An Iterative Approach to Characterize Various Advanced Non-Uniformly Doped Channel Profiles

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ABSTRACT

In this paper, an efficient drain current model for sub-100nm channel engineered LDD, halo and their combination, has been presented. Drain Induced Barrier Lowering (DIBL) effect has been incorporated in the analytical model through Voltage Doping Transformation (VDT) method, which replaces the influence of the lateral drain-source field by an equivalent reduction in the channel doping concentration. The analytical assessment require an iterative approach for evaluation of the short channel depletion width for regions of different doping, from which the surface potential, surface electric field and hence drain current model have been evolved. Comparisons have been drawn among the studied devices based on their improved subthreshold and on-state performances.

Keywords: ATLAS-2D, DIBL, hot carrier reliability, NUDC, and VDT

1 INTRODUCTION

Since past three decades, in the pursuit of superior performances relative to high-speed circuits and packing density, miniaturization of device dimensions has been adopted as a powerful tool. Gradually, as device feature sizes move into sub-100nm regime, the device characteristics degrade due to the emergence of typical Short Channel Effects (SCEs) such as steep threshold voltage roll-off, increased off-state leakage current, DIBL, hot carrier effect and the degradation of carrier mobility. To combat these SCEs, the design of ultra-small devices necessitates the use of various channel engineered [1-2] architectures using Non-Uniform Doping Channel (NUDC) profiles.

In this paper, an efficient drain current model for sub-100nm channel engineered LDD, halo and their combination, has been presented. Using Poisson's equation, a simple 2D potential distribution model in the channel for NUDC MOSFETs as shown in Fig.1, has been developed using which the drain current model is obtained. The model incorporates DIBL effect using Voltage Doping Transformation (VDT) [3] method, which replaces the influence of the lateral drain-source field by an equivalent reduction in the channel doping concentration. The analytical evaluation of *d* –the short channel depletion width of differently doped region, requires iterative solution and the process flow to develop the drain current model is described in the flowchart given in Fig. 2. Comparisons have been drawn among the studied devices based on their improved subthreshold and on-state performances.

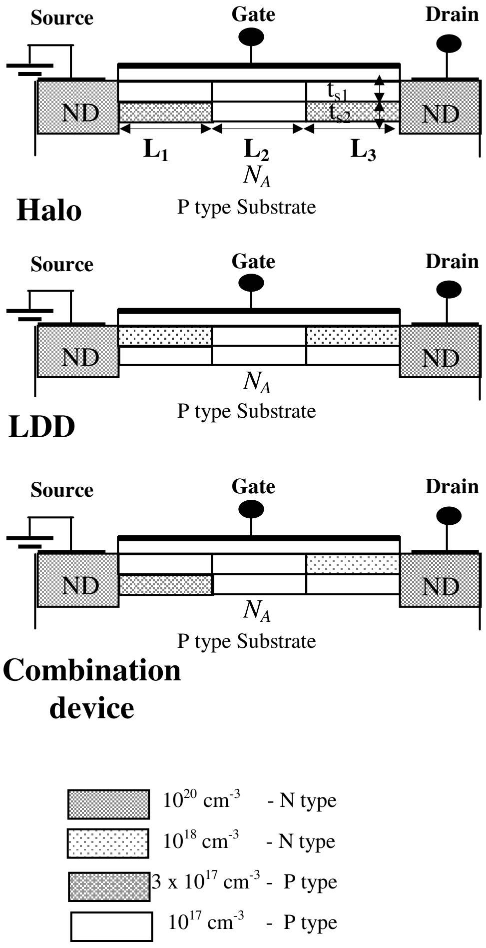


Fig.1: Schematic Design of various devices under consideration with their doping profiles. Channel Length = L (L_1:L_2:L_3 =1:1:1), W=1000nm, ε_{si} = 3.9, t_{ox}= 3nm, t_{s1} = 10nm, t_{s2} = 10nm, X_j=30nm and $q\Phi_M$ = 4.77 eV.

