

A Non-Charge-Sheet Analytic Theory for DG MOSFETs using SPP Approach

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OUTLINE

- ◆ **NEED** for physics based DG modeling
- ◆ **THEORY** for the analytical model
- ◆ **RESULT** and verification of model
- ◆ **CONCLUSION**

MOTIVATION

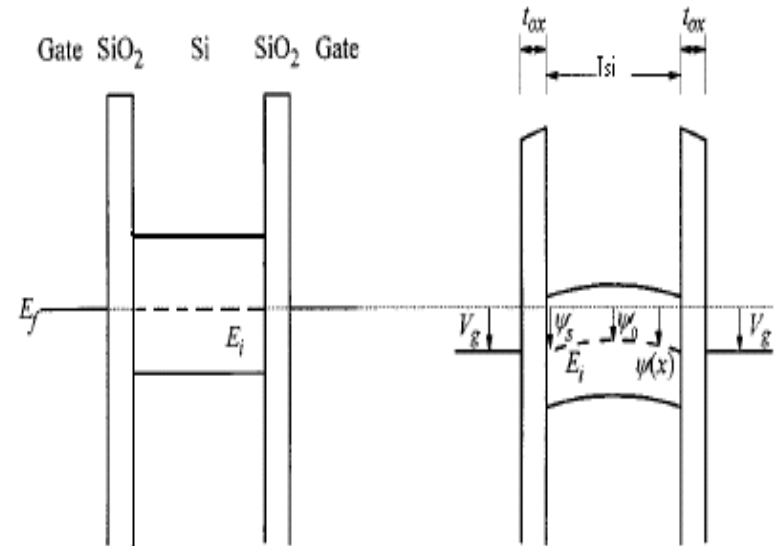
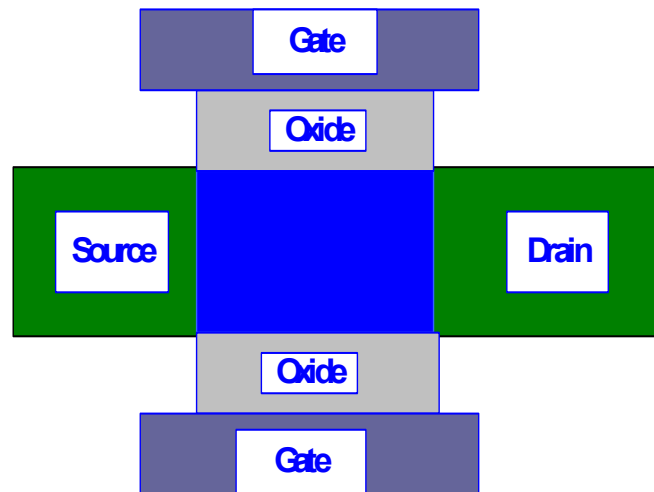
- ◆ **DG MOSFET**: Ideal Performance and Scaling characteristic
- ◆ **Previous DG Models**: charge-sheet approximation or V_{th} based
- ◆ **Charge-sheet model** does not work well for UTB DG: Volume inversion and DG Coupling
- ◆ **V_{th} based model** encounters continuity and symmetric issue
- ◆ **Physics based non-charge-sheet compact model** is required for DG modeling

WHAT IS SPP

Surface-Potential-Plus (SPP) is BSIM next generation Bulk model, which possess main features

- ◆ **NON-CHARGE-SHEET** physics;
- ◆ **NON- V_{th} , continuity** and symmetry in all regions and scales;
- ◆ **HIGH ACCURACY** with computational efficiency;
- ◆ **EXTENSIBILITY** for SOI,UTB, DG, SG, MG, etc.;
- ◆ **INCLUSION** of all second-order effects in physical path: 2-D, 3-D, QME, DGE, Saturation, Retro+Halo

DG MOSFET



◆ Structure of DG MOSFETs

◆ Energy diagram of DG

THEORY DEVELOPMENT

- ◆ Start with Poisson equation

$$\frac{d^2 \phi}{dx^2} = \frac{qn}{\epsilon_{si}}$$

- ◆ *Boltzmann statistics*

$$n = n_i \exp\left(\frac{q(\phi - v_{ch})}{kT}\right)$$

- ◆ *Master equation of Electron*

$$\frac{d^2 n}{dx^2} = \frac{1}{n} \left(\frac{dn}{dx}\right)^2 + \frac{q^2 n^2}{\epsilon kT}$$

