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Compact Model for Manufacturing Design and Fluctuation Study

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Introduction

Process fluctuations, which are due to lithography, etch, thin film, and diffusion process variation, are inevitable in practice. The major in-line variation include:

- ✓ In-line poly CD variation;
- ✓ In-line gate oxide thickness variation;
- ✓ In-line channel profile variation and so on…

The major end-of-line (EOL) variation for transistor include:

- ✓ Threshold voltage (V_{th}) variation;
- ✓ Saturation current (I_{dsat}) variation;
- ✓ Off-current (I_{off}) variation and so on…

Approach

To correlate these in-line variation to the EOL variation in a systematic and quantifiable way, a set of compact model for threshold voltage [1] and drain current [2] from XSIM has been employed.

$$V_{th} = f(V_{FB}, \phi_s, N_s, T_{ox}, L_{eff}, V_{bs}, V_{ds})$$

$$I_{ds} = f(V_{th}, \mu_{eff}, R_{sd}, N_s, T_{ox}, L_{eff}, W, X_j, V_{bi}, v_{sat}, V_{dsat}, T, V_{bs}, V_{ds})$$

The model is chosen as it is derive analytically and made up from in-line device parameters, such as T_{ox}, L_{eff}, N_s, X_j and so on…

Threshold Voltage Model

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

$$\gamma = \sqrt{2q\varepsilon_{si}N_{eff}}\,/C_{ox}$$

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

$$V_{FB} = V_{fbb} - 0.5\phi_{s0} - Q_o/C_{ox}$$

$$L_{eff} = L_g - 2\sigma X_j$$

$$\phi_{s0} = 2\phi_F$$

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

$$V_{bi} = \frac{2kT}{q}ln\left(\frac{N_{sd}N_{eff}}{n_i^2}\right)$$

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

$$N_{pile} = \kappa N_s$$

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

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

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

$$\kappa = \kappa_0 + b_\kappa V_{bs}$$

$$i = i_0 + b_i V_{bs}$$

$$N_{eff} = N_s + N_{pile}\left(\frac{\sqrt{\pi}\,erf\left(L_{eff}/l_\beta\right)}{\left(L_{eff}/l_\beta\right)}\right)$$

$$j = j_0 + b_j V_{bs}$$

Drain Current Model (I)

$$I_{ds} = I_{dm} + I_{ded} + I_{lk}$$

$$I_{dm} = \frac{I_{d4}}{1 + \frac{R_{sd} I_{d4}}{V_{deff}}}$$

$$I_{d4} = I_{d3} \times \frac{1}{1 + V_{deff} / (E_{sat} L_{eff})} \times g$$

$$I_{d3} = \mu_{eff} C_{ox} \frac{W}{L_{eff}} V_{ge}$$

$$V_{geff} = \frac{2nV_{tm} \ln\left(1 + \exp\left(\frac{V_{gs} - V_{th}}{2nV_{tm}}\right)\right)}{1 + \frac{2nC_{ox}}{C_d} \exp\left(-\frac{V_{gs} - V_{th} - 2V_{off}}{2nV_{tm}}\right)}$$

$$V_{deff} = V_{dsat} - \frac{1}{2}\left[V_{dsat} - V_{ds} - \delta + \sqrt{(V_{dsat} - V_{ds} - \delta)^2 + 4\delta V_{dsat}}\right]$$

$$V_{ge} = \frac{V_{gg}}{\left(W_{ge} / \sqrt{1 + W_{ge}^2}\right)}$$

$$V_{gg} = \frac{2nV_{tm} \ln\left(1 + \exp\left(\frac{V_{gs} - V_{th}}{2nV_{tm}}\right)\right) V_{de}}{1 + \frac{2nV_{de} C_{ox} \exp\left(-\frac{V_{gs} - V_{th} - 2V_{off}}{2nV_{tm}}\right)}{V_{tm} C_d \left(1 - \exp(-V_{ds}/V_{tm})\right)}}$$

$$W_{ge} = \frac{n \exp\left(\frac{V_{gs} - V_{th}}{2nV_{tm}}\right)}{A_b \left(1 - \exp(-V_{ds}/V_{tm})\right)}$$

$$V_{de} = V_{deff}\left(1 - \frac{A_b}{2} \frac{V_{deff}}{V_{geff}}\right)$$

Drain Current Model (II)

$$\mu_{eff} = \frac{\mu_1}{1 + \frac{\mu_1}{\mu_2} E_{eff,\perp}^{1/3} + \frac{\mu_1}{\mu_3} E_{eff,\perp}^{2}}$$

$$A_b = 1 + \frac{n_\nu \gamma}{2\sqrt{\phi_{s0} + V_{sb}}}$$

$$E_{eff} = \frac{V_{geff} + 2V_{teff}}{6t_{ox}}$$

$$E_{sat} = \frac{2v_{sat}}{\mu_{eff}}$$

$$V_a = -\left(V_{FB} + 2\phi_F\right)$$

$$C_{ox} = \frac{\varepsilon_{ox}}{T_{ox}}$$

$$V_{tsub} = -\frac{\gamma^2}{2} + \gamma\sqrt{\frac{\gamma^2}{4} + V_{gs} - V_{bs} - V_{FB}}$$