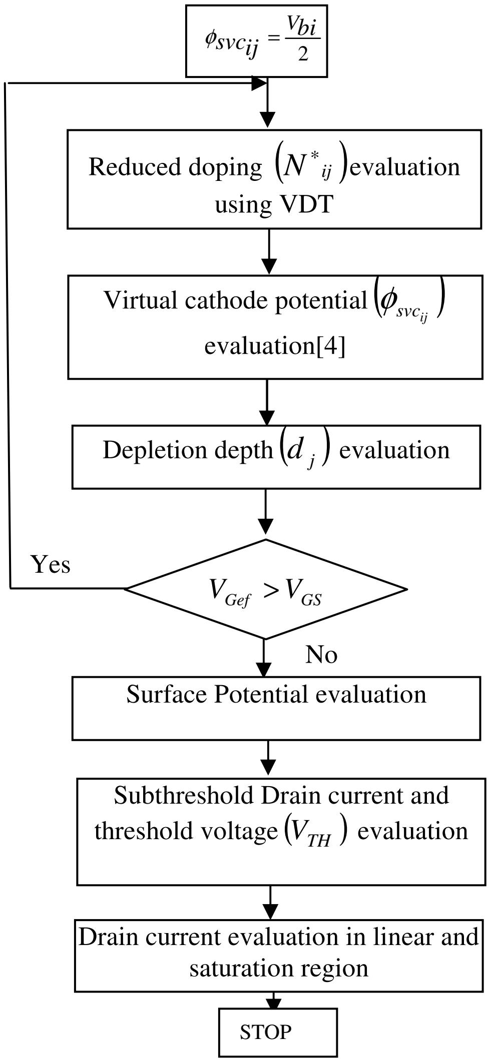


Fig.2 Flow chart for analytical model evaluation. (i=1,2 corresponds to region I, II, III and IV, V, VI respectively and j=1,2,3 corresponds to region I and IV; II and V; III and VI respectively.)

2 MODEL FORMULATION

The lateral influence of source and drain field onto the vertical growth of substrate depletion region is provided by the concept of VDT [2]. The lateral field influence initiated by the *S/D* junctions causes an equivalent reduction in effective substrate doping and the effective doping in the channel region is calculated as

$$N'_{Aij} = N_{Aij} - \frac{2\varepsilon_{si}}{qLc_{1j}} V^*_{Dij} \tag{1}$$

$$V^*_{Dij} = \begin{cases} V_{i1} = V_{bi} - \phi_{sL1} + 2\left(V_{bi} - \phi_{svc_{i1}}\right) + \\ 2\sqrt{\left(V_{bi} - \phi_{svc_{i1}}\right)\left(\phi_{sL1} - \phi_{svc_{i1}}\right)} & 0 < x \le L_1 \\ V_{i2} = \phi_{sL1} - \phi_{sL2} + 2\left(\phi_{sL1} - \phi_{svc_{i2}}\right) + \\ 2\sqrt{\left(\phi_{sL1} - \phi_{svc_{i2}}\right)\left(\phi_{sL2} - \phi_{svc_{i2}}\right)} & L_1 < x \le L_1 + L_2 \\ V_{i3} = \phi_{sL2} - \left(V_{bi} + V_{DS}\right) + 2\left(\phi_{sL2} - \phi_{svc_{i3}}\right) + \\ 2\sqrt{\left(\phi_{sL2} - \phi_{svc_{i3}}\right)\left(V_{bi} + V_{DS} - \phi_{svc_{i3}}\right)} \\ \qquad L_1 + L_2 < x \le L_1 + L_2 + L_3 \\ \hline \qquad t_1 < y \le t_2 \left(= t_{s1} + t_{s2}\right) \\ 2V_{bi} + V_{DS} - 2\sqrt{V_{bi}\left(V_{bi} + V_{DS}\right)} & 0 < x \le L \;\&\; y > t_2 \end{cases} \tag{2}$$

