PHYSICS-BASED THRESHOLD VOLTAGE MODELING WITH REVERSE SHORT CHANNEL EFFECT

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Abstract

This paper presents a physics-based reverse short channel effect (RSCE) model for threshold voltage ($V_{th}$) modeling of deep submicron MOSFETs. Unlike those conventional empirically-based RSCE models, the proposed model is derived based on two Gaussian pile-up profiles located at the source and drain edges of a MOSFET. The model has a simple compact form that can be utilized to characterize the advanced halo-implant MOSFETs. A detailed comparison of the proposed RSCE model with the previously proposed model is also presented. The analytical model has been applied to, and verified with, experimental data of a 0.25-µm CMOS process for ten different gate lengths as well as various drain 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. Basically, non-uniform doping profiles can be categorized into vertical non-uniformity and lateral non-uniformity, as shown in Fig. 1. The vertical non-uniformity can be due to additional implantation for threshold voltage adjustment or for punchthrough prevention. On the other hand, lateral non-uniformity may be due to the intended pocket implantation for deep submicron technology or the unavoidable transient enhanced diffusion of boron impurity in nMOS. Therefore, one of the key factors to model threshold voltage 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 for 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] for efficient circuit simulation. Despite that RSCE observed in $V_{th}$ - $L_g$ curve is solely due to the lateral doping non-uniformity, the complete $V_{th}$ model of advance MOSFETs should also include the other critical effects, such as drain induced barrier lowering, charge sharing effect as well as the effect of vertical non-uniformity. In the $V_{th}$ model that is presented in this paper, all short channel effects, except for the RSCE, are modeled as in a recent published article [7]. The model for vertical non-uniform doping profile of MOSFET has been explained in [1].

![Fig. 1: MOSFET with both vertical and horizontal non-uniform doping profiles.](image-url)

In Section 2 of this paper, formulation of the proposed model is presented. Comparison of the model with the empirical hyperbolic cosine RSCE model [7] is discussed in Section 3, together with experimental verification of the proposed model. Finally, a brief summary is given in Section 4.
2. Model

RSCE in nMOSFETs is mainly caused by the boron dopant 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 edges. The Gaussian profile is expressed as:

\[ N_p(y) = N_{\text{pile}} \exp\left(\frac{(y/L_{\beta})^2}{2}\right) \]  

where \( y \) represents the distance across the channel and \( L_{\text{eff}} \) is the metallurgical channel length of the MOSFET. \( N_{\text{pile}} \) and \( I_{\beta} \) 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 sides. With these conceptual pile-up profiles, as shown in Fig. 1, the profiles are summed up mathematically along the entire metallurgical channel length of the MOSFET. It is then divided by the metallurgical channel length to obtain an averaged effective concentration expression, as follows:

\[
N_{\text{eff}} = \frac{\int_0^{L_{\text{eff}}} \left[ N_{\text{pile}} \exp\left(\frac{-(y/L_{\beta})^2}{2}\right) + N_s \right] dy}{L_{\text{eff}}}
\]

where \( N_s \) is the effective vertical non-uniform substrate doping without considering the lateral pile-up charge [1]. Notice that the pile-up terms at the source and drain edges are only differentiated by an \( L_{\text{eff}} \) translation term. 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.

![Fig. 2: MEDICI simulated doping profiles across MOSFET channel](image)

Fig. 2 shows the MEDICI-simulated doping profiles across the surface channel for four different devices with increasing channel length starting from 0.24 \( \mu \)m up to 1 \( \mu \)m. As shown in Fig. 2, when the channel length is long, such as in the case of \( L_s = 0.5 \mu \)m and 1 \( \mu \)m, their center channel doping profiles overlap each other, thus producing a threshold voltage independent of the channel length. But this is not true for the case when \( L_s = 0.24 \mu \)m, where its center channel doping profile is higher than its long-channel counterpart. Its center channel profile is higher because the two pile-up profiles at the source and drain edges overlap each other, thereby causing RSCE to be observed as the device shrinks.

The threshold voltage expression consists of three main terms, namely, the flat-band voltage, the surface potential and the voltage across the insulated gate dielectric. \( V_{FB} \), \( \gamma_s \), \( n_i \), and
$V_{bi}$ are the flat-band voltage, body-effect factor, intrinsic doping concentration, and built-in potential, respectively. $\phi_d$ and $\phi_s$ are the surface potentials without and with considering the barrier-lowering effect. $\Delta \phi_s$ is the surface potential barrier lowering based on quasi-2D formulation, with $L_{th}$ being the characteristic length of the non-uniform surface potential profile. The square root term in the $V_{th}$ expression is based on charge sharing formulation. $N_{pile}$, $\alpha$, $\lambda$, $i$, and $j$ are process-dependent fitting parameters in the $V_{th}$ model. However, there are only two parameters that determine the RSCE, which are used to characterize the lateral non-uniform Gaussian profiles. They are the characteristic length $l_\beta$ (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 of MOSFET reduces, its effective concentration decreases, and (4) is fixed to $6\times 10^{17}\text{cm}^{-3}$, and (4) employs a hyperbolic cosine function. Unlike the proposed model, it shows no roll-up until $L_g$ is below 1 $\mu$m, and a abrupt roll-up is observed. Therefore, the hyperbolic cosine model tends to give a more abrupt $V_{th}$ roll-up as compared to the proposed model.

