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

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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}) at the edge of the metallurgical channel (L_{eff}) and lateral characteristic length (l_b). However, the effect of the pile-up charge centroid (l_m) was not considered, which is conceptually an important parameter subject to process variations.

This paper is motivated to explore the effect of l_m with a modified effective channel doping (N_{eff}) based on [4]. The Gaussian profile is modified to include l_m, which is expressed as $N(y) = N_{pile}\exp\left\{-\left[(y - l_m)/l_b\right]^2\right\}$ where y is the distance across the channel (Fig. 1). After integrating two Gaussian profiles over L_{eff}, the new effective channel doping becomes $N_{eff} = N_{ch} + N_{pile}\left[\sqrt{\pi}/(L_{eff}/l_b)\right]\left\{\mathrm{erf}\left[(L_{eff} - l_m)/l_b\right] + \mathrm{erf}(l_m/l_b)\right\}$ where N_{ch} is the channel doping without lateral pile-up charge. The effect of l_m on N_{eff} and V_t is conducted at fixed values of all fitting parameters (Fig. 2). It is observed that N_{eff} in the short-channel regime tends to decrease at increasing l_m (when $l_m > L_{eff}/2$) since the total integrated charge (N_{eff}) is decreased at a given L_{eff} when the pile-up centroid moves towards the center, which is reflected in the $V_t - L_g$ roll-up and roll-off characteristics. In other words, the $V_t - L_g$ behavior can be effectively "tuned" by l_m.

The V_t model [4], [5] has 11 process-dependent fitting parameters, which requires a one-iteration extraction procedure. Applying the 5-step algorithm of V_t parameter extraction 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_m (Fig. 3, *symbols*). All fitting parameters are found to have a parabolic dependence on l_m except for α, which is constant. l_m 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 $V_{bs} = -3$ V) as well as κ'' (V_t roll-up extracted at $V_{bs} = 0$), and has little effect on α (barrier lowering). Semi-empirical parabolic equations for the fitting parameters (except for α) are formulated based on three values of $l_m = 0$, 45, and 75 nm (Fig. 3, *lines*). Applying the semi-empirical model (with l_m as a parameter) on the linear threshold voltage (V_{t0}), the root-mean-square (RMS) error with respect to the MEDICI data over all L_g is computed (Fig. 4, *lines*) and compared with the fitting results (Fig. 4, *symbols*). The minimum RMS error in V_{t0} is observed at $l_m = 45$ nm. The complete semi-empirical V_t equation at $l_m = 45$ nm (Fig. 5, *lines*) is used to predict the MEDICI $V_t - L_g$ data (Fig. 5, *symbols*) at low and high drain and substrate biases.

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.

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Topic: ***Model Calibration and Validation*** **Application**: ***Semiconductors and Microelectronics***

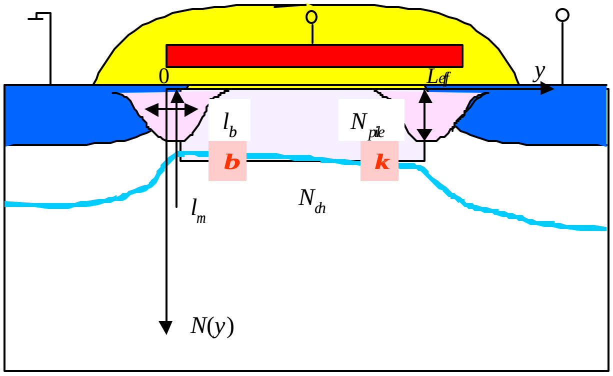

Fig. 1 Cross-sectional view of a MOSFET depicting the pile-up charges at the source/drain modeled by Gaussian profiles with peak doping N_{pile}, lateral spread l_b, and the newly-proposed centroid l_m.

