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Unification of MOS Compact Models with the Unified Regional Modeling Approach

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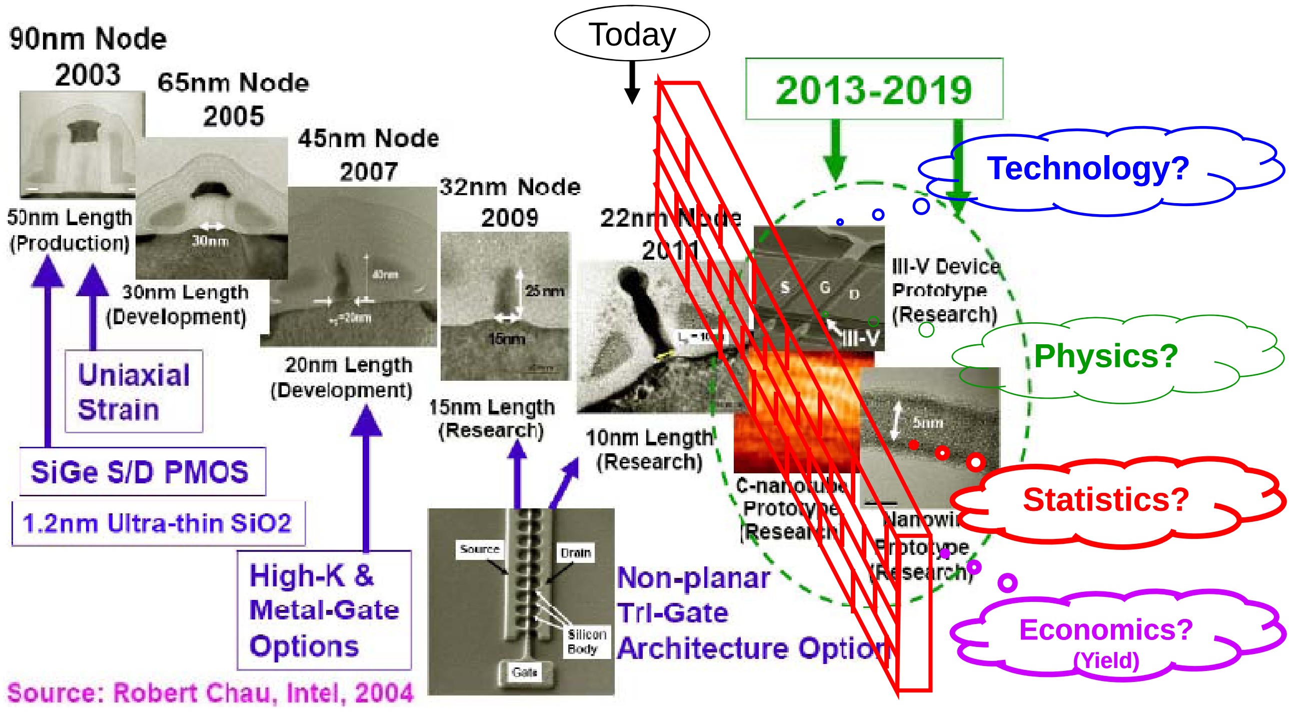
Outline

- **Motivation for MOS Model Unification**
- **Unified Regional Modeling (URM) Approach**
  - **Surface potential of generic MOSFET for bulk/SOI/DG/GAA**
  - **Body doping and thickness scaling**
  - **Model symmetry and asymmetric MOS modeling**
- **Model Extension to SB/DSS Modeling**
  - **Shottky-barrier (SB) MOS with ambipolar transport**
  - **Dopant-segregated Shottky (DSS) MOS with subcircuit approach**
- **Xsim Model Summary**

CMOS Technology Generations and Scaling Limits



Today

90nm Node 2003 — 50nm Length (Production)

65nm Node 2005 — 30nm Length (Development)

45nm Node 2007 — 20nm Length (Development)

32nm Node 2009 — 15nm Length (Research)

22nm Node 2011 — 10nm Length (Research)

2013-2019

III-V Device Prototype (Research)

C-nanotube Prototype (Research)

Nanowire Prototype (Research)

Uniaxial Strain

SiGe S/D PMOS

1.2nm Ultra-thin SiO2

High-K & Metal-Gate Options

Non-planar Tri-Gate Architecture Option

Technology?