The parameters $l_\beta$ and $N_{pile}$ control the roll-up part of the $V_{th}$ vs. $L_g$ curve. When $l_\beta$ or $N_{pile}$ increases, larger RSCE is observed. The effect of $l_\beta$ and $N_{pile}$ on $V_{th}$ roll-up is illustrated in Figs. 6a and 6b. The two parameters contribute differently to the $V_{th}$ roll-up characteristic. When $l_\beta$ changes, there is no change at the roll-off portion of the $V_{th}$ vs. $L_g$ curve. The roll-off portion will only shift when $N_{pile}$ changes, as shown in Fig. 4b. This is because $l_\beta$ represents the characteristic length of the pile-up profile, which determines the spread of the pile-up profile. When $l_\beta$ increases, the two pile-up profiles will meet at a longer channel length, thereby causing the onset of $V_{th}$ roll-up occurring at a longer channel length. Once the two profiles meet, the amount additional pile-up charges will remain the same as long as $N_{pile}$ is unchanged, so the roll-off characteristic will be the same based on the principle of charge sharing. On the other hand, if $N_{pile}$ increases, there will be more pile-up charges, thereby causing a consistent shift in the roll-off portion of the $V_{th}$ vs. $L_g$ curve, but the onset of roll-up will remain the same. In Fig. 4a, the onset of $V_{th}$ roll-up for different $l_\beta$ is clearly related to the intrinsic nature of the proposed model, which has a gradual roll-up characteristic. If similar $l_\beta$ changes are applied to the empirical RSCE model (4), its onset roll-up is clearly related to the $l_\beta$ value, as seen in Fig. 5a. Fig. 5a and Fig. 5b are reproduced from Fig. 2d and Fig. 2e of [7], with the same respective $l_\beta$ and $N_{pile}$ changes as in Figs. 4a and 4b. It is clearly seen from Fig. 5b that when $N_{pile}$ changes, the onset of roll-up is not altered, which confirms the physical representations of $l_\beta$ and $N_{pile}$.

3. Discussion
There exist various empirical RSCE models, which are introduced based on the anomalous RSCE trend observed in advanced MOSFETs. One of the empirical models that is very similar to the proposed model is explained in [7], and rewritten below:

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

Similar to the proposed effective channel-doping model, this empirical model has two important terms, namely, the effective vertical doping ($N_s$) and the lateral non-uniform pile-up. The pile-up term has two process-dependent fitting parameters, $N_{pile}$ and $l_\beta$, which are same as the proposed model. However, the proposed model and the empirical model have different pile-up functionality. The proposed model is an error function for the horizontal non-uniformity whereas (4) employs a hyperbolic cosine function. Unlike the proposed model that assumes two Gaussian-shaped pile-up profiles at the source and drain edges, the empirical model is borrowed from the quasi-2D potential barrier lowering solution [7]. Fig. 3 compares the two $N_{eff}$ models. The solid lines illustrate the characteristic of the proposed $N_{eff}$ model for three increasing $l_\beta$ values (0.08; 0.1; 0.12 $\mu$m), whereas the dashed lines represent the characteristic of the hyperbolic cosine $N_{eff}$ model for the same set of $l_\beta$. The $N_s$ terms in (2) and (4) are both fixed to $6\times 10^{17}\text{cm}^{-3}$, and $N_{pile}$ is fixed to $2\times 10^{17}\text{cm}^{-3}$. As seen from Fig. 3, the roll-up behavior of the proposed model begins at a longer channel length. Its roll-up rate is gradual with smaller initial roll-up rate followed by steeper roll-up rate when $L_g$ is below 1 $\mu$m. As for the empirical hyperbolic cosine model, it shows no roll-up until $L_g$ is below 1 $\mu$m, and a abrupt roll-up is observed. Therefore,
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. Fig. 6a and Fig. 6b plot the same set of MEDICI-simulated $V_{th}$ data for three different characteristic lengths ($l_β = 0.08, 0.1,$ and $0.12 \, \mu m$) in three different symbols. The lines in Fig. 6a represent the newly proposed model, whereas the lines in Fig. 6b are the empirical $V_{th}$ model [7]. Although both can model the $V_{th}$ roll-up behavior, the new model shows a better match as compared to the hyperbolic cosine function, especially when the characteristic length is large. 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. The empirical model is limited to pile-up profile that is abrupt with small characteristic length.

Fig. 6: 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.

Fig. 7a and Fig. 7b further verify the proposed RSCE $V_{th}$ model by comparing to the experimental data for a 0.25-µm CMOS technology with ten different channel lengths from 10 µm down to 0.2 µm. Four different $V_{bs}$ conditions with low and high drain bias conditions are compared as shown in Figs.
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7a and 7b, respectively. As is clearly shown, the proposed model can accurately model the actual experimental V_{th} data.

![Graph](image)

Fig. 7: Threshold voltage for various substrate biases. Symbols: experimental data, Lines: model data. (a) V_{ds} = 0.1V; (b) V_{ds} = 2.5V.

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. It is more robust as compared to the previous proposed hyperbolic cosine model [7]. It is relatively easy to use and has good value to technology development and device modeling.

References