such that

$$\phi_{sL1} = -\left(\frac{R_1}{R_1 + R_2 + R_3}\right) V_{DS} + \left[V'_{GS_1} + \frac{qN_{11}\varepsilon_{si}}{\varepsilon_{ox}^2} t_{ox}^2 \left(1 + \sqrt{1 + \frac{2}{qN_{11}\varepsilon_{si}\varepsilon_{ox}^2} t_{ox}^2 \left(V'_{GS_1} + V_{bi}\right)}\right)\right] + V_1 \tag{3}$$

$$\phi_{sL2} = -\left(\frac{R_1 + R_2}{R_1 + R_2 + R_3}\right) V_{DS} + \left[V'_{GS_3} + \frac{qN_{13}\varepsilon_{si}}{\varepsilon_{ox}^2} t_{ox}^2 \left(1 + \sqrt{1 + \frac{2}{qN_{13}\varepsilon_{si}\varepsilon_{ox}^2} t_{ox}^2 \left(V'_{GS_3} + V_{bi}\right)}\right)\right] + V_2 \tag{4}$$

$$R_j = \frac{L_j}{q\mu_{1j} N_{1j} t_{s1} W(width)} \qquad \text{for} \quad j=1,2,3 \tag{5}$$

$\phi_{s\,vc}$ is the potential distribution along *y-axis* and is obtained using $\phi_{vc}(y) = \psi(x=0, y)$.[4]

$$Lc_{ij} = \begin{cases} Lc_{1j} = L_j & 0 < y \le t_1 (= t_{s1}) \\ Lc_{2j} = L_j + \alpha_j & t_1 < y \le t_2 (= t_{s1} + t_{s2}) \\ Lc_3 = \sum_{j=1}^{3} L_j + \beta_j & y > t_2 \quad \text{for } i=1,2 \;\; j=1,2,3 \end{cases} \tag{6}$$

here α_j and β_j are the extra lengths of current lines in the second layer and bulk.

So, the expression for depletion depth d_j is given as

$$d_j = t_{s1} + t_{s2} + U_j \qquad \text{for } j=1,2,3 \tag{7}$$

where

$$U_j = \sqrt{\left(t_{s1} + t_{s2} + t_{ox}\frac{\varepsilon_{si}}{\varepsilon_{ox}}\right)^2 + \frac{2\varepsilon_{si}}{qN^*_3}\left(V'_{GS_j} - V_{gj}\right)} - \left(t_{s1} + t_{s2} + t_{ox}\frac{\varepsilon_{si}}{\varepsilon_{ox}}\right) \tag{8}$$

$$\mathrm{V_{gj}} = \frac{q}{\varepsilon_{si}} N^{*}{}_{2j} t_{s2}\left(t_{s1} + \frac{t_{s2}}{2} + \varepsilon_{si}\frac{t_{ox}}{\varepsilon_{ox}} \right) + \frac{q}{\varepsilon_{si}} N^{*}{}_{1j} t_{s1}\left(\frac{t_{s1}}{2} + \varepsilon_{si}\frac{t_{ox}}{\varepsilon_{ox}} \right) \tag{9}$$

$$W_d = \begin{cases} d_1 & 0 \geq x \geq L_1 \\ d_2 & L_1 > x \geq L_1 + L_2 \\ d_3 & L_1 + L_2 > x \geq L_1 + L_2 + L_3 \end{cases} \tag{10}$$