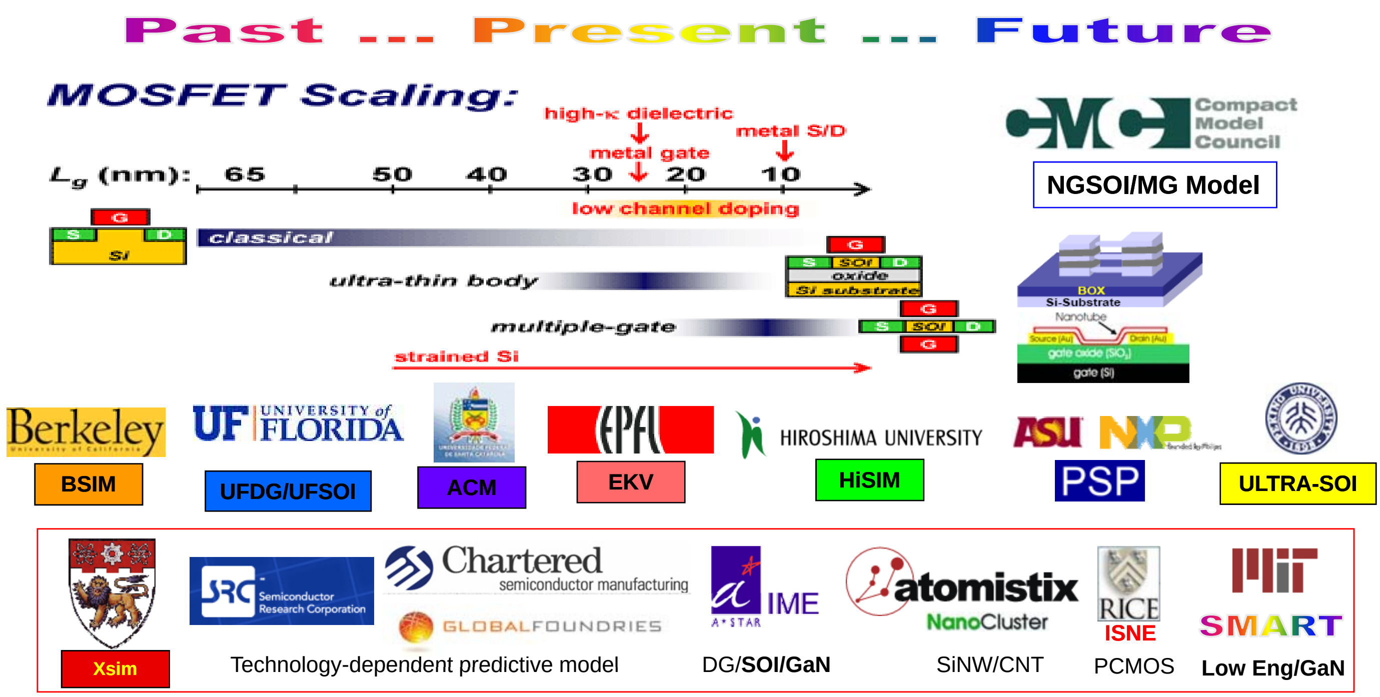
Physics?

Statistics?

Economics? (Yield)

Source: Robert Chau, Intel, 2004

Models and Modeling Groups



Past ... Present ... Future

MOSFET Scaling:

L_g (nm): 65 50 40 30 20 10

high-κ dielectric

metal gate

metal S/D

low channel doping

classical

ultra-thin body

multiple-gate

strained Si

Compact Model Council

NGSOI/MG Model

Berkeley	UF University of Florida		EPFL	Hiroshima University	ASU NXP	
BSIM	UFDG/UFSOI	ACM	EKV	HiSIM	PSP	ULTRA-SOI

Xsim

SRC Semiconductor Research Corporation; Chartered semiconductor manufacturing; GLOBALFOUNDRIES — Technology-dependent predictive model

