Modeling of Threshold Voltage with Reverse Short Channel Effect

Khee Yong Lim, Xing Zhou, and Yuwen Wang

School of Electrical & Electronic Engineering, Nanyang Technological University, Nanyang Avenue, Singapore 639798. exzhou@ntu.edu.sg

ABSTRACT

This paper presents a new reverse short channel effect (RSCE) model for threshold voltage modeling of submicrometer MOSFETs. Unlike those conventional empirically-based RSCE models, the proposed model is derived and simplified based on two Gaussian profiles to simulate boron pile-up at the source and drain edges of nMOS devices. The model has a simple compact form that can be utilized to study and characterize the pile-up profile of advanced halo-implant MOSFETs. The analytical model has been applied to, and verified with, experimental data of a 0.25-μm CMOS process for various channel length and substrate bias conditions.

Keywords: RSCE, lateral non-uniform profile, threshold voltage, compact model, MOSFET.

1 INTRODUCTION

Advanced MOSFETs are non-uniformly doped as a result of complex process flow. Therefore, one of the key factors to model threshold voltage (V_{th}) accurately is to model its non-uniform doping profile. Currently, there are many V_{th} models [1-6] that are able to model the vertical non-uniform doping profile of a MOSFET. However, all the V_{th} models for lateral non-uniform doping profiles due to reverse short channel effect (RSCE) [7-12] are empirical, which are normally modeled by simply adding exponential functions to its long channel V_{th} expression. Hence, the focus here is to transform the lateral 2-D pile-up profile across the channel to an effective doping expression that can be applied directly to the compact V_{th} expression [7]. On the other hand, the model for vertical non-uniform doping profile of MOSFET has been explained in [1].

In Section 2 of this paper, formulation of the proposed model is presented. Comparison of the model with the hyperbolic RSCE model [7] is discussed in Section 3, together with experimental verification of the model.

2 MODEL

RSCE in nMOSFETs is mainly caused by the boron dopants pile-up phenomenon at the edge of the source and drain regions. Therefore, the basis of the model is to assume two Gaussian profiles at the source and drain edge, as illustrated in Fig. 1. The Gaussian profile is expressed as:

$$N_p = N_{pile}\exp\left(-\left(y/l_b\right)^2\right) \qquad (1)$$

where y represents the distance across the channel. N_{pile} and l_b are the peak pile-up doping concentration and the characteristic length, respectively. Since the pile-up profile is due to boron redistribution along the channel after the post-LDD annealing process or due to direct pocket implant at the source and drain side, it can be assumed symmetrical for both the source and drain side. With these conceptual pile-up profiles, as shown in Fig. 1, the profiles are summed up mathematically along the metallurgical channel length (L_{eff}) of the MOSFET. It is then divided by the metallurgical channel length to obtain an average effective concentration expression as follows:

$$\begin{aligned} N_{eff} &= \frac{\int_0^{L_{eff}}\left\{N_{pile}\left[\exp\left(-\left(\frac{y}{l_b}\right)^2\right)+\exp\left(-\left(\frac{L_{eff}-y}{l_b}\right)^2\right)\right]+N_s\right\}dy}{L_{eff}} \\ &= N_s+\frac{l_b}{L_{eff}}N_{pile}\left[\int_0^{L_{eff}/l_b}\exp\left(-t^2\right)dt-\int_{L_{eff}/l_b}^{0}\exp\left(-t^2\right)dt\right] \\ &= N_s+N_{pile}\left(\frac{\sqrt{p}\,erf\left(L_{eff}/l_b\right)}{\left(L_{eff}/l_b\right)}\right) \end{aligned} \qquad (2)$$

where N_s is the substrate doping without considering the lateral pile-up charge [1]. The final effective concentration expression is an error function of its metallurgical channel length as well as the peak value and characteristic length of its pile-up profile.