- ◆ *Analytical Solution*

$$n(x) = \frac{n_0}{\cos^2 \left[\left(\frac{q^2 n_0}{2 \epsilon kT} \right)^{1/2} x \right]}$$

POTENTIAL, FIELD, CHARGE

- ◆ Surface potential

$$\phi_s = v_{ch} + \frac{kT}{q} \ln \left[\frac{n_0}{n_i} \cos^{-2} \left[\left(\frac{q^2 n_0}{2 \epsilon k T} \right)^{1/2} \frac{T_{si}}{2} \right] \right]$$

- ◆ Surface electric field

$$E_s = \left[\frac{2 n_0 k T}{\epsilon} \right]^{1/2} \tan \left[\left(\frac{q^2 n_0}{2 \epsilon k T} \right)^{1/2} \frac{T_{si}}{2} \right]$$

- ◆ Inversion charge

$$Q_{in} = [2 \epsilon n_0 k T]^{1/2} \tan \left[\left(\frac{q^2 n_0}{2 \epsilon k T} \right)^{1/2} \frac{T_{si}}{2} \right]$$

- ◆ Gauss's law

$$V_G - \Delta \psi_i = \phi_s + E_{ox} t_{ox} = \phi_s + \frac{Q_{in}}{\epsilon_{ox}} t_{ox}$$

- ◆ Exact Model

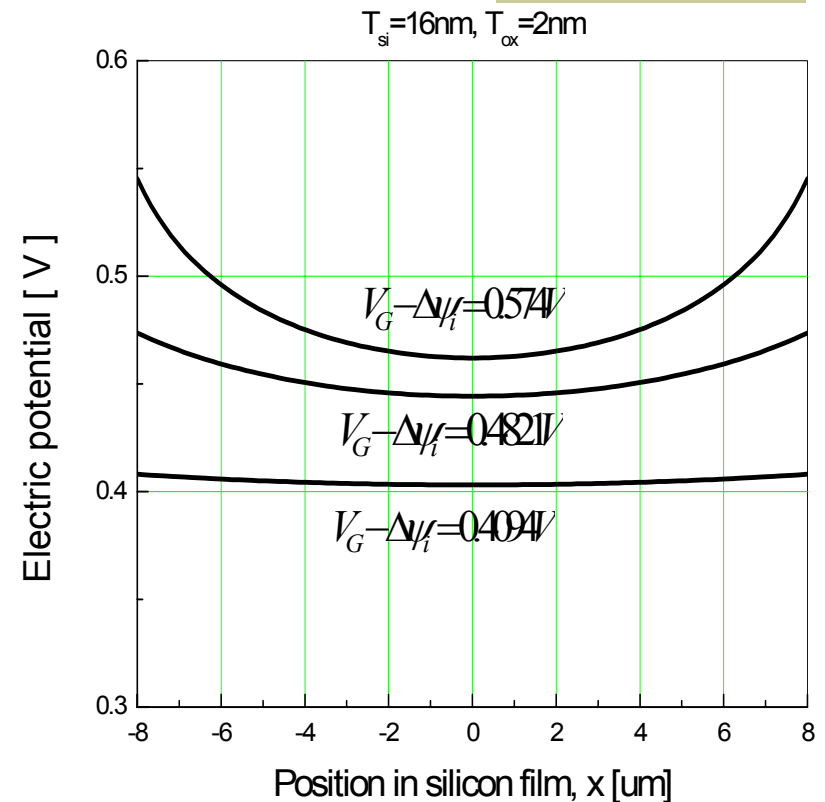
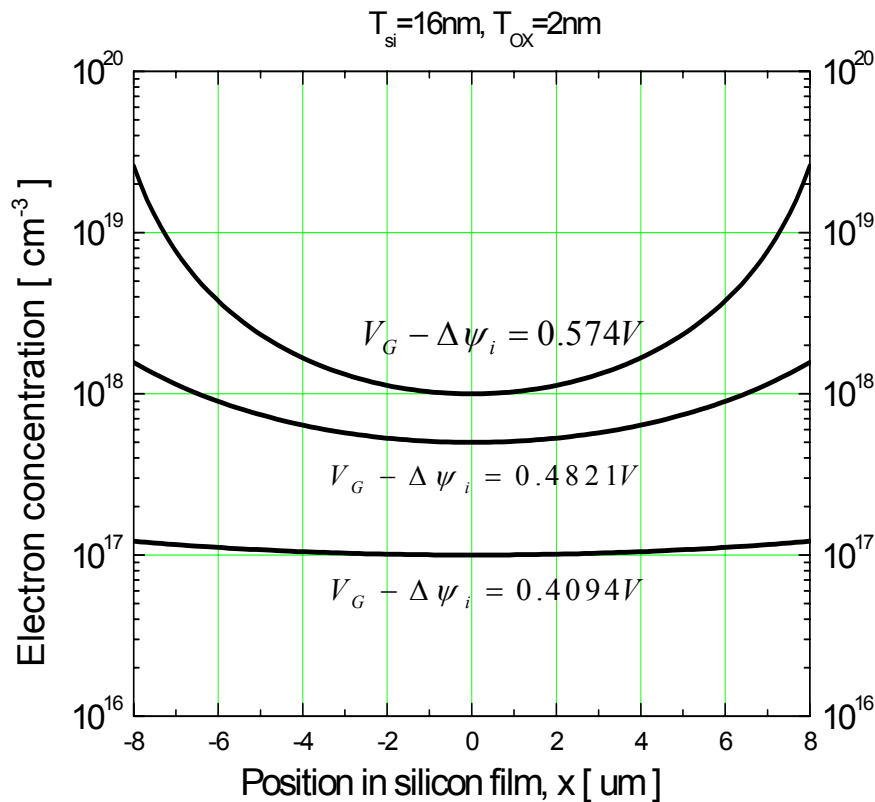
$$V_G - \Delta \psi_i - v_{ch} = \frac{kT}{q} \ln \left[\frac{n_0}{n_i} \cos^{-2} \left[\left(\frac{q^2 n_0}{2 \epsilon k T} \right)^{1/2} \frac{T_{si}}{2} \right] \right] + \frac{\epsilon_{si}}{\epsilon_{ox}} t_{ox} \left[\frac{2 n_0 k T}{\epsilon} \right]^{1/2} \tan \left[\left(\frac{q^2 n_0}{2 \epsilon k T} \right)^{1/2} \frac{T_{si}}{2} \right]$$