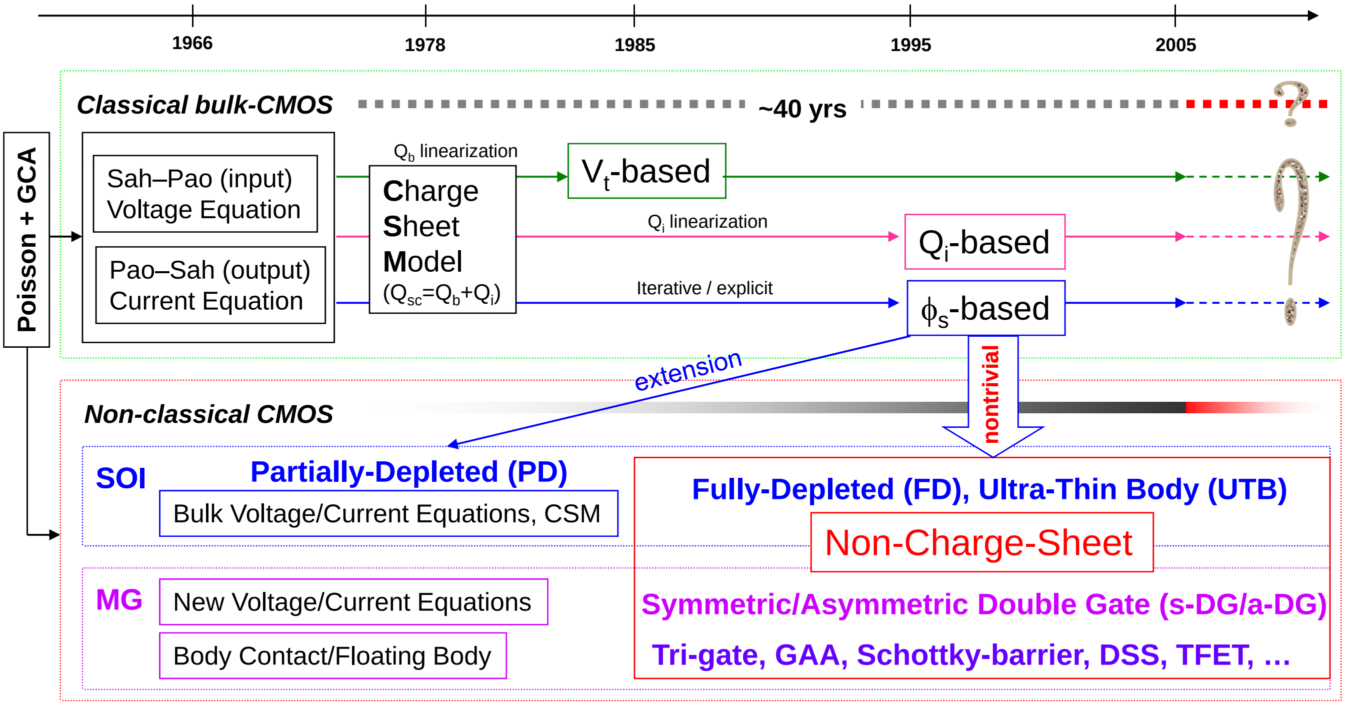
A*STAR IME — DG/**SOI/GaN**

atomistix NanoCluster — SiNW/CNT

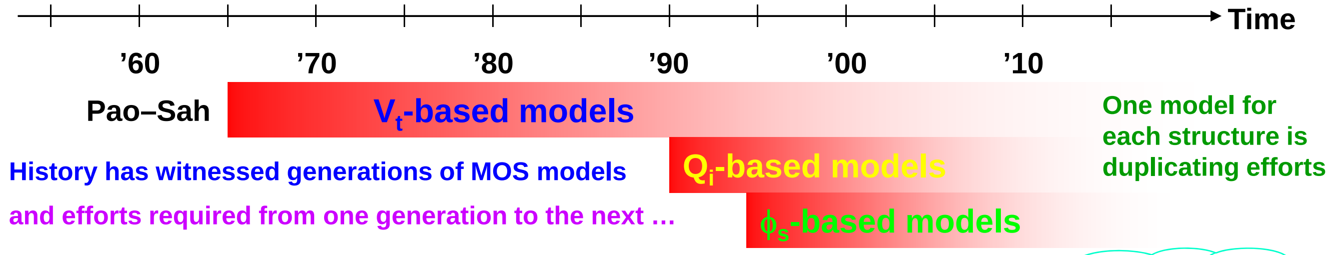
RICE ISNE — PCMOS

MIT SMART — **Low Eng/GaN**

MOSFET Compact Models: History and Future



Need for an Extendable Core Model for Future Generation



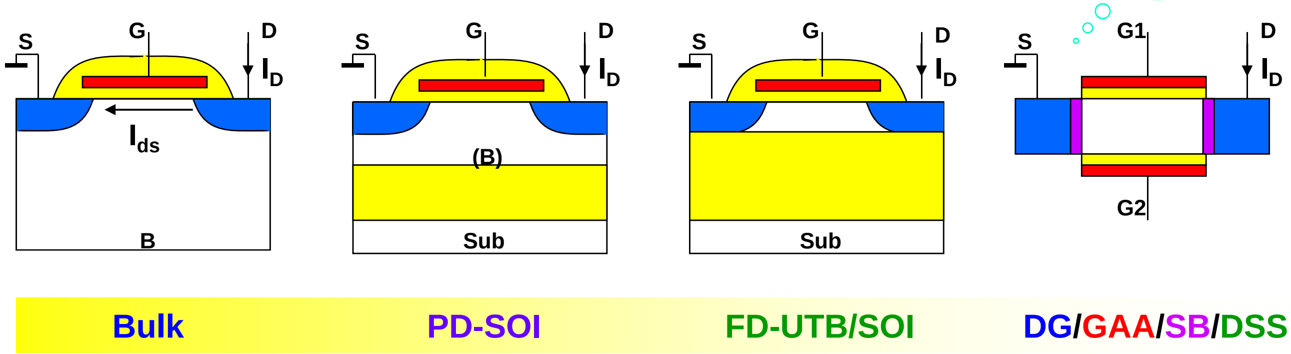
One model for each structure is duplicating efforts