Using the superposition principle, the 2D analytical solutions for potential is obtained as

$$\xi(x,y) = \xi_l(y) + \xi_s(x,y)\,;\ 0 \leq x \leq L \ \&\ 0 \leq y \leq W_d \tag{11}$$

where $\xi_l(y) = \dfrac{qN'_A(y - W_d)^2}{2\varepsilon_{si}} + V_{sub}$;

$$\xi_s(x,y) = \xi_{s1}(x,y) + \xi_{s2}(x,y)$$

$$\xi_{s1}(x,y) = \sum_{r=1}^{\infty} \sin\left(\frac{r\pi x}{L}\right) \times \left(\frac{\chi 1_r \sinh\left(\frac{r\pi y}{L}\right) + \chi 2_r \sinh\left(\frac{r\pi (W_t - y)}{L}\right)}{\sinh\left(\frac{r\pi W_t}{L}\right)} \right) \tag{12}$$

$$\xi_{s2}(x,y) = \sum_{r=1}^{\infty} \sin\left(\frac{r\pi y}{W_t}\right) \times \left(\frac{\chi 3_r \sinh\left(\frac{r\pi x}{W_t}\right) + \chi 4_r \sinh\left(\frac{r\pi (L_t - x)}{W_t}\right)}{\sinh\left(\frac{r\pi L}{W_t}\right)} \right) \tag{13}$$

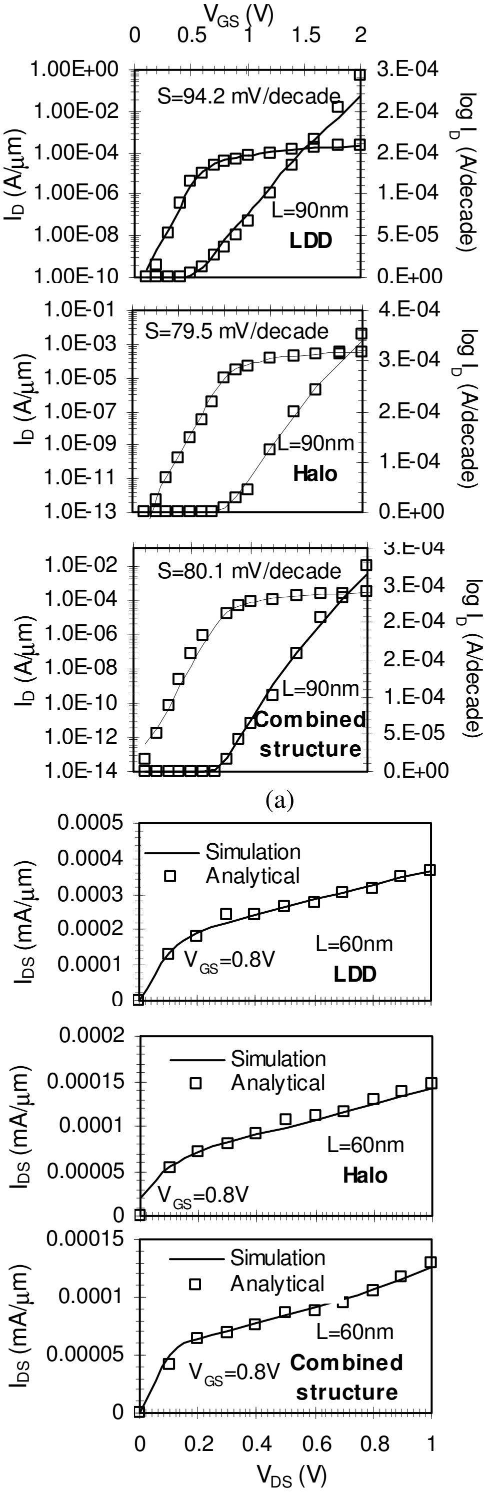
N'_A is the reduced doping (in the respective region) and W_d is the depletion depth obtained using VDT. 2D-channel potential is used to model subthreshold drain current from which threshold voltage (V_{TH}) is evaluated. Using V_{TH} drain current in the linear and saturation region can be calculated analytically as a function of V_{GS} and V_{DS} as

$$I_{DLinear} = \frac{\mu W C_{ox}\left((V_{GS} - V_{TH}) V_{DS} - \frac{1}{2} a_o V_{DS}{}^2 \right)}{\left(1 + \frac{V_{DS}}{LE_c} \right) L} \tag{14}$$

$$I_{DSAT} = \frac{\mu W C_{ox}\left((V_{GS} - V_{TH}) V_{DSAT} - \frac{1}{2} a_o V_{DSAT}{}^2 \right)}{\left(1 + \frac{V_{DSAT}}{(L - \Delta L) E_c} \right) (L - \Delta L)} \tag{15}$$

