Semi-Empirical Approach to Modeling Reverse Short-Channel Effect in Submicron MOSFET's

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ABSTRACT

A model for effective channel doping in submicron LDD nMOSFET's is presented by adding the effect of the lateral nonuniform pile-up charge centroid to the Gaussian profile with peak doping near the edge of the metallurgical channel. The effect of the pile-up centroid on the threshold voltage parameter extraction is elaborated, from which semi-empirical relationships on all fitting parameters are formulated. Threshold voltage versus gate length data from MEDICI-simulated devices with lateral Gaussian pile-up doping profiles are used for the verification of this model.

Keywords: Reverse short-channel effect, effective channel doping, pile-up charge centroid, submicron MOSFET.

1 INTRODUCTION

The nMOSFET threshold voltage (V_t) roll-up at decreasing gate length (L_g) in the submicron regime, which is the well-known Reverse Short-Channel Effect (RSCE) [1], has been attributed to the boron pile-up due to transient enhanced diffusion [2] or pocket implantation (halo) [3]. Two Gaussian profiles have been proposed [4] to model the lateral nonuniform profile with peak doping (N_{pile}) and lateral characteristic length (l_β) at the edge of the metallurgical channel (L_{eff}). However, it was assumed that the lateral Gaussian profile peaks at the edge of the S/D junctions. The location of the pile-up doping ("pile-up centroid") was not considered, which is conceptually an important parameter subject to process variations.

This paper is motivated to explore the effect of the pile-up centroid (l_μ) with a modified effective channel doping (N_{eff}) expression based on the same idea as in [4]. Having l_μ in the model greatly affects the behavior of N_{eff} and V_t as well as its associated process-dependent parameters. The model allows RSCE to be "captured" by this single compact-model parameter.

In Section 2, formulation of the proposed model is presented. The relationship of l_μ to all fitting parameters is investigated through a set of MEDICI-simulated MOSFET structures and the semi-empirical model for the fitting parameters are formulated, which will be discussed in Section 3.

2 MODEL FORMULATION

The model for the lateral nonuniform doping is based on the Gaussian profile centered at some distance, l_μ, to the edges of the S/D junctions, which is modified from [4] to include l_μ, expressed as

$$N(y) = N_{pile} \exp\left[-\left(\frac{y-l_\mu}{l_\beta}\right)^2\right] \tag{1}$$

where y is the distance across the channel, as schematically shown in Fig. 1. The lateral nonuniform profile, which is due to boron redistribution along the channel after annealing processes, is assumed symmetrical on the source and drain sides. Three parameters are used to characterize the lateral nonuniform Gaussian profile. They are the lateral characteristic length l_β, the pile-up charge centroid l_μ, and the peak concentration N_{pile}.

The effective channel concentration is modeled by the integration ("average") of the channel doping profile:

$$\begin{aligned} N_{eff} &= \frac{1}{L_{eff}} \int_0^{L_{eff}} \left\{ N_{pile} \exp\left[-\left(\frac{y-l_\mu}{l_\beta}\right)^2\right] \right. \\ &\quad \left. + N_{pile} \exp\left[-\left(\frac{L_{eff}-(y+l_\mu)}{l_\beta}\right)^2\right] + N_{ch} \right\} dy \\ &= \frac{N_{pile}}{L_{eff}/l_\beta} \left\{ \left[\int_{-(l_\mu/l_\beta)}^{(L_{eff}-l_\mu)/l_\beta} \exp(-t^2)\,dt \right] \right. \\ &\quad \left. - \left[\int_{(L_{eff}-l_\mu)/l_\beta}^{-(l_\mu/l_\beta)} \exp(-t^2)\,dt \right] \right\} + N_{ch} \\ &= \frac{\sqrt{\pi} N_{pile}}{L_{eff}/l_\beta} \left[\mathrm{erf}\left(\frac{L_{eff}-l_\mu}{l_\beta}\right) + \mathrm{erf}\left(\frac{l_\mu}{l_\beta}\right) \right] + N_{ch} \end{aligned} \tag{2}$$

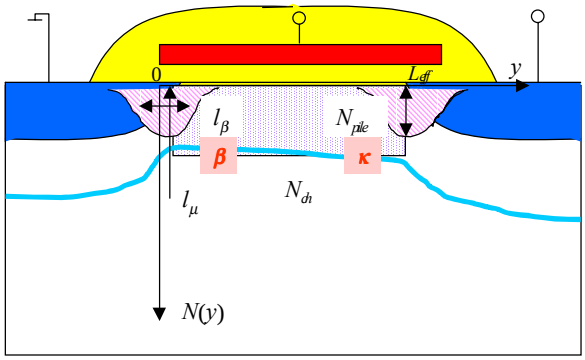

Figure 1: Cross-sectional view of a MOSFET depicting the pile-up charges at the source/drain modeled by Gaussian profiles with peak doping N_{pile}, lateral spread l_β, and the newly-proposed centroid l_μ.