COMPACT MODELING

- ◆ Good approximation in sub-reg $Q_{in} = qn_0T_{si} / 2$
- ◆ Master charge equation $V_G - \Delta\psi_i - v_{ch} + \frac{fkT}{q} \ln(qn_0T_{si} / 2) = \frac{kT}{q} \ln Q_{in} + \frac{Q_{in}}{\epsilon_{ox}/t_{ox}}$
- ◆ Pao-Sah current formulation $I_{ds} = \mu w C_{ox} \left(\frac{kT}{q} \right)^2 q_{in} \frac{dv_{ch}}{dy}$
- ◆ Master current equation $I_{ds} = \frac{\mu w}{L} C_{ox} \left(\frac{kT}{q} \right)^2 \left[\frac{q_s^2 - q_d^2}{2} + (q_s - q_d) \right]$

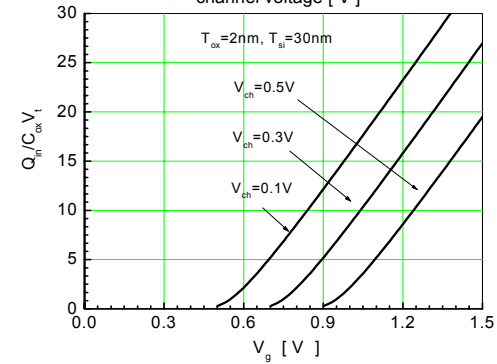
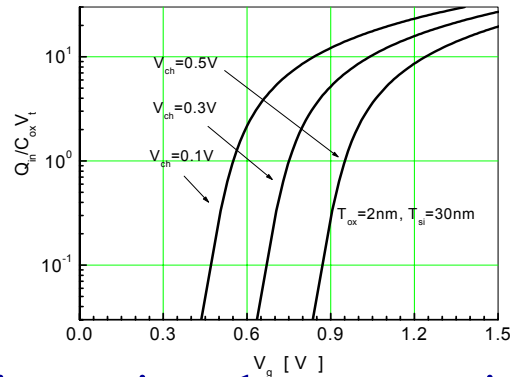
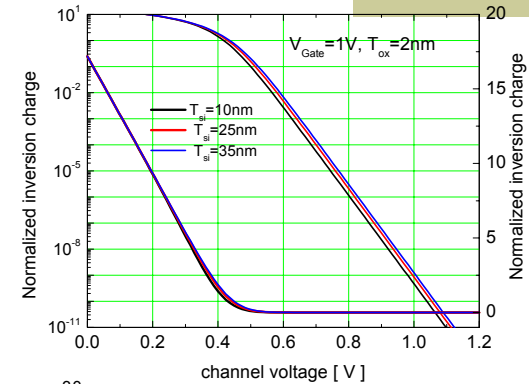
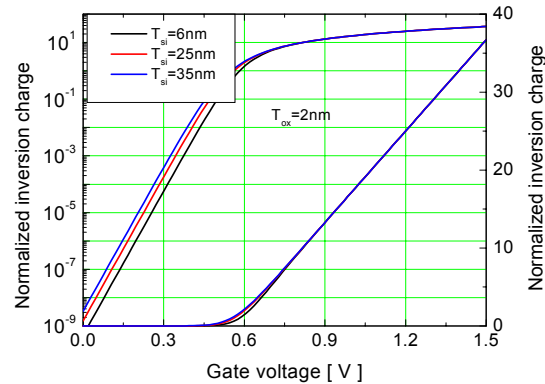
Note: Master current and charge equations of DG take quite same formulation with that of SPP except gemo term and slope

ELECTRON, POTENTIAL in Si



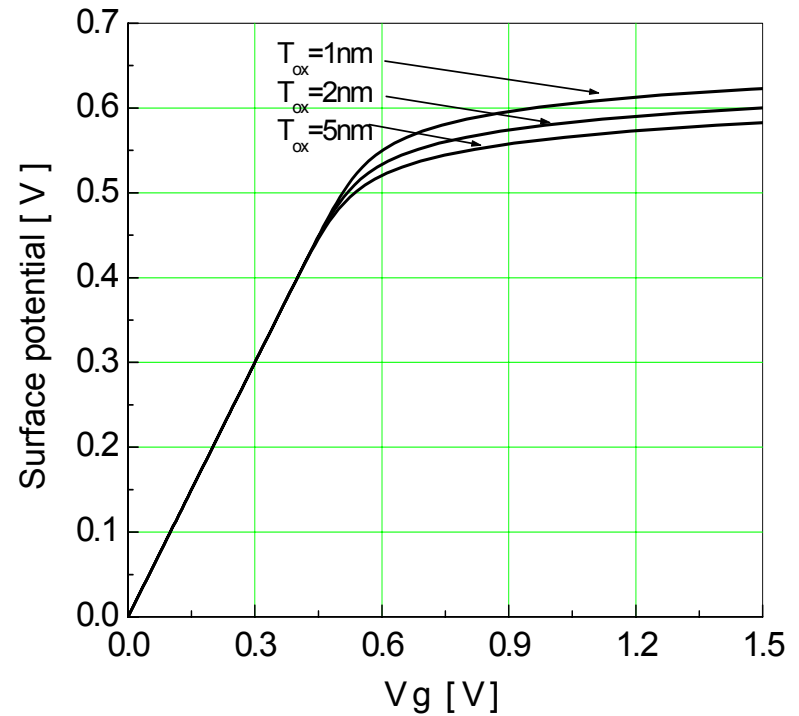
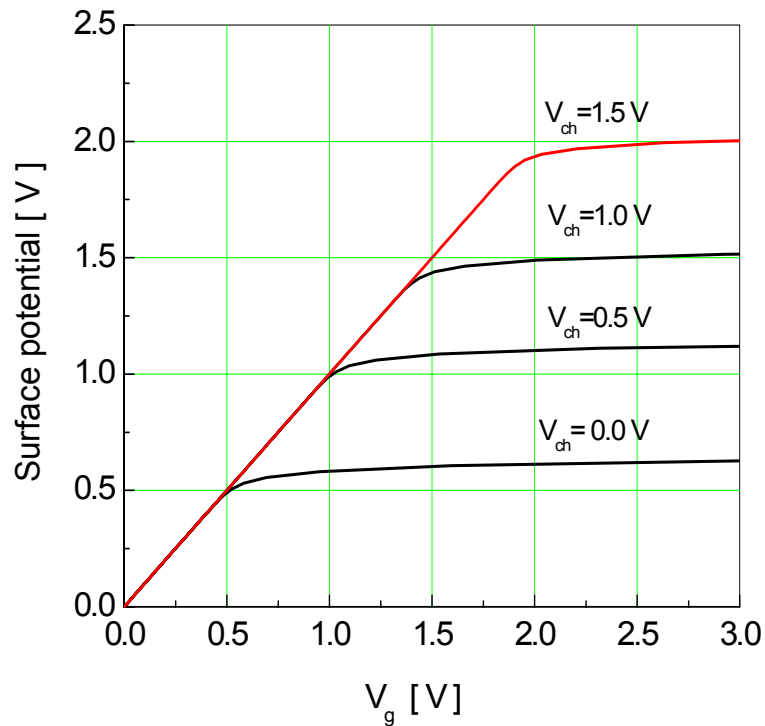
The mobile electron and potential distribution in Silicon for DG undoped MOSFETs.