As seen in Fig. 1, as the channel length shrinks, its lateral channel doping rises correspondingly. This is due to the overlap of the pile-up profiles as channel length decreases. Two parameters are used to characterize the lateral Gaussian profiles. They are the characteristic length l_b (which determines the lateral spread of the pile-up) and the peak concentration N_{pile} (which determines the amount of the pile-up). As the channel length reduces, its effective doping value increases exponentially, causing a roll-up characteristic of the V_{th}–L_g curve at decreasing L_{eff}, as shown in Fig.3, which is known as the RSCE.

The short channel V_{th} model used in this paper is from [13]:

$$V_{th} = V_{FB} + \phi_s + \gamma\sqrt{\phi_{s0} - V_{bs}}\left[1 - \frac{\lambda\zeta}{L_{eff}}\left(\sqrt{\phi_s - V_{bs}} + \frac{jV_{ds}}{\sqrt{\phi_s - V_{bs}}}\right)\right]$$

$$\zeta = \sqrt{\frac{2\varepsilon_{si}}{qN_{eff}}}$$

$$\phi_{s0} = \frac{2kT}{q}\ln\left(\frac{N_{eff}}{n_i}\right)$$

$$\phi_s = \phi_{s0} - \Delta\phi_s$$

$$\Delta\phi_s = \frac{1}{\cosh\left(\frac{L_{eff}}{2l_\alpha}\right)}\left[\left(V_{bi} - \phi_{s0}\right)\cosh\left(\frac{z}{2}\right) + \frac{iV_{ds}}{2}\frac{\sinh\left(\frac{L_{eff}}{2l_\alpha} - \frac{z}{2}\right)}{\sinh\left(\frac{L_{eff}}{2l_\alpha}\right)}\right]$$

$$l_a = \alpha\left(\phi_{s0} - V_{bs}\right)^{0.25}$$

$$l_b = \beta\left(\phi_{s0} - V_{bs}\right)^{0.25}$$

$$z = \ln\left(\frac{V_{bi} - \phi_{s0} + V_{ds}}{V_{bi} - \phi_{s0}}\right) \quad (3)$$

where V_{FB}, γ, n_i, and V_{bi} are the flat-band voltage, body-effect factor, intrinsic doping concentration, and built-in potential, respectively. ϕ_{s0} and ϕ_s are the surface potentials without and with considering the barrier-lowering effect. N_{pile}, α, β, λ, i, and j are process-dependent fitting parameters in the V_{th} model.

3 RESULTS AND DISCUSSION

The parameters l_b and N_{pile} control the roll-up part of the V_{th}–L_g curve. As l_b increases, the onset of V_{th} roll-up occurs at a longer channel length. This will not affect the V_{th} roll-off portion. On the other hand, the peak value of the V_{th}–L_g curve is increased as N_{pile} increases. Therefore, it will affect the roll-off portion of the V_{th}–L_g curve. The effect of l_b and N_{pile} on V_{th} roll-up is illustrated in Figs. 2a and 2b. As compared to the results shown in Figs. 2d and 2e of [7], the described roll-up characteristic of l_b and N_{pile} for the proposed new model is less pronounced. This is because the proposed model is an error function that has a more gradual roll-up characteristic, whereas the RSCE model in [7] is a hyperbolic cosine function, given by

$$N_{eff} = N_s + \frac{N_{pile}}{\cosh\left(L_{eff}/2l_b\right)} \quad (4)$$

that has a steeper roll-up characteristic.

Fig. 3 compares the two N_{eff} models in (2) and (4). The solid lines illustrate the characteristic of the proposed N_{eff} model for three increasing l_b values (0.08; 0.1; 0.12μm), whereas the dashed lines represent the characteristic of the hyperbolic cosine N_{eff} model as in (4) for the same set of l_b. The N_s terms in (2) and (4) are both fixed to 6×10^{17}cm^{-3}, and N_{pile} are fixed to 2×10^{17}cm^{-3}. As seen in Fig. 3, the roll-up behavior of the hyperbolic cosine model tends to be more abrupt as compared to the one shown by the proposed model.