where N_{ch} is the channel doping without lateral pile-up charge and is related to N_{pile} by $\kappa = N_{pile}/N_{ch}$. The N_{eff} expression results in two error functions instead of one as proposed in [4], with L_{eff}, l_β, and l_μ as parameters. The effective channel length is related to poly-gate length as $L_{eff} = L_g - 2\sigma x_j$, where x_j is the LDD junction depth and σ is the LDD lateral diffusion parameter.

The V_t model is expressed in terms of N_{eff} as:

$$V_t = V_{FB} + \phi_s + \gamma_{eff}\sqrt{\phi_{s0} - V_{bs}} \tag{3}$$

$$\gamma_{eff} = \gamma - \frac{\lambda}{L_{eff}}\frac{2\varepsilon_{si}}{C_{ox}}\left(\sqrt{\phi_s - V_{bs}} + \frac{\delta V_{ds}}{\sqrt{\phi_s - V_{bs}}}\right) \tag{3a}$$

$$\gamma = \frac{\sqrt{2q\varepsilon_{si}N_{eff}}}{C_{ox}} \tag{3b}$$

where V_{FB} is the flat band voltage. ϕ_s is the surface potential at strong inversion ($2\phi_F$), including the barrier-lowering effect ($\Delta\phi_s$) as in [5], [6] with a fitting parameter α. γ_{eff} is the effective body-effect factor (γ) including charge-sharing effect (with the fitting parameters λ as well as δ for drain-induced barrier lowering). Other symbols have their usual meanings.

The effect of l_μ on N_{eff} and V_t is demonstrated in Figs. 2 and 3 with fixed values of all fitting parameters ($\sigma = 0.7$, $\lambda = 0.3826$, $\alpha = 0.0123$ μm/V$^{0.25}$, $\beta = 0.0617$ μm/V$^{0.25}$, $\kappa' = 0.241$, and $\kappa'' = 0.232$). From the N_{eff} definition (1), it is easy to understand that when the pile-up charge is centered at the edge of the metallurgical channel (i.e., $l_\mu = 0$, as was previously modeled [4]), N_{eff} increases monotonously at decreasing L_{eff} due to increased average pile-up charges. However, when the pile-up charge centroid moves towards the channel center, it is observed that N_{eff} in the short-channel regime (Fig. 2) tends to decrease at increasing l_μ (for $l_\mu > L_{eff}/2$) and maximum N_{eff} occurs at $l_\mu = L_{eff}/2$ when the two pile-up profiles overlap.

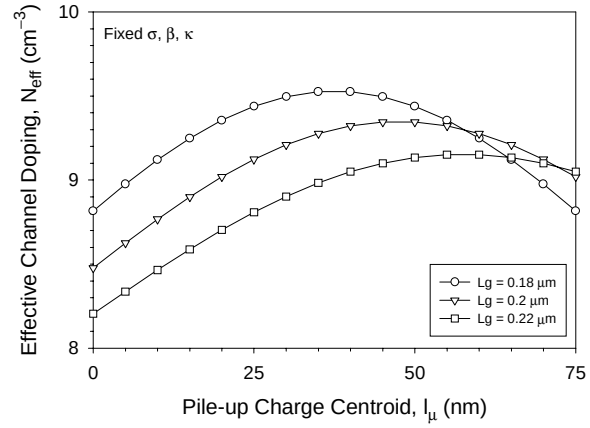

Figure 2: Effective channel doping vs. pile-up centroid for three short-channel devices L_g = 0.18, 0.2, 0.22 μm.