$$V_{teff} = V_{th} + V_a - \frac{1}{2}\left(V_{th} + V_a - V_{tsub} - \delta + \sqrt{\left(V_{th} + V_a - V_{tsub} - \delta\right)^2 + 4\delta\left(V_{th} + V_a\right)}\right)$$

$$V_{tm} = \frac{kT}{q}$$

$$R_{sd} = R_s + R_d = r_1 + R_{int}$$

$$n = 1 + \frac{C_d}{C_{ox}}$$

$$R_{int} = \frac{r_2}{V_{geff} + V_{tm} A_b \left(1 - exp\left(-V_{ds}/V_{tm}\right)\right)}$$

$$C_d = \sqrt{q\varepsilon_{Si} N_{sub} / \left(2\left(1.5\phi_F + V_{sb}\right)\right)}$$

Drain Current Model (III)

$$V_{dsat} = \frac{-b-\sqrt{b^2-4ac}}{2a}$$

$$I_{lk} = I_{s0} q n_i \sqrt{2\varepsilon_{Si}\left(V_{bi}+V_{ds}+V_{sb}\right)/q}$$

$$I_{ded} = I_{dm}\left(W_0, S_{c0} V_{th}\right)$$

$$\begin{cases} a = \left(A_b W C_{ox} v_{sat} R_s\right) \\ b = -\left\{V_{gs}-V_{th}+\left(V_{gs}-V_{th}\right) W C_{ox} v_{sat}\left[2R_s + A_b\left(R_s+R_d\right)\right] + A_b E_{sat} L_{eff}\right\} \\ c = E_{sat} L_{eff}\left(V_{gs}-V_{th}\right) + 2 W C_{ox} v_{sat}\left(R_s+R_d\right)\left(V_{gs}-V_{th}\right)^2 \end{cases}$$

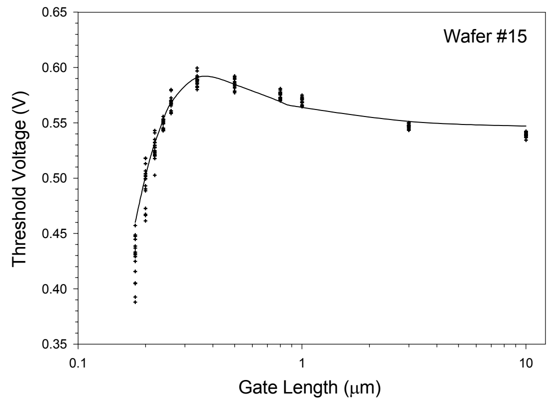
$$g = \left(1+\frac{V_{ds}-V_{deff}}{V_{Aeff}}\right)$$

$$h = \frac{c\left[1+\sqrt{1+\left(\frac{V_{ds}-V_{deff}}{lE_{sat}}\right)^2}\right]}{\sqrt{1+\left(\frac{V_{ds}-V_{deff}}{lE_{sat}}\right)^2} - c\left(V_{ds}-V_{deff}\right)}$$

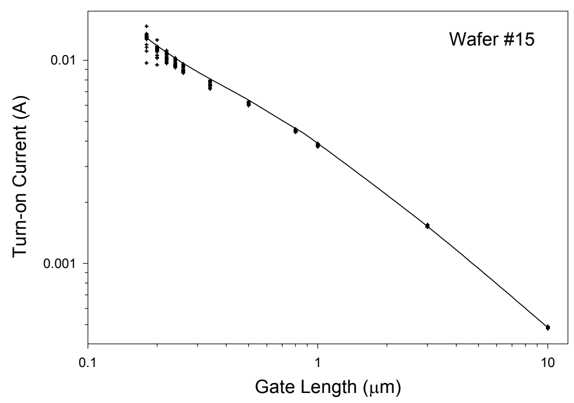
$$V_{Aeff} = \frac{E_{sat} L_{eff}\left[1+h\left(V_{ds}-V_{deff}\right)\right]+V_{deff}}{h V_{deff}}$$

Experimental Data

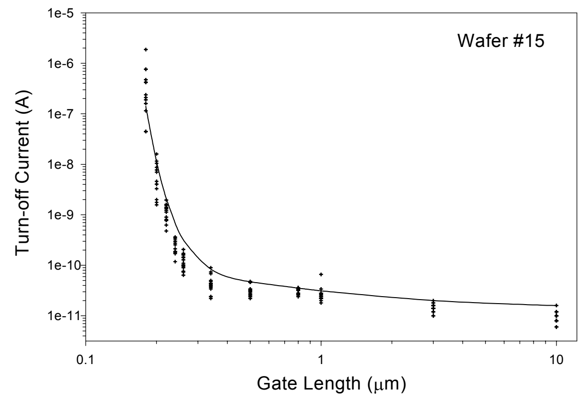
The EOL parameters from seventeen sites of measurement (cross symbols); the fitted model (lines) for different channel length.