The derived model employs an error function instead of the empirical hyperbolic cosine function as proposed in [7]. Although it is less computationally efficient for error function as compared to hyperbolic cosine function, the proposed model has shown more accurate and physical results. Figures 4a and 4b plot the same set of Medici simulated V_{th} data for three different characteristic lengths (l_b = 0.08, 0.1 and 0.12 μm) in three different symbols. The lines in Fig. 4a represent the newly proposed model, whereas the lines in Fig. 4b are the V_{th} model in [7]. Although both can model the roll-up V_{th} behavior, the new model has a more gradual change as compared to the hyperbolic cosine function. It can be clearly seen from the figures that the new model provides a better match as compared to the hyperbolic cosine function.

As observed from Fig. 4a, the line is more accurate for pile-up profiles with a larger characteristic length. This is because the formulation of the model is based on the average of the individual local profiles, which is more accurate as the pile-up profile becomes more gradual. If the pile-up profile were made to be very abrupt, then the hyperbolic cosine model would be more appropriate as it has a steeper slope as compared to error function.

Fig. 5 shows the new RSCE V_{th} model as compared to the experimental data for a 0.25-μm CMOS technology with ten different channel lengths and four different V_{bs} conditions. As clearly shown, the proposed model can accurately model the actual experimental V_{th} data.

4 CONCLUSION

In conclusion, the well-known RSCE has been characterized and modeled through the proposed N_{eff} model. The model is developed based on two gradual Gaussian pile-up profiles and further reduced to a useful compact expression. Its fidelity will be much affected for a pile-up profile that is very abrupt which, in turn, is unphysical in actual transistor structures. To the authors' knowledge, this is the first physically derived model that can successfully integrate RSCE into a compact threshold voltage formulation. It is relatively easy to use and has good value to technology development and device modeling.

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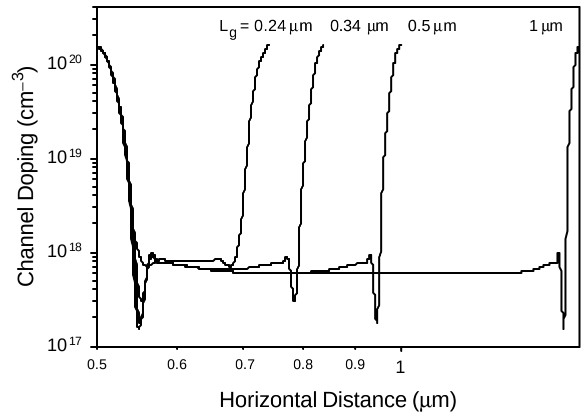

Figure 1: MEDICI simulated doping profiles across MOSFET channel for L_g = 0.24, 0.34, 0.5 and 1 µm.

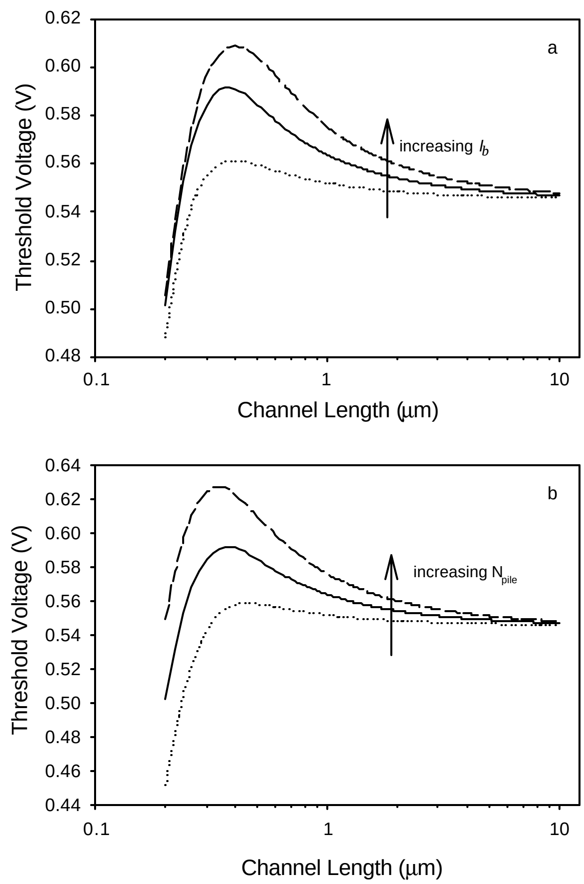

Figure 2: Threshold voltage against channel length for (a) l_β variation and (b) N_{pile} variation.