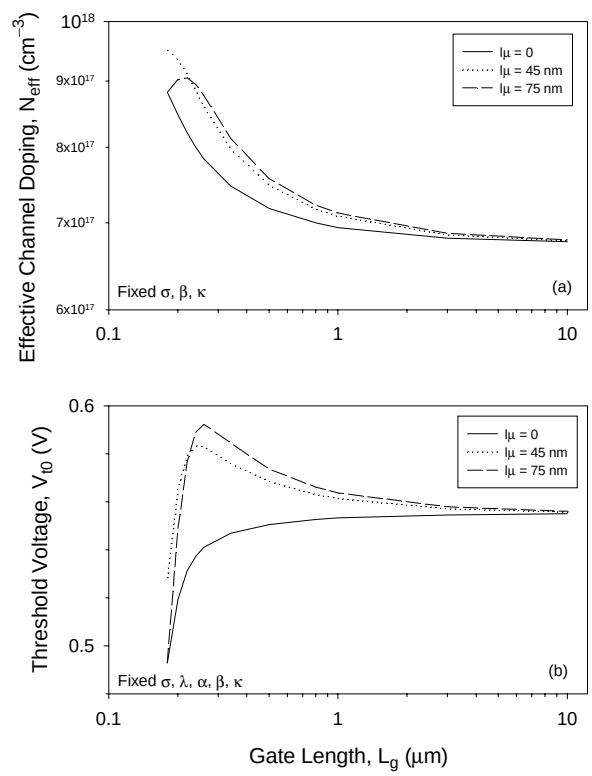

Figure 3: Characteristics of (*a*) effective channel doping ($N_{eff} - L_g$) and (*b*) threshold voltage ($V_{t0} - L_g$) for three values of pile-up charge centroid l_μ = 0, 45, 75 nm.

This phenomenon is reflected in the $V_t - L_g$ roll-up and roll-off characteristics, as shown in Fig. 3b. It is observed that increase in l_μ tends to increase the RSCE, where V_t roll-up effect increases and V_t roll-off effect becomes more abrupt. Furthermore, V_t reaches its maximum point when $l_\mu = L_{eff}/2$. In other words, the $V_t - L_g$ behavior can be "tuned" by l_μ. Although l_μ is a compact-model parameter based on definition (1), we also observed similar behavior in the numerical $V_t - L_g$ data having different l_μ.

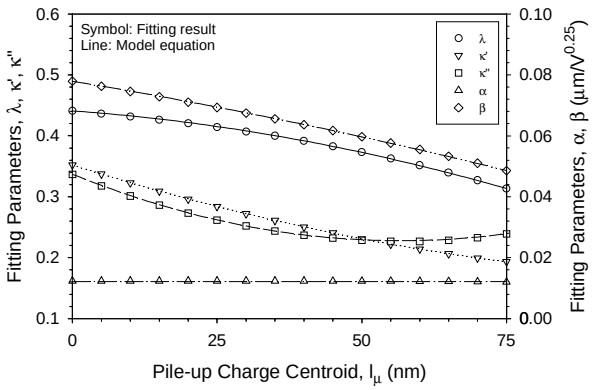

Figure 4: *Symbols*: best-fitted parameters for 16 values of l_μ. *Lines*: semi-empirical parabolic equations for the fitting parameters formulated using the data at l_μ = 0, 45, 75 nm.

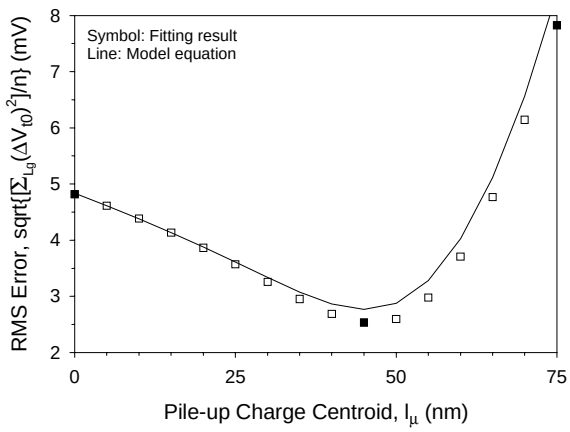

Figure 5: RMS error in V_{t0} over all L_g for 16 values of l_μ. *Symbol*: best-fitted result. *Line*: semi-empirical equations formulated based on the parameters extracted at l_μ = 0, 45, 75 nm (*solid squares*).

3 PROCESS-DEPENDENT FITTING PARAMETERS

Threshold voltage is the most sensitive parameter that characterizes the MOSFET drain current I_{ds}. In order to fully characterize I_{ds}, the proposed V_t model [4], [5] is used to encapsulate RSCE and SCE effects with 11 process-dependent fitting parameters, which requires a one-iteration extraction procedure. Applying the 5-step algorithm of V_t parameter extraction [5] on a set of $V_t - L_g$ data from MEDICI-simulated devices with lateral Gaussian pile-up doping charges, the best-fit parameter sets have been obtained with 16 different values of l_μ, each of which has a different set of values (λ, α, β, κ', κ''), as shown in Fig. 4 (*symbols*). All the fitting parameters are found to have a parabolic dependence on l_μ except for α, which is a constant. It is observed that l_μ mostly affects λ (V_t roll-off due to charge sharing), β (onset of V_t roll-up), κ' (V_t roll-up extracted at $V_{bs} = -2.7$ V) as well as κ'' (V_t roll-up extracted at $V_{bs} = 0$), and has little effect on α (barrier lowering).