History has witnessed generations of MOS models

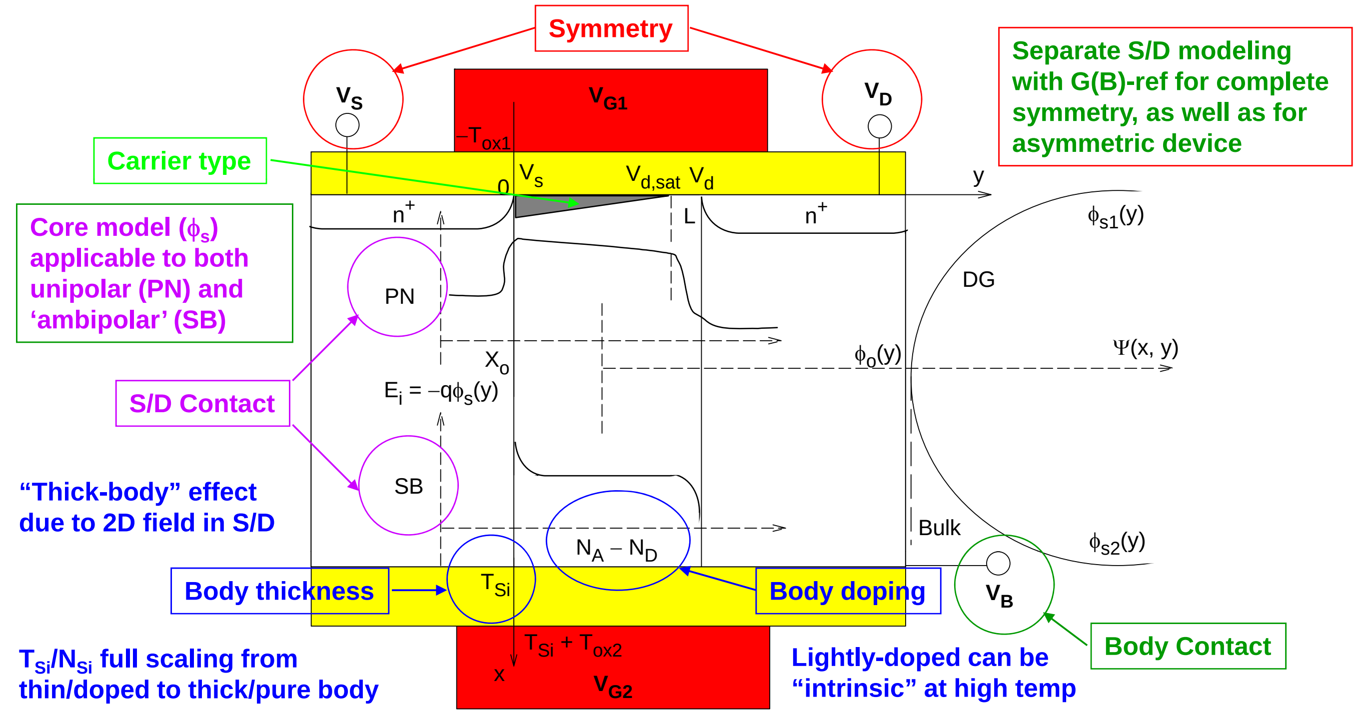
and efforts required from one generation to the next …

— Need for a core model *extendable* to future generations, and with less duplicating efforts

MG/FinFET is just a special case



New Challenges in SOI/MG/GAA MOSFET Modeling



Symmetry

Separate S/D modeling with G(B)-ref for complete symmetry, as well as for asymmetric device

Carrier type

Core model (ϕ_s) applicable to both unipolar (PN) and 'ambipolar' (SB)