Threshold Voltage



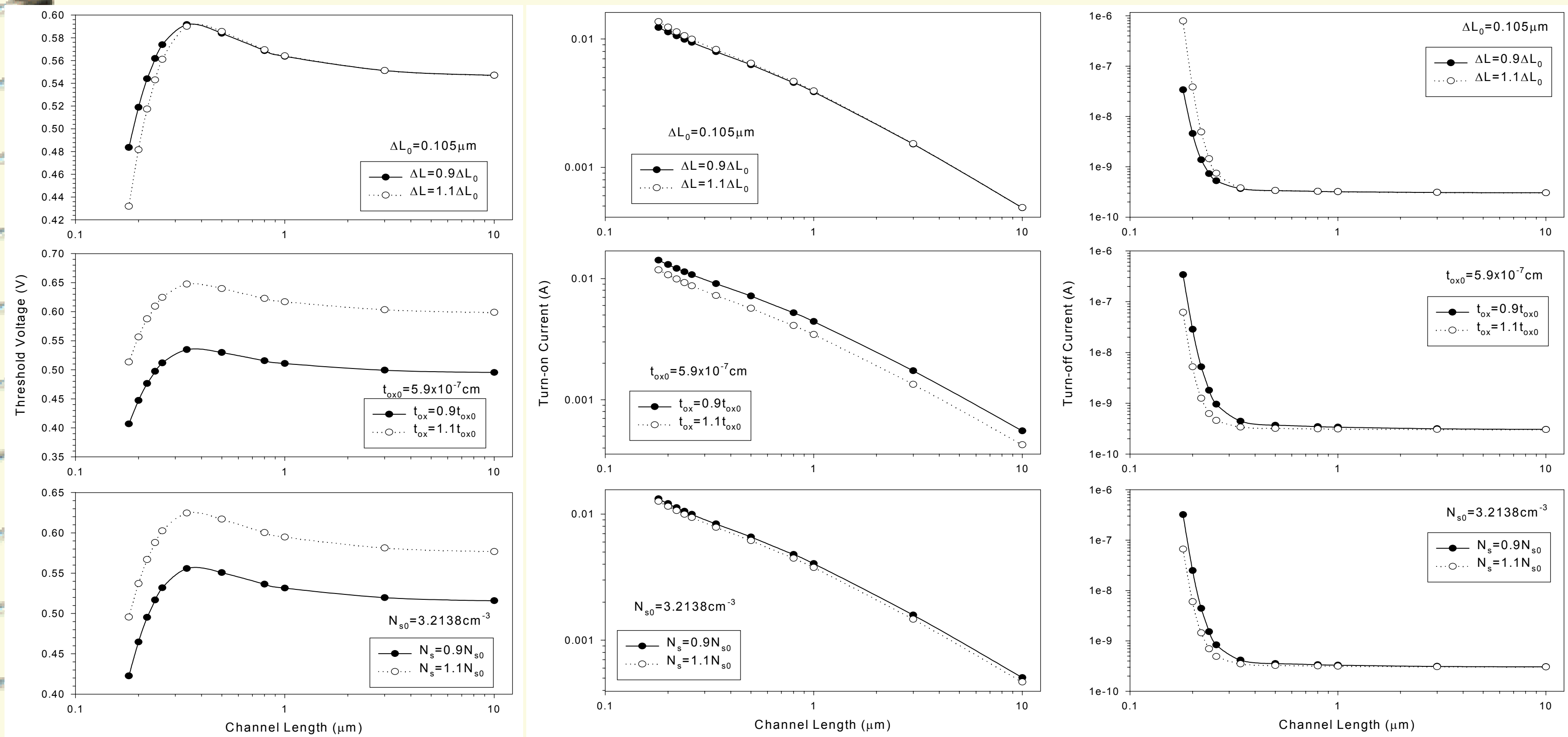
On-state Current



Off-state Current

The data are from 0.25μm CMOS technology, CSM

EOL Parameters Variation from Model



V_{th}, I_{on}, I_{off} variations due to small fluctuation of channel length, oxide thickness and channel doping. Solid lines: -10% of nominal value; Dotted lines: +10% of nominal value.

Model for Manufacturing Fluctuation Study

A well-calibrated physical model [1,2] is a useful tool for determining the possible cause for resultant device variation. Based on the analytical model, a mathematical expression that relates threshold voltage variance in terms of process-related parameter variances [3] is shown as,

$$\left(\sigma\delta V_{th}\right)^2 = \left(\left.\frac{\partial\delta V_{th}}{\partial\delta L}\right|_{L_{spec}} \sigma\delta L\right)^2 + \left(\left.\frac{\partial\delta V_{th}}{\partial\delta t_{ox}}\right|_{tox_{spec}} \sigma\delta t_{ox}\right)^2 + \left(\left.\frac{\partial\delta V_{th}}{\partial\delta N_s}\right|_{Ns_{spec}} \sigma\delta N_s\right)^2 +$$

$$\left(\left.\frac{\partial\delta V_{th}}{\partial\delta Q_{ss}}\right|_{Qss_{spec}} \sigma\delta Q_{ss}\right)^2 + \ldots$$

