases at higher doping concentration and smaller radius.

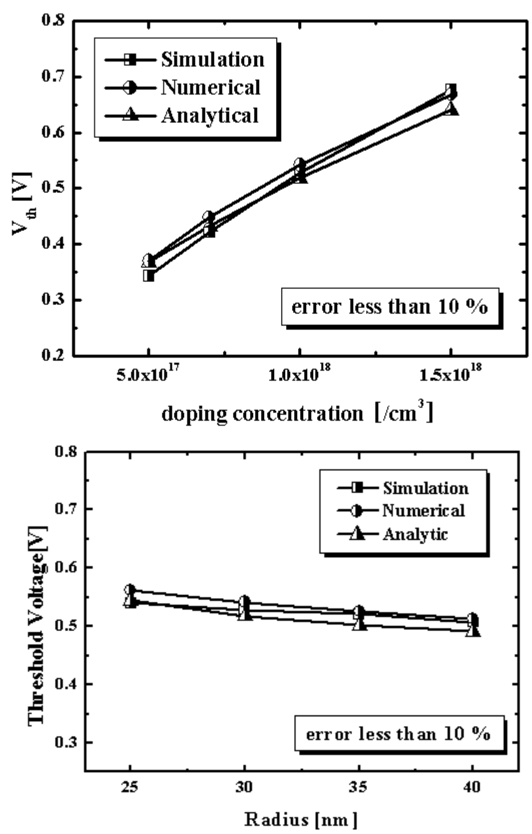

Fig. 4. Comparison the model to simulation and numerical calculation result.

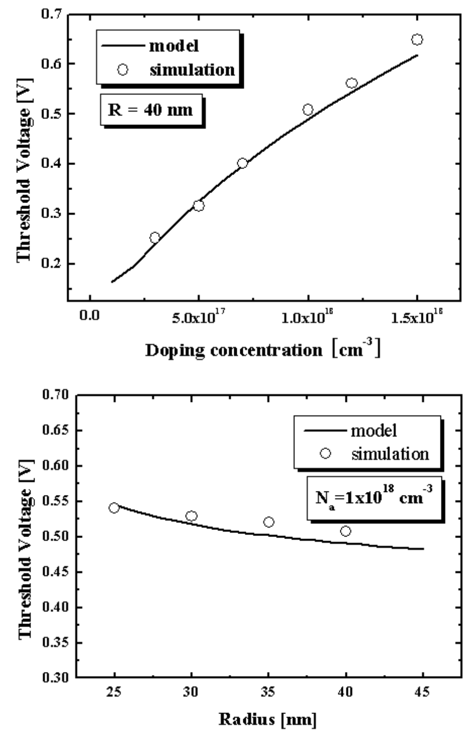

Fig. 5. Calculated threshold voltage as a function of N_A and R.

III. CONCLUSIONS

A new analytical model for threshold voltage of RC MOSFETs has been proposed. The model shows good matching compared to simulation result in spite of approximation during deriving the equation. Threshold voltage tends to increases as doping concentration increases and radius decreases. If we know the size of device and doping concentration, threshold voltage can be obtained easily by using this model.

ACKNOWLEDGMENTS

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