S/D Contact

"Thick-body" effect due to 2D field in S/D

Body thickness

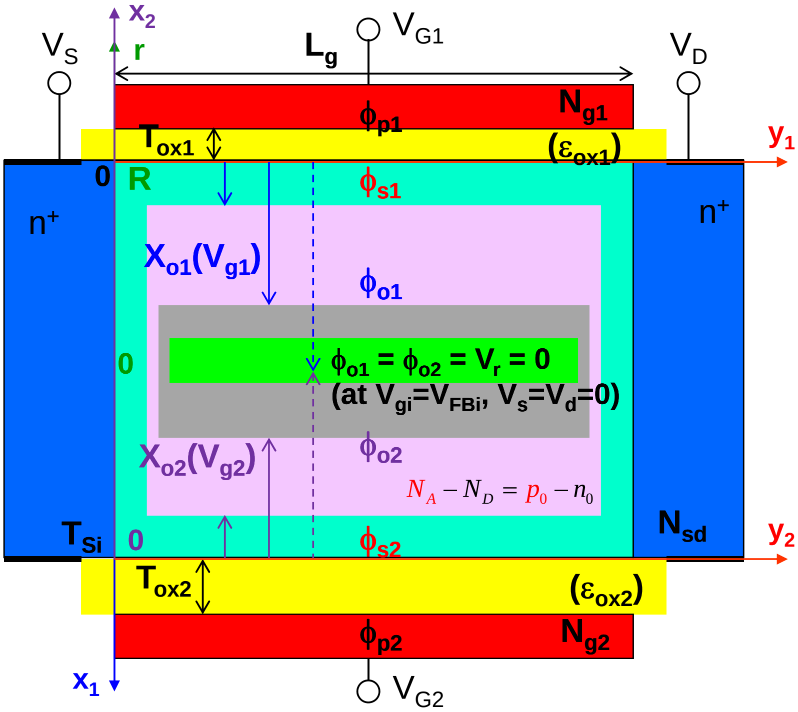
Body doping

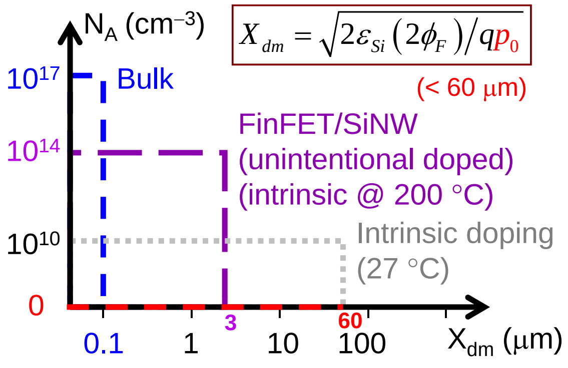
Body Contact

T_{Si}/N_{Si} full scaling from thin/doped to thick/pure body

Lightly-doped can be "intrinsic" at high temp

Generic Double-Gate MOSFET with Any Body Doping





$$X_{dm} = \sqrt{2\varepsilon_{Si}\left(2\phi_F\right)/qp_0}$$

(< 60 μm)

($N_A = N_D = 0$: undoped = "pure" Si)

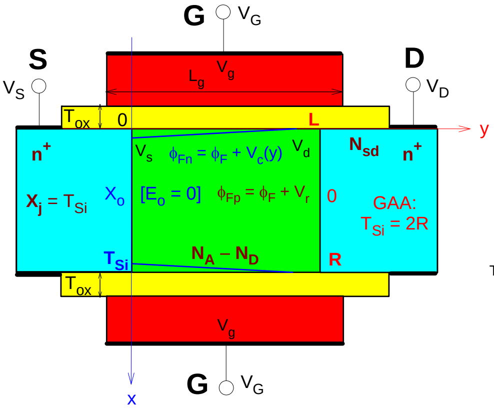
Bulk: $T_{Si} >> X_{dm}$, with BC: $\phi_o = V_b = V_B$

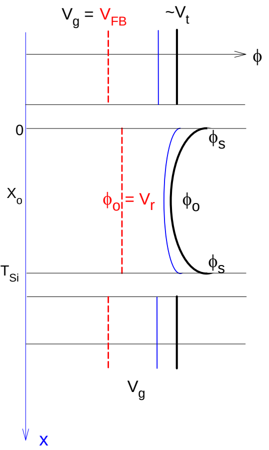
SOI: $T_{Si} > X_{dm}$, without BC: ϕ_o **'floating'**

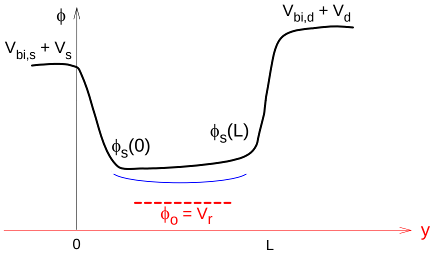
DG/GAA: $\frac{T_{Si}}{2}/R << X_{dm}$: **'volume inversion'**

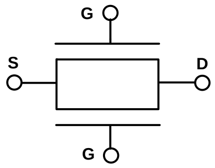
(ϕ_o: 'virtual electrode')

DG FinFETs / GAA SiNWs



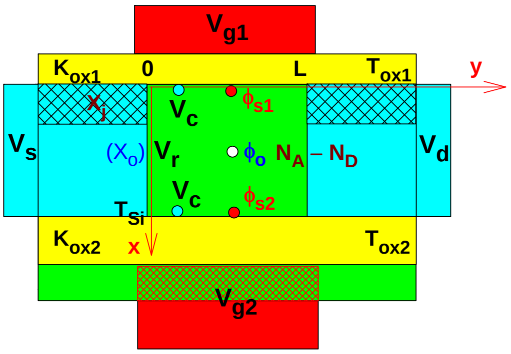






- ☐ **In undoped 'long'/thick-body DG/GAA, potential reference (V_r) is at one point: ϕ_o at $V_{gr} = V_{FB}$ and $V_{ds} = 0$**
  - ➢ **"Volume inversion" for $V_{FB}<V_{gr}<V_t$: ϕ_o follows V_g**
  - ➢ **"Strong inversion" for $V_{gr}>V_t$**
- ☐ **In 'short'/thick-body DG/GAA, source/drain (S/D) region 2D fields extend to the channel, causing V_{FB} to be T_{Si} dependent**
- ☐ **'Thin-body' DG/GAA have 'long'-channel behaviors**