Model for Manufacturing Fluctuation Study

Similarly, for I_{on} and I_{off},

$$(\sigma\delta I_{on})^2 = \left(\frac{\partial \delta I_{on}}{\partial \delta L}\bigg|_{L_{spec}} \sigma\delta L \right)^2 + \left(\frac{\partial \delta I_{on}}{\partial \delta t_{ox}}\bigg|_{tox_{spec}} \sigma\delta t_{ox} \right)^2 + \left(\frac{\partial \delta I_{on}}{\partial \delta N_s}\bigg|_{Ns_{spec}} \sigma\delta N_s \right)^2 +$$

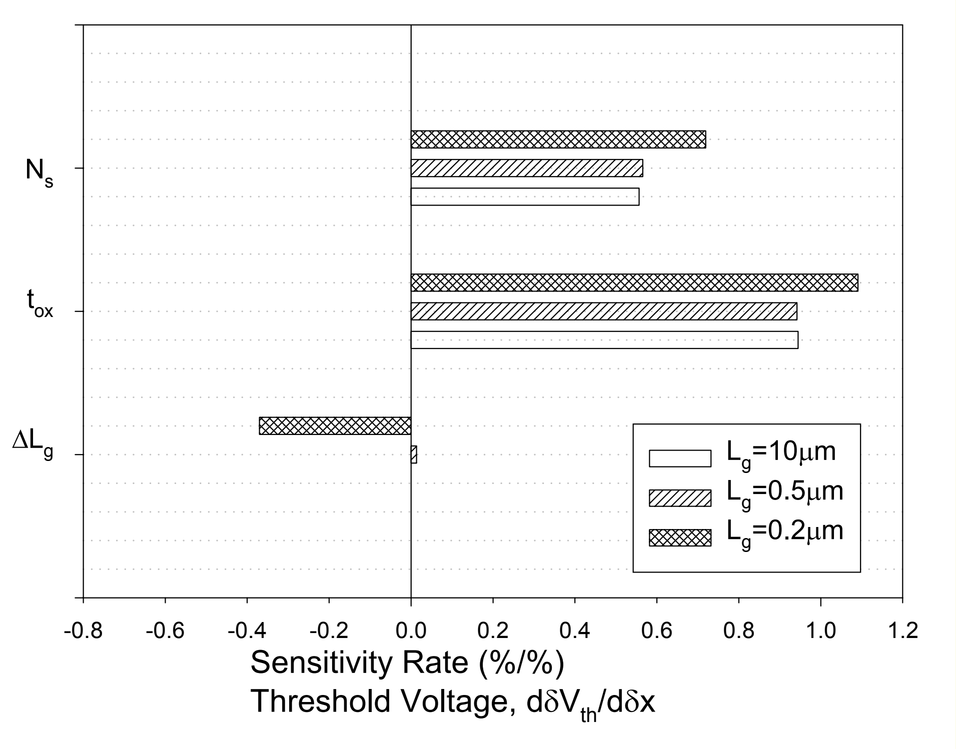
$$\left(\frac{\partial \delta I_{on}}{\partial \delta W}\bigg|_{W_{spec}} \sigma\delta W \right)^2 + \ldots$$

$$(\sigma\delta I_{off})^2 = \left(\frac{\partial \delta I_{off}}{\partial \delta L}\bigg|_{L_{spec}} \sigma\delta L \right)^2 + \left(\frac{\partial \delta I_{off}}{\partial \delta t_{ox}}\bigg|_{tox_{spec}} \sigma\delta t_{ox} \right)^2 + \left(\frac{\partial \delta I_{off}}{\partial \delta N_s}\bigg|_{Ns_{spec}} \sigma\delta N_s \right)^2 +$$

$$\left(\frac{\partial \delta I_{off}}{\partial \delta W}\bigg|_{W_{spec}} \sigma\delta W \right)^2 + \left(\frac{\partial \delta I_{off}}{\partial \delta N_{sd}}\bigg|_{Nsd_{spec}} \sigma\delta N_{sd} \right)^2 + \left(\frac{\partial \delta I_{off}}{\partial \delta W_0}\bigg|_{W_{0\,spec}} \sigma\delta W_0 \right)^2 + \ldots$$