l_μ is a conceptual parameter to model the pile-up charge centroid in the compact model. Since the process-dependent fitting parameters, which physically describe different aspects of the SCE/RSCE in the compact V_t model, are functionally related to l_μ, semi-empirical parabolic equations for the fitting parameters (except for α) can be easily formulated based on three values of l_μ = 0, 45, and 75 nm rather than using 16 fitting values. The semi-empirical equations such formulated are as follows:

$$\begin{aligned}
\lambda &= 0.441 - 6.924\times10^{-4} l_\mu - 1.345\times10^{-5} l_\mu^2 \\
\alpha &= 0.01223 \\
\beta &= 0.0779 - 3.14\times10^{-4} l_\mu - 1.028\times10^{-6} l_\mu^2 \\
\kappa' &= 0.352 - 3.024\times10^{-3} l_\mu + 1.209\times10^{-5} l_\mu^2 \\
\kappa'' &= 0.337 - 3.865\times10^{-3} l_\mu + 3.418\times10^{-5} l_\mu^2
\end{aligned} \tag{4}$$

where l_μ is in nm, α and β are in μm/V$^{0.25}$, and others are dimensionless. Results based on (4) are shown in Fig. 4 (*lines*).

In practice, an actual pile-up charge centroid for a given technology is unknown (although conceptually exists). In our proposed approach, with three "trial" values of l_μ in some appropriate range, a complete semi-empirical V_t model can be obtained with l_μ as a parameter.

To determine the "optimum" value of l_μ, we use the root-mean-square (RMS) error of the modeled linear threshold voltage (V_{t0}) with respect to the MEDICI data over all gate lengths L_g:

$$V_{t0-\mathrm{RMS}} = \left[\frac{1}{n} \sum_{L_g} \left(V_{t0-\mathrm{model}} - V_{t0-\mathrm{data}} \right)^2 \right]^{1/2} . \tag{5}$$

The RMS error in V_{t0} is computed using the semi-empirical equations (4), as shown in Fig. 5 (*line*) and compared with the ones from individual fitting results (*symbols*), which demonstrates pretty good approximation using three values of l_μ. The minimum RMS error in V_{t0} is observed at l_μ = 45 nm.

The complete semi-empirical V_t equation with l_μ = 45 nm is used to predict the MEDICI $V_t - L_g$ data at low and high drain and substrate biases, as shown in Fig. 6. V_t prediction by the compact model at an intermediate V_{bs} value verifies the accuracy of the proposed model.

4 CONCLUSION

In conclusion, the proposed N_{eff} model is used to characterize the well-known RSCE with the addition of the pile-up charge centroid in the lateral Gaussian pile-up profiles. Physics-based compact model parameters can be

empirically correlated to the pile-up controid and characterized at three trial values. Due to the physics built into the fitting parameters of the compact V_t model, the proposed semi-empirical approach is simple and physical in extracting and predicting RSCE for experimental submicron MOSFET's, which will prove to be very useful for submicron technology development and device compact modeling.

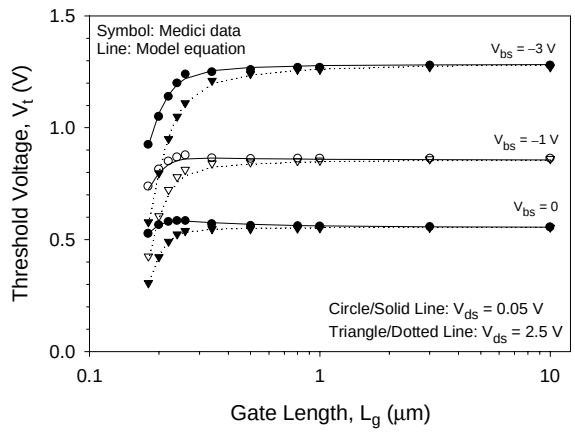

Figure 6: $V_t - L_g$ characteristics for the MEDICI data (*symbols*) and model (*lines*) with l_μ = 45 nm (minimum RMS error in V_{t0}) at the indicated bias conditions. $V_t - L_g$ at $V_{bs} = -1$ V (*open symbols*) is fully by prediction of the semi-empirical model.

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