The Generic SOI/DG/GAA MOSFET



Zero-field potential: ϕ_o $[\phi_o'(X_o) = 0]$

Imref-split: $V_{cr} = \phi_{Fn} - \phi_{Fp} = V_c - V_r$

$V_r = V_b$ (BC: body-contacted)
$V_r = V_{min} = \min(V_s, V_d)$ ("FB": w/o BC)

- ➢ **Bulk**: special case of s-DG
- ➢ **SOI**: special case of ia-DG

☐ Common/symmetric-DG [GAA]

- $V_{g1} = V_{g2} = V_g$: two gates with one bias
- $C_{ox1} = C_{ox2}$: **s-DG** ($X_o = T_{Si}/2$; [R])
- **Full-depletion**: $V_{FD} = V_g(X_d=T_{Si}/2)$
- $C_{ox1} \neq C_{ox2}$: **ca-DG** ($X_o < T_{Si}$)

☐ Independent/asymmetric-DG

- $V_{g1} \neq V_{g2}$: **ia-DG**, biased independently
- Zero-field location may be outside body
- Consider two "independent" gates; linked through **full-depletion** condition:
  $\boxed{X_{d1} + X_{d2} = T_{Si}}$

☐ Unification of MOS

- SOI ← $\boxed{\text{ia-DG}}$ ↔ ca-DG ↔ $\boxed{\text{s-DG}}$ → bulk ($\text{s-DG} \uparrow$ GAA)

The Poisson–Boltzmann Equation and Solution

GCA: $\frac{d^2\phi}{dy^2} << \frac{d^2\phi}{dx^2}$

$$\boxed{\begin{aligned}\frac{d^2\phi}{dx^2} &= -\frac{\rho}{\varepsilon_{Si}} = -\frac{q\left(p-n+N_D-N_A\right)}{\varepsilon_{Si}} = \frac{q}{\varepsilon_{Si}}\left(n-p+N_A-N_D\right)\\ &= \frac{qp_0}{\varepsilon_{Si}}\left[e^{(\phi-2\phi_F-V_c)/v_{th}} - e^{-(\phi-V_b)/v_{th}} + 1 - e^{-(2\phi_F+V_{cb})/v_{th}}\right] \equiv \frac{qp_0}{\varepsilon_{Si}}G\left(\phi,V_{cb}\right)\end{aligned}}$$

Charge neutrality:

$$\boxed{\begin{aligned}p_0-n_0 &= N_A-N_D\\ &= n_i\left(e^{\phi_F/v_{th}} - e^{-\phi_{Fn}/v_{th}}\right)\end{aligned}}$$

$$n = n_i e^{(\phi-\phi_{Fn})/v_{th}}$$

$$p = n_i e^{-(\phi-\phi_{Fp})/v_{th}}$$

$$n_0 \equiv n\big|_{\phi=V_b} = n_i e^{-(\phi_F+V_{cb})/v_{th}} \qquad p_0 \equiv p\big|_{\phi=V_b} = n_i e^{\phi_F/v_{th}} = n_i \exp\left[\sinh^{-1}\left(\frac{N_A-N_D}{2n_i}\right)\right]$$

B.C.'s: $\left(X_o >> X_{dm}\right)$

$$\boxed{\begin{aligned}&\phi\left(0,y\right)=\phi_s\left(y\right),\ E_x\left(0,y\right)=E_s\left(y\right)\\ &\phi\left(X_o,y\right)=V_b=0,\ E_x\left(X_o,y\right)=0\end{aligned}}$$

$$\phi_{Fp} = \phi_F + V_b \qquad \frac{d^2\phi}{dx^2} = -\frac{dE_x}{dx} = -\frac{dE_x}{d\phi}\frac{d\phi}{dx} = E_x\frac{dE_x}{d\phi} \qquad E_x = -\frac{d\phi}{dx}$$

$$\phi_{Fn} = \phi_F + V_c$$

$$v_{th} = kT/q \qquad \frac{E_s^2}{2} = \int_0^{E_s} E_x dE_x = \int_0^{\phi_s}\frac{d^2\phi}{dx^2}d\phi = \frac{qp_0}{\varepsilon_{Si}}\int_0^{\phi_s} G\left(\phi,V_{cb}\right)d\phi \qquad F_s\left(\phi_s,V_{cb}\right) \equiv \left[\int_0^{\phi_s} G\left(\phi,V_{cb}\right)d\phi\right]^{1/2}$$

$$\boxed{E_s^2 = \frac{2qp_0}{\varepsilon_{Si}}\left\{e^{-(2\phi_F+V_{cb})/v_{th}}\left[v_{th}\left(e^{\phi_s/v_{th}}-1\right)-\phi_s\right]+v_{th}\left(e^{-\phi_s/v_{th}}-1\right)+\phi_s\right\} \equiv \frac{2qp_0}{\varepsilon_{Si}}F_s^2\left(\phi_s,V_{cb}\right)}$$