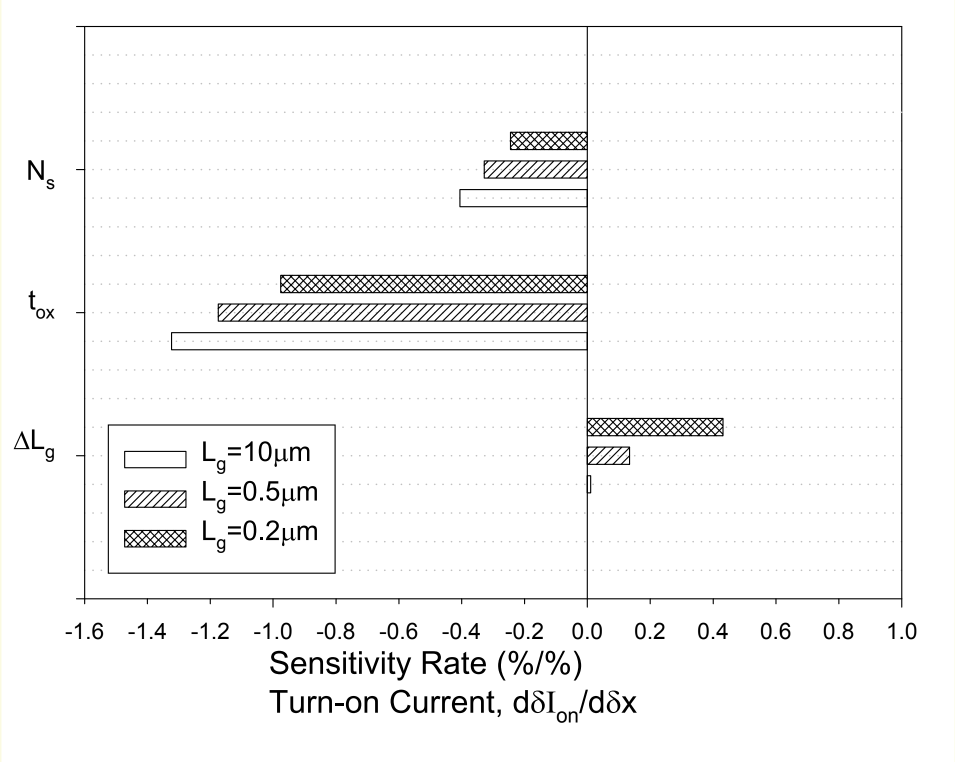
All the quantities are normalized, which is indicated by the symbol δ, that is $\delta V_{th} = \left(V_{th} - \overline{V_{th}}\right) / \overline{V_{th}}$. $(\sigma\delta V_{th})^2$ and $\partial\delta V_{th} / \partial\delta L$ are the normalized variance and the sensitivity rate of threshold voltage with respect to channel length, respectively.

Sensitivity Rate (V_{th})



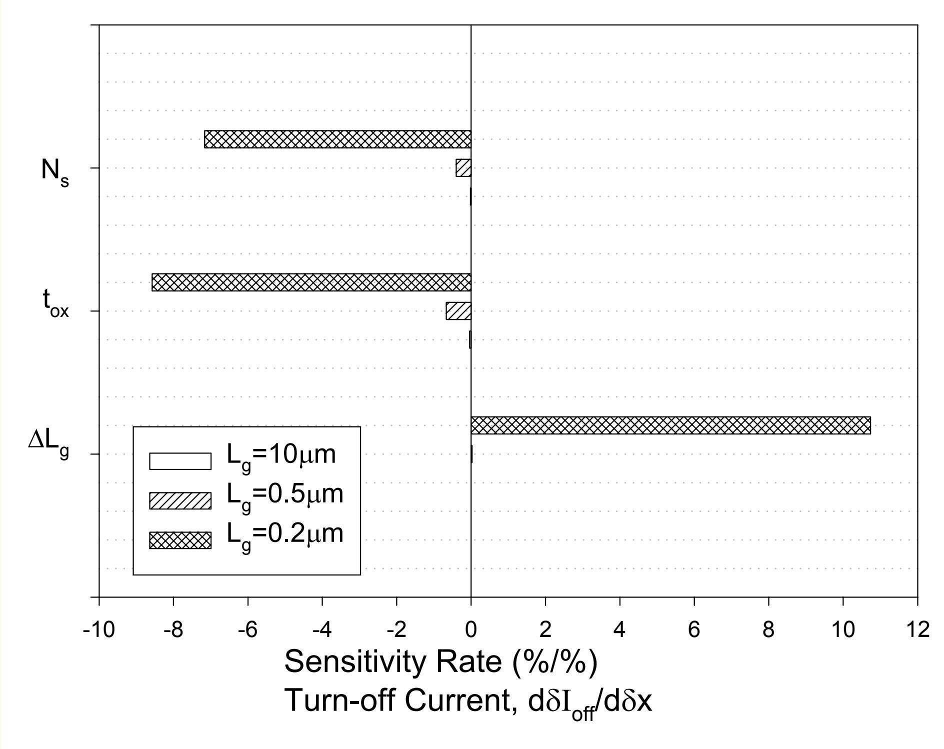
Histogram showing normalized V_{th} sensitivity rate to ΔL, t_{ox} *and* N_s for long-, medium-, and short-channel devices .

Sensitivity Rate (I_{on})