CHARGE vs. BIAS



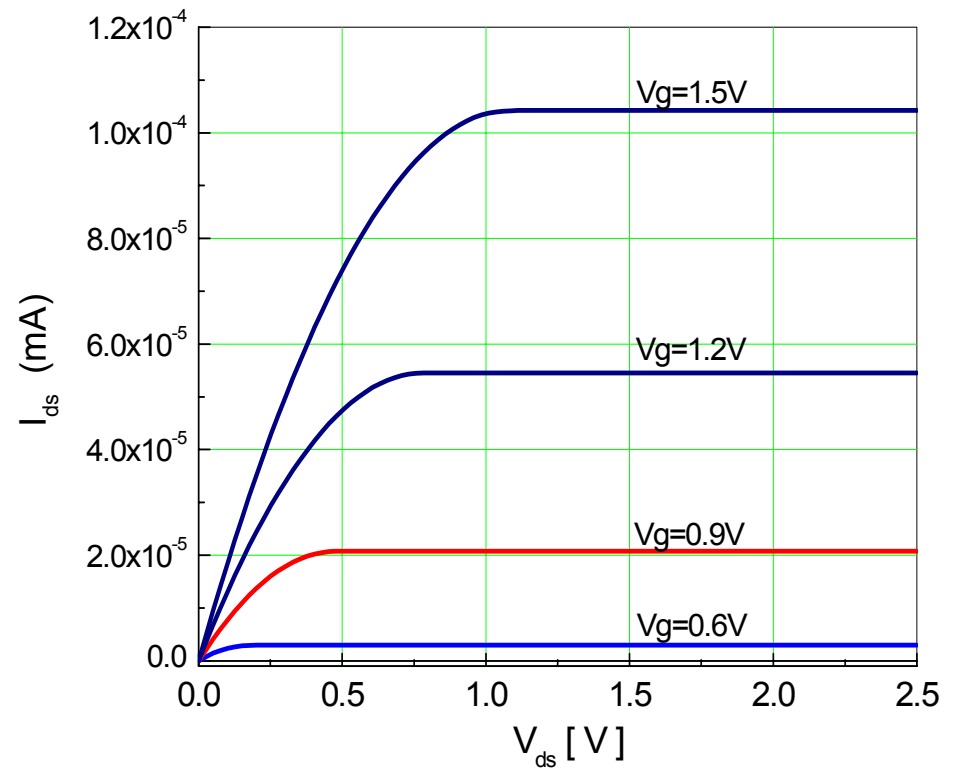
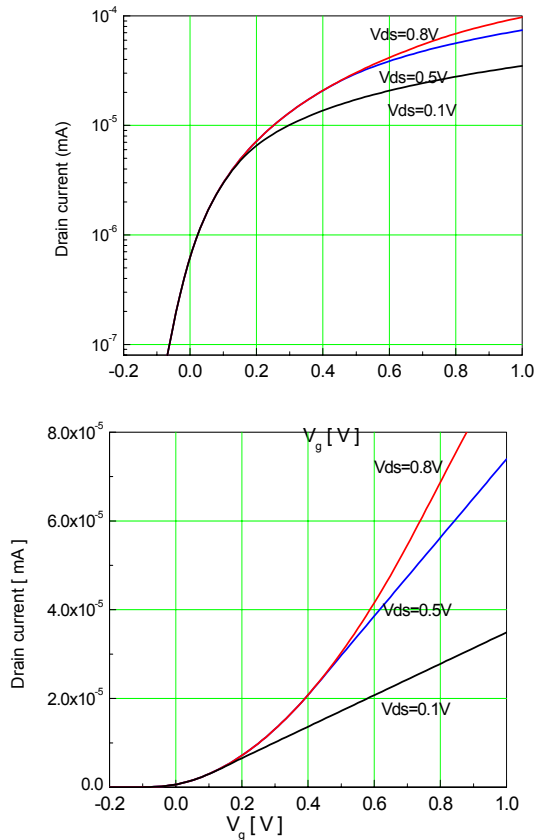
Volume inversion demonstration and charge as a function of gate voltage and channel voltage