$$\boxed{\Upsilon = \frac{\sqrt{2q\varepsilon_{Si}p_0}}{C_{ox}}}$$

$$\boxed{F_s\left(\varphi_s,v_{cb}\right) = \frac{E_s}{\sqrt{2qp_0/\varepsilon_{Si}}} = \operatorname{sgn}\left(\varphi_s\right)\sqrt{v_{th}\left[e^{-(2\varphi_F+v_{cb})}\left(e^{\varphi_s}-1-\varphi_s\right)+\left(e^{-\varphi_s}-1+\varphi_s\right)\right]}}$$

$$\varphi_s = \phi_s/v_{th}$$

$$\varphi_F = \phi_F/v_{th}$$

$$v_{cb} = V_{cb}/v_{th}$$

The Complete ("Sah–Pao") Voltage Equation

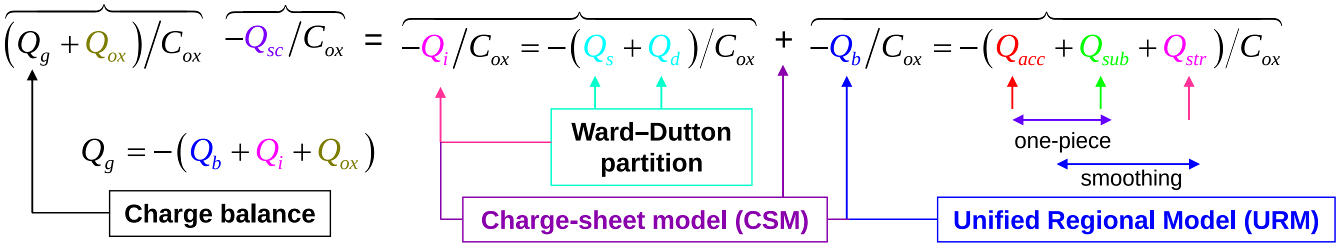
Gauss law: $\boxed{\varepsilon_{Si}E_s - \varepsilon_{ox}E_{ox} = Q_{ox}}$ $\boxed{\varepsilon_{ox}E_{ox} = Q_g}$ $\boxed{-\varepsilon_{Si}E_s = Q_{sc}}$ $\boxed{C_{ox} = \varepsilon_{ox}/T_{ox}}$

Potential balance: $\boxed{V_{gb} = \phi_{MS} + V_{ox} + \phi_s}$ $\boxed{V_{FB} = \phi_{MS} - Q_{ox}/C_{ox}}$ $\boxed{\Upsilon = \sqrt{2q\varepsilon_{Si}p_0}/C_{ox}}$ $\boxed{E_{ox} = V_{ox}/T_{ox}}$

Poisson

$$E_s = \frac{\varepsilon_{ox}E_{ox}+Q_{ox}}{\varepsilon_{Si}} = \frac{\varepsilon_{ox}\left(V_{ox}/T_{ox}\right)+Q_{ox}}{\varepsilon_{Si}} = \frac{C_{ox}\left(V_{gb}-\phi_{MS}-\phi_s\right)+Q_{ox}}{\varepsilon_{Si}} = \frac{C_{ox}\left(V_{gb}-V_{FB}-\phi_s\right)}{\varepsilon_{Si}}$$

$$\boxed{\begin{aligned}V_{gb}-V_{FB}-\phi_s &= \operatorname{sgn}\left(\phi_s\right)\Upsilon\sqrt{f_\phi} \qquad \left(n\right) \qquad \left(p\right) \qquad \left(N_A\right) \qquad \left(N_D\right)\\ &= \operatorname{sgn}\left(\phi_s\right)\Upsilon\sqrt{v_{th}\exp\left(-\frac{2\phi_F+V_{cb}}{v_{th}}\right)\left[\exp\left(\frac{\phi_s}{v_{th}}\right)-1\right]+v_{th}\left[\exp\left(-\frac{\phi_s}{v_{th}}\right)-1\right]+\phi_s-\phi_s\exp\left(-\frac{2\phi_F+V_{cb}}{v_{th}}\right)}\end{aligned}}$$



$$\overbrace{\left(Q_g+Q_{ox}\right)/C_{ox}}\ \ \overbrace{-Q_{sc}/C_{ox}} = \overbrace{-Q_i/C_{ox} = -\left(Q_s+Q_d\right)/C_{ox}} + \overbrace{-Q_b/C_{ox} = -\left(Q_{acc}+Q_{sub}+Q_{str}\right)/C_{ox}}$$

$$Q_g = -\left(Q_b+Q_i+Q_{ox}\right)$$

Charge balance

Ward–Dutton partition

Charge-sheet model (CSM)

one-piece

smoothing

Unified Regional Model (URM)