3 RESULTS AND DISCUSSION

Fig. 3 presents the comparison between the modeled and simulated drain current (I_{DS}) variation (on linear and log scale) with V_{GS} and with V_{DS} for different structures. The obtained analytical results are in fair agreement with the simulated results obtained using ATLAS 2D: device simulation software.



(a)

(b)

Fig. 3 Drain current variation along the channel for Halo, LDD and combined structure. $q\Phi_M = 4.77$ eV, V_{GS}=0.8V and V_{DS}=0.05V.

Fig. 4 presents the variation of the I_{on}, I_{off} and their ratio, I_{on}/I_{off} with the channel length down to 60nm. It has been observed that off-state current (I_{off}) is lowest in halo due to the presence of highly doped regions near the S/D junctions that prevents dopant out diffusion in subthreshold regime of device operation. LDD, on the other hand demonstrates higher on-state current (I_{on}) on account of having lower threshold voltage as compared to other structures. Hence, the combination bearing the benefits of both halo and LDD, exhibits I_{off} and I_{on} values in between the range, set by the two devices and hence, presents higher I_{on}/I_{off} ratio – an essential figure of merit for digital performance.

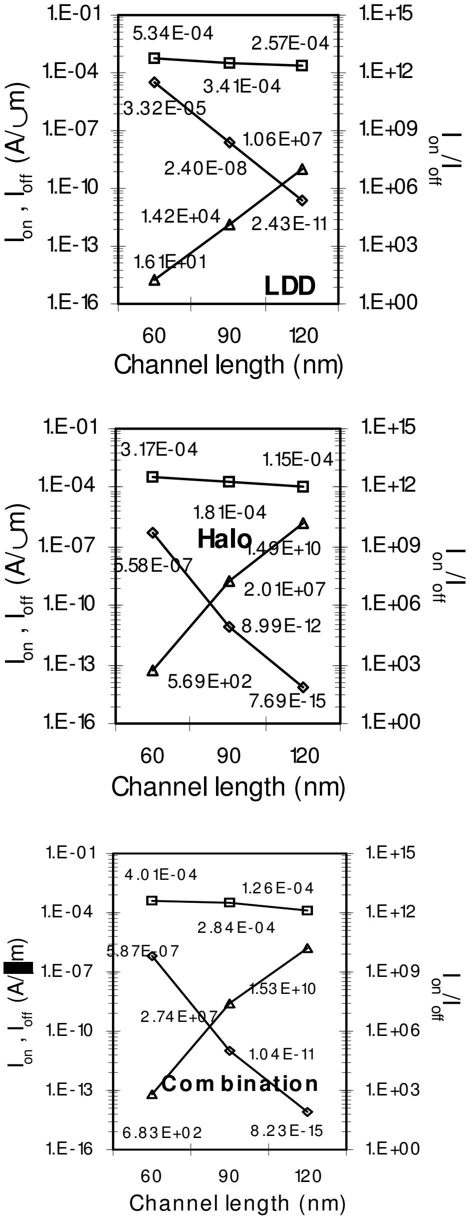


Fig.4 Variation of I_{on} and I_{off} with channel length for Halo, LDD and combination architecture. V_{DS} = 1.0Vand $q\Phi_M$ = 4.77 eV. (□□- I_{on}, ◇◇- I_{off} and ΔΔ - I_{on}/I_{off}).

4 CONCLUSION

A new simple and computationally efficient two-dimensional analytical model that can accurately model various advanced MOSFET structures incorporating the effect of DIBL via VDT has been presented and verified. The combined structure, incorporating the beneficial effect of both asymmetric halo and LDD, proves out to be the best candidate for switching applications.

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