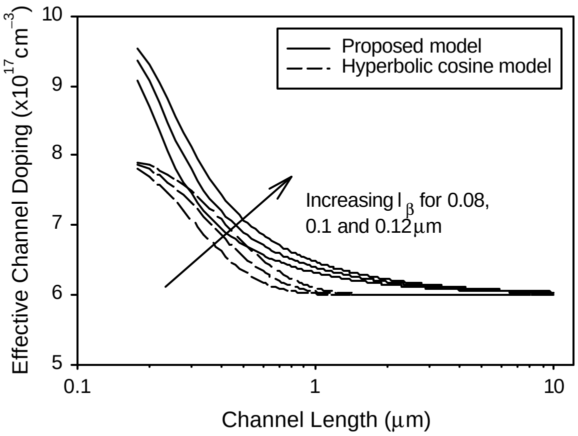

Figure 3: Effective channel doping against channel length for three different characteristic lengths. Solid lines: proposed RSCE model; Dashed lines: hyperbolic cosine model [7].

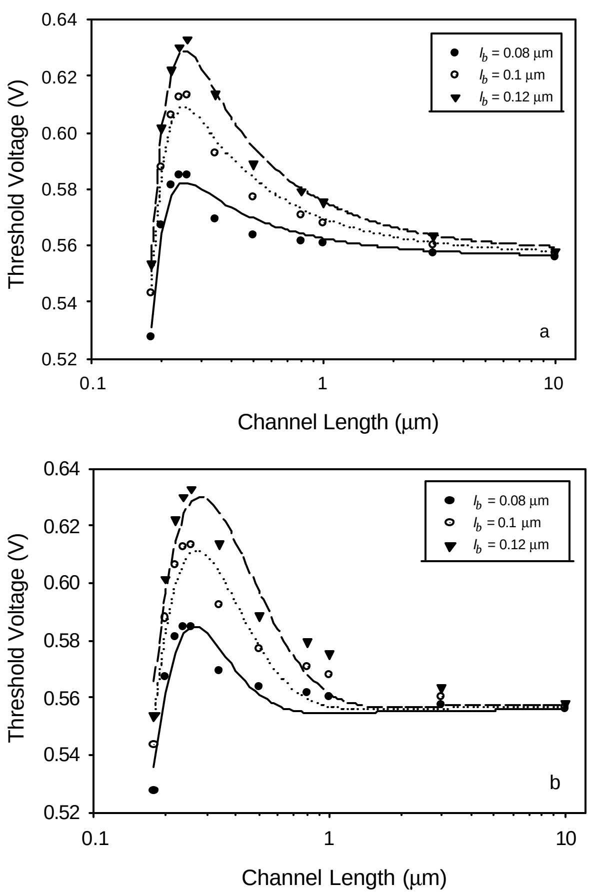

Figure 4: Threshold voltage against channel length for three different characteristic lengths. (a) proposed RSCE model; (b) hyperbolic cosine model [7]. Symbols: MEDICI data, Lines: model data.

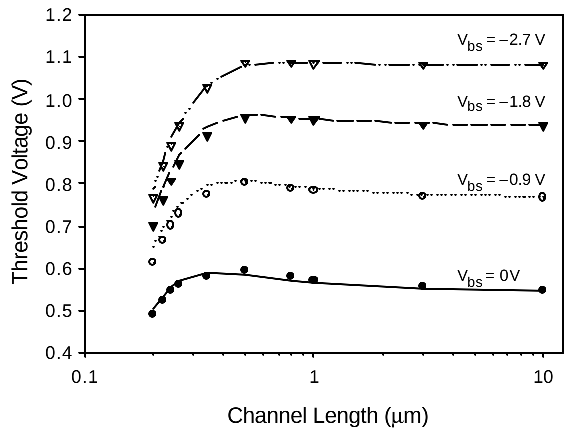

Figure 5: Threshold voltage for various substrate biases. Symbols: experimental data, Lines: model data.