The Surface-Potential Solutions – Piecewise Regional

$$\boxed{V_{gb} - V_{FB} - \phi_s = \mathrm{sgn}(\phi_s)\,\Upsilon\sqrt{f_\phi}} \quad = \begin{cases} -\Upsilon\sqrt{v_{th} e^{-\phi_s/v_{th}}} & (V_{gb} \ll V_{FB}),\ \text{Accumulation} \\ +\Upsilon\sqrt{\phi_s} & (V_{FB} < V_{gb} < V_t),\ \text{Depletion} \\ +\Upsilon\sqrt{v_{th} e^{-(2\phi_F + V_{cb})/v_{th}} e^{\phi_s/v_{th}}} & (V_{gb} \gg V_t),\ \text{Strong inversion} \end{cases}$$

❑ Piecewise regional solutions

$$\phi_s = \begin{cases} \phi_{cc} = V_{gb} - V_{FB} + 2v_{th}\mathcal{L}\{W_{cc}\} & (V_{gb} \ll V_{FB}),\ \text{Only holes, } p \\ \phi_{dd} = \left(-\dfrac{\Upsilon}{2} + \sqrt{\dfrac{\Upsilon^2}{4} + V_{gb} - V_{FB}}\right)^2 & (V_{FB} < V_{gb} < V_t),\ \text{Only acceptors, } N_A \\ \phi_{ss} = V_{gb} - V_{FB} - 2v_{th}\mathcal{L}\{W_{ss}\} & (V_{gb} \gg V_t),\ \text{Only electrons, } n \end{cases}$$

$$W_{cc} = \frac{\Upsilon}{2\sqrt{v_{th}}}\exp\left(-\frac{V_{gb} - V_{FB}}{2v_{th}}\right)$$

$$W_{ss} = \frac{\Upsilon}{2\sqrt{v_{th}}}\exp\left(\frac{V_{gb} - V_{FB} - 2\phi_F - V_{cb}}{2v_{th}}\right)$$

$\mathcal{L}\{W\}$ is the **Lambert W** function, which is the solution of the equation: $\exp(X) + aX + B = 0$

where $X_{cc} = \dfrac{-\phi_{cc}}{2v_{th}}, B_{cc} = \dfrac{V_{gb} - V_{FB}}{\Upsilon\sqrt{v_{th}}},\quad X_{ss} = \dfrac{\phi_{ss} - 2\phi_F - V_{cb}}{2v_{th}}, B_{ss} = -\dfrac{V_{gb} - V_{FB} - 2\phi_F - V_{cb}}{\Upsilon\sqrt{v_{th}}},$ and $W = \dfrac{1}{a}\exp\left(-\dfrac{B}{a}\right), a = \dfrac{2\sqrt{v_{th}}}{\Upsilon}$

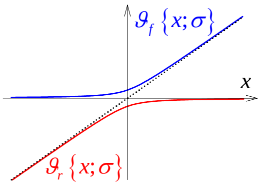
The Surface-Potential Solutions – Unified Regional

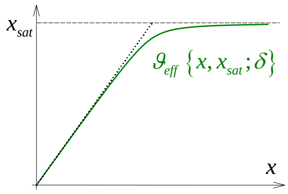
❑ Smoothing and transition functions

$$\vartheta_f\{x;\sigma\} \equiv 0.5\left(x + \sqrt{x^2 + 4\sigma}\right)$$

$$\vartheta_r\{x;\sigma\} \equiv 0.5\left(x - \sqrt{x^2 + 4\sigma}\right)$$

$$\vartheta_{eff}\{x, x_{sat}; \delta\} \equiv x_{sat} - 0.5\left[x_{sat} - x - \delta + \sqrt{(x_{sat} - x - \delta)^2 + 4\delta x_{sat}}\right]$$





❑ Unified regional solutions

$$\phi_s = \begin{cases} \phi_{acc} = \phi_{cc}\big|_{V_{gb} - V_{FB} = V_{gbr}} = V_{gbr} + 2v_{th}\mathcal{L}\{W_{cc}\} \\ \phi_{sub} = \phi_{dd}\big|_{V_{gb} - V_{FB} = V_{gbf}} = \left(-\dfrac{\Upsilon}{2} + \sqrt{\dfrac{\Upsilon^2}{4} + V_{gbf}}\right)^2 \\ \phi_{str} = \phi_{ss}\big|_{V_{gb} - V_{FB} = V_{gbf}} = V_{gbf} - 2v_{th}\mathcal{L}\{W_{ss}\} \end{cases}$$

$$V_{gbr} = \vartheta_r\{V_{gb} - V_{FB}; \sigma_a\} \qquad \boxed{V_{gbr} + V_{gba} \equiv V_{gb} - V_{FB}}$$

$$V_{gbf} = \vartheta_f\{V_{gb} - V_{FB}; \sigma_f\} \qquad V_{gba} = \vartheta_f\{V_{gb} - V_{FB}; \sigma_a\}$$

- Turn σ_f to satisfy charge neutrality $\phi_s(V_{FB}) = 0$;
- Tune σ_a for smoothness at $V_{gb} = V_{FB}$.

❑ Single-piece unified solutions