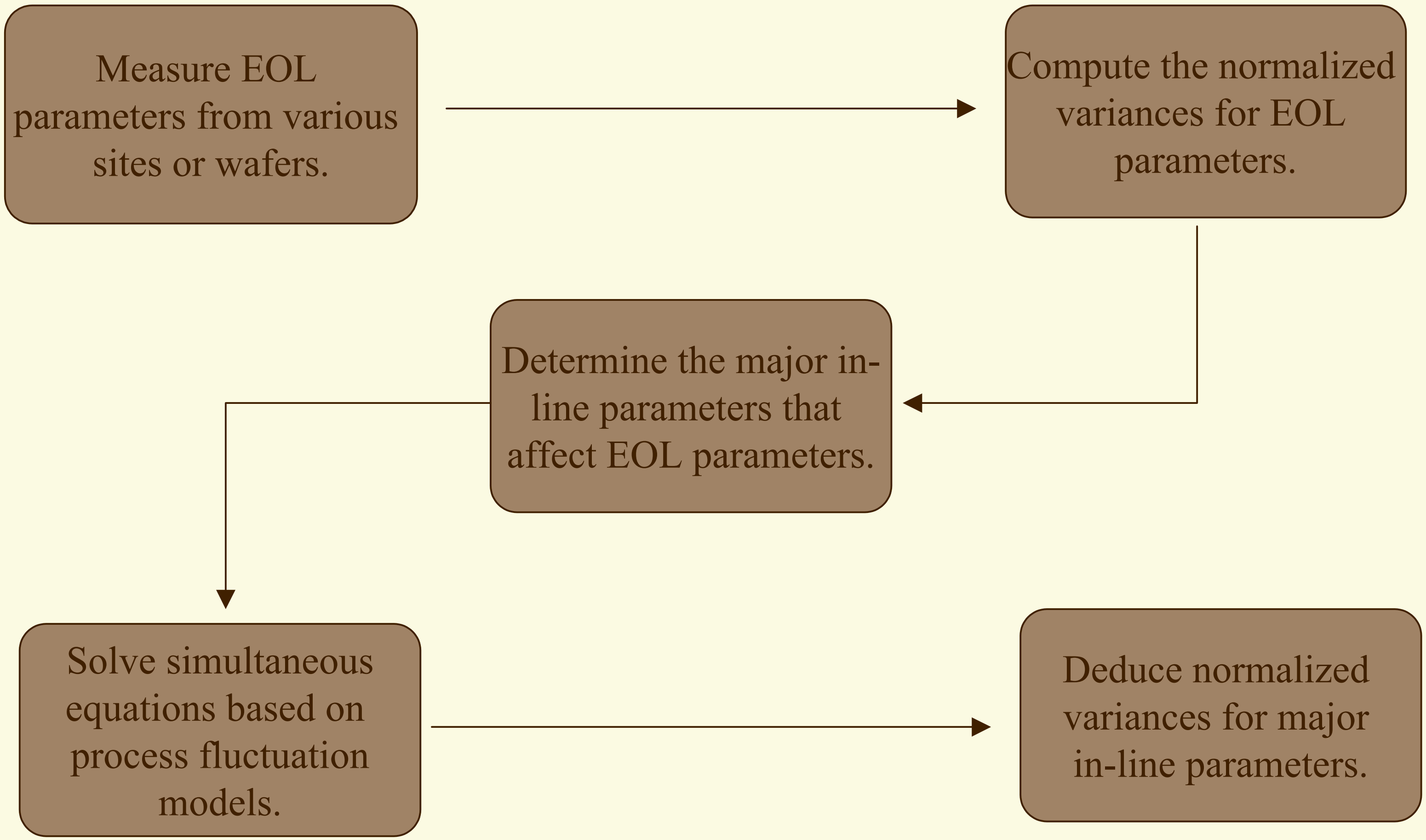
Histogram showing normalized I_{on} sensitivity rate to ΔL, t_{ox} *and* N_s for long-, medium-, and short-channel devices.

Sensitivity Rate (I_{off})



Histogram showing normalized I_{off} sensitivity rate to ΔL, t_{ox} *and* N_s for long-, medium-, and short-channel devices .

Application (I)



Example

The long-channel example below presents the concept of determining process fluctuations from electrical parameter measurement fluctuations. Based on previous expression,

$$(\sigma\delta V_{th})^2 = \left(\left. \frac{\partial \delta V_{th}}{\partial \delta t_{ox}} \right|_{tox_{spec}} \sigma\delta t_{ox} \right)^2 + \left(\left. \frac{\partial \delta V_{th}}{\partial \delta N_s} \right|_{Ns_{spec}} \sigma\delta N_s \right)^2 + R_1$$

$$1.7 \times 10^{-5} = 0.89(\sigma\delta t_{ox})^2 + 0.31(\sigma\delta N_s)^2 + R_1$$

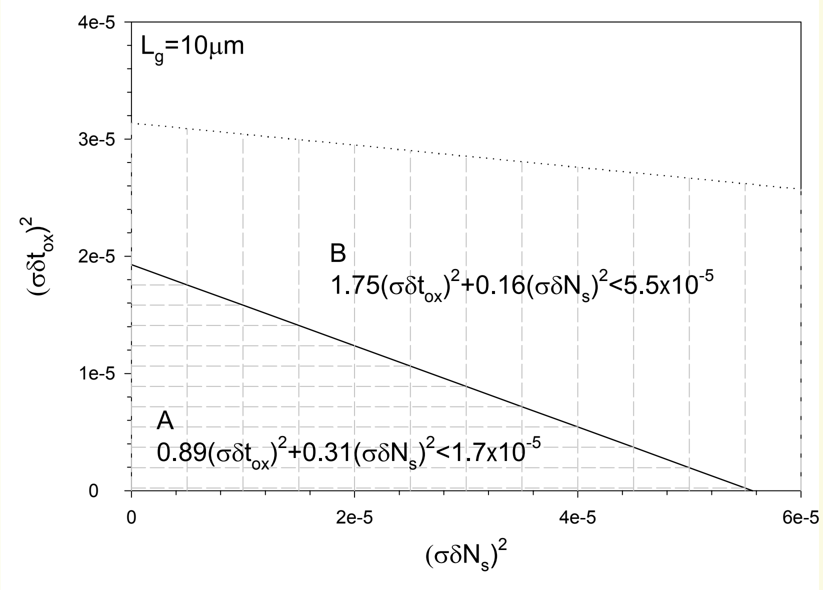
$$(\sigma\delta I_{on})^2 = \left(\left. \frac{\partial \delta I_{on}}{\partial \delta t_{ox}} \right|_{tox_{spec}} \sigma\delta t_{ox} \right)^2 + \left(\left. \frac{\partial \delta I_{on}}{\partial \delta N_s} \right|_{Ns_{spec}} \sigma\delta N_s \right)^2 + R_2$$