SURFACE POTENTIAL VS. BIAS



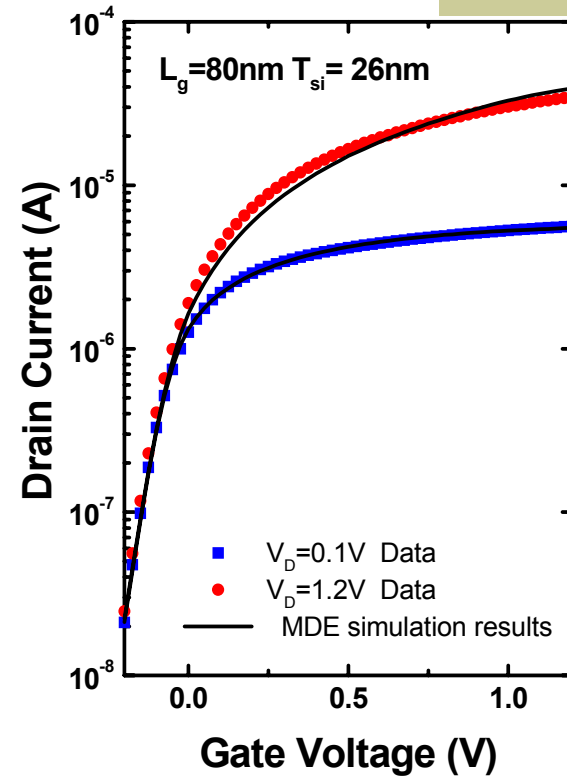
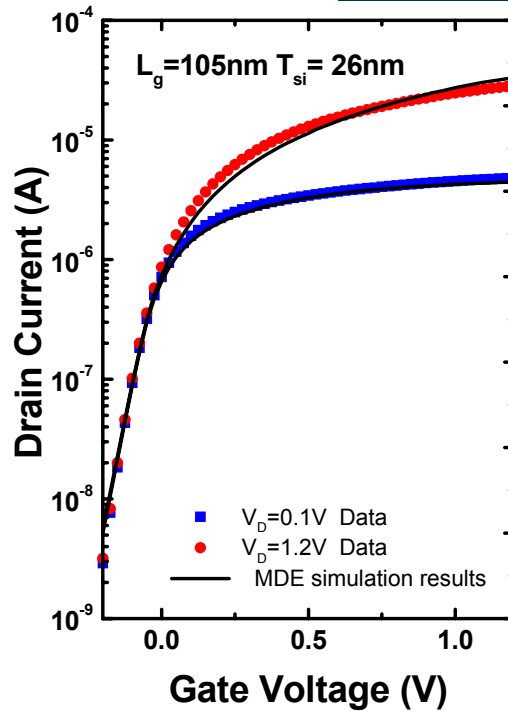
Surface potential versus gate voltage with different oxide thickness and channel voltage for DG .

I-V PREDICTION



The drain current versus the gate and drain voltage for a 10um DG undoped MOSFETs.

VERIFICATION OF MODEL



Comparison between the analytical model and AMD double-gate data.

SUMMARY

- ◆ Physical model for DG MOSFET developed
- ◆ Exact and approximate solution are derived
- ◆ Model results are discussed and verified

- ◆ Model equations of DG take quite formulation with bulk model of SPP, which can share the same modular for SCE, QME, GDE, et., great simplifying compact modeling structure for various MOSFETs.

- ◆ We can expect SOI, UTB, SG and Multiple-gate also take the same model master equation from the device physics and theory derivation

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