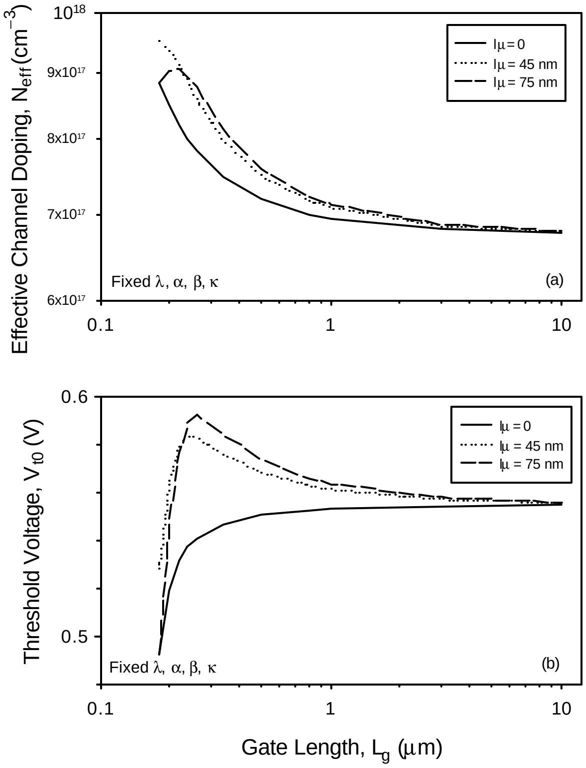

Fig. 2 Characteristics of (*a*) effective channel doping (N_{eff}–L_g) and (*b*) linear threshold voltage (V_{t0} – L_g) for three values of the pile-up charge centroid l_m = 0, 45, and 75 nm as indicated, at one set of fixed fitting parameters: l = 0.3826, a = 0.0123 μm/$V^{0.25}$, b = 0.0617 μm/$V^{0.25}$, k' = 0.241, and k'' = 0.232.

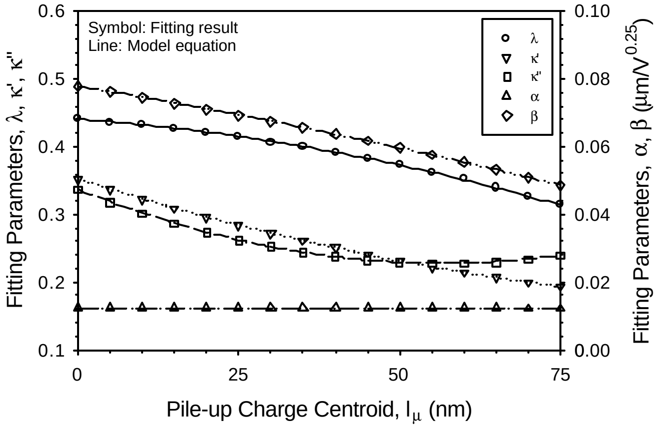

Fig. 3 *Symbols*: best-fitted parameters for seven values of l_m. *Lines*: semi-empirical parabolic equations for the fitting parameters formulated using the data at l_m = 0, 45, and 75 nm.

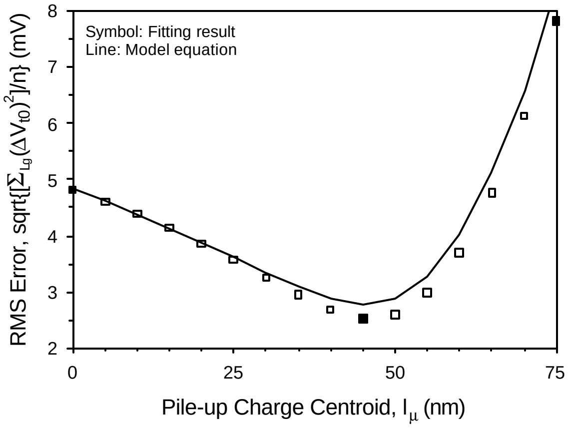

Fig. 4 RMS error in V_{t0} over all L_g for seven values of l_m. *Symbol*: best-fitted result. *Line*: semi-empirical equation formulated based on the parameters extracted at l_m = 0, 45, and 75 nm (*solid squares*).

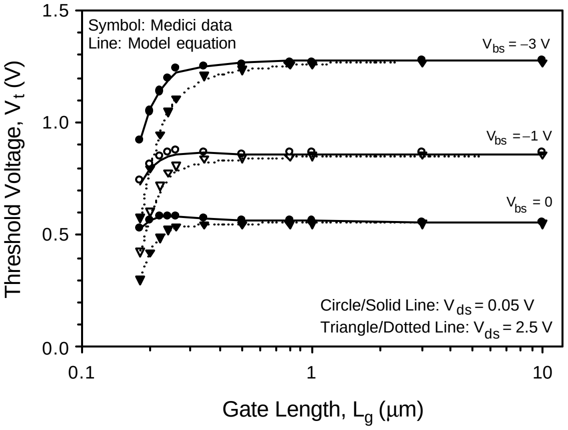

Fig. 5 V_t – L_g characteristics for the MEDICI data (*symbols*) and model (*lines*) with l_m = 45 nm (minimum RMS error in V_{t0}) at the indicated bias conditions. V_t – L_g at V_{bs} = –1V (*open symbols*) is fully by prediction of the semi-empirical model.