$$5.5 \times 10^{-5} = 1.75(\sigma\delta t_{ox})^2 + 0.16(\sigma\delta N_s)^2 + R_2$$

where R_1 and R_2 are the residue variance of V_{th} and I_{on}, respectively, due to other process-related parameters.

Example

Since R_1 and R_2 are not known, the following inequality equations can be formulated,



$$0.89(\sigma\delta t_{ox})^2 + 0.31(\sigma\delta N_s)^2 \leq 1.7\times10^{-5}$$

$$1.75(\sigma\delta t_{ox})^2 + 0.16(\sigma\delta N_s)^2 \leq 5.5\times10^{-5}$$

$$(\sigma\delta t_{ox})^2 \geq 0$$

$$(\sigma\delta N_s)^2 \geq 0$$

$(\sigma\delta t_{ox})^2$ and $(\sigma\delta N_s)^2$ lie in the overlap region A. The maximum normalized variance of t_{ox} and N_s is $1.9\text{x}10^{-5}$ and $5.5\text{x}10^{-5}$, respectively. This in turn is translated to maximum standard deviation of 0.26Å and $2.38\text{x}10^{15}\text{cm}^{-3}$, respectively for the 0.25μm process.

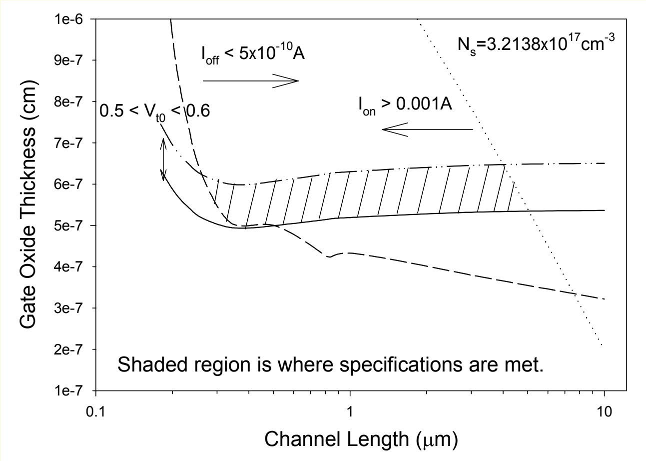
Application (II)

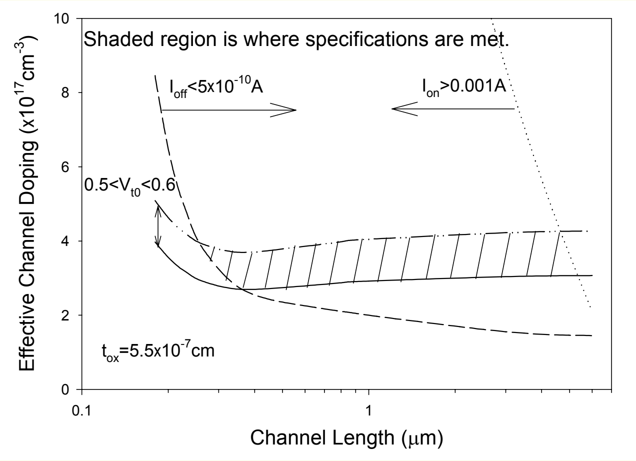
Design Specification:

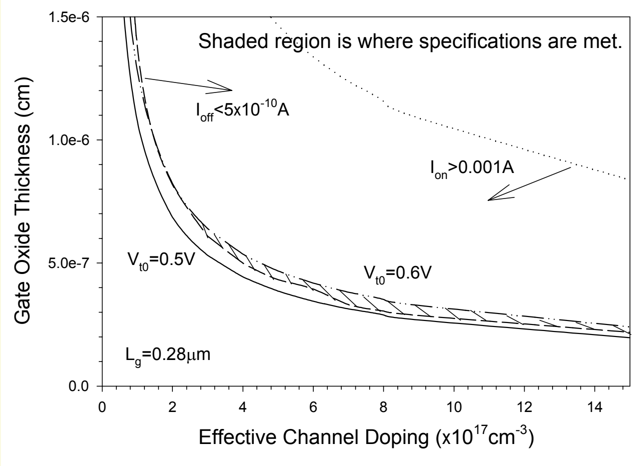
$$I_{on} \geq 0.001A,$$

$$0.5V \leq V_{th} \leq 0.6V,$$

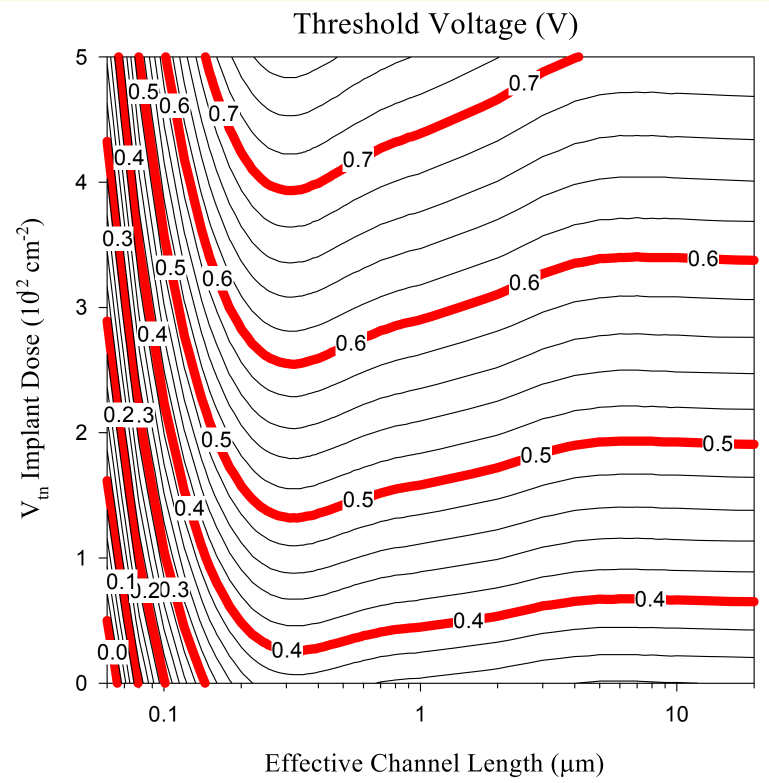
$$I_{off} \leq 5 \times 10^{-5} A$$



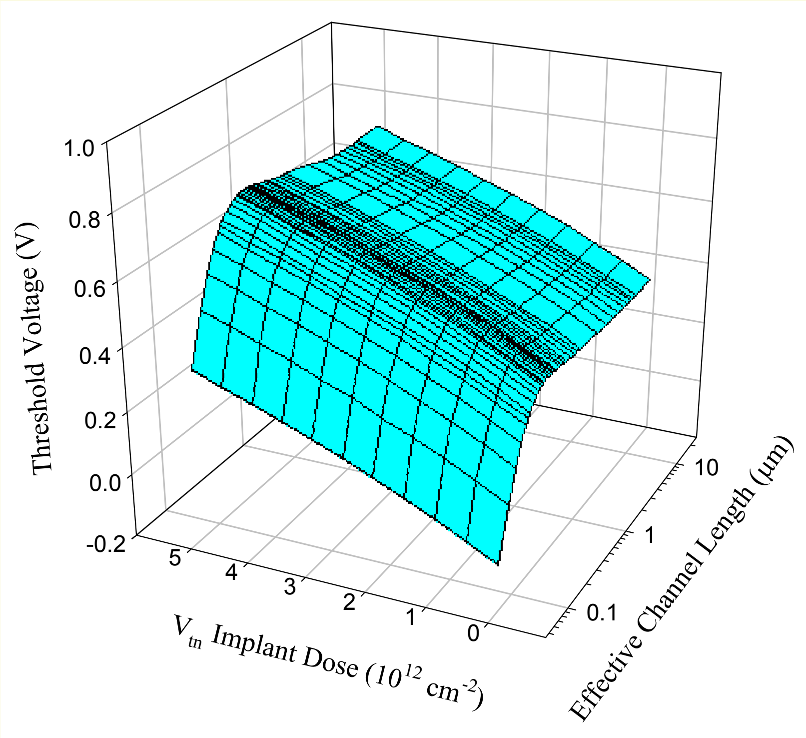




Application (II)



2-D contour plot of V_{th} for various implant doses and channel lengths.



3-D mesh plot of V_{th} for various implant doses and channel lengths.

Conclusion

A compact model has been employed to quantify and correlate EOL ET parameters with in-line process-related device parameters.
The approach has shown new possibility of applying physics-based compact model in the field of manufacturing design and fluctuation study.

References

[1] X. Zhou, K. Y. Lim, and D. Lim, "A general approach to compact threshold voltage formulation based on 2-D numerical simulation and experimental correlation for deep-submicron ULSI technology development," *IEEE Trans. Electron Devices*, vol. 47, pp. 214–221, Jan 2000.
[2] X. Zhou and K. Y. Lim, "Unified MOSFET compact *I–V* model formulation through physics-based effective transformation." *IEEE Trans. Electron Devices*, vol. 48, pp. 887–896, May 2001.
[3] R. Sitte, S. Dimitrijev, and H. B. Harrison, "Device parameter changes caused by manufacturing fluctuations of deep submicron MOSFET's," *IEEE Trans. Electron Devices*, vol. 41, pp. 2210–2215, Nov. 1994.

Question & Answer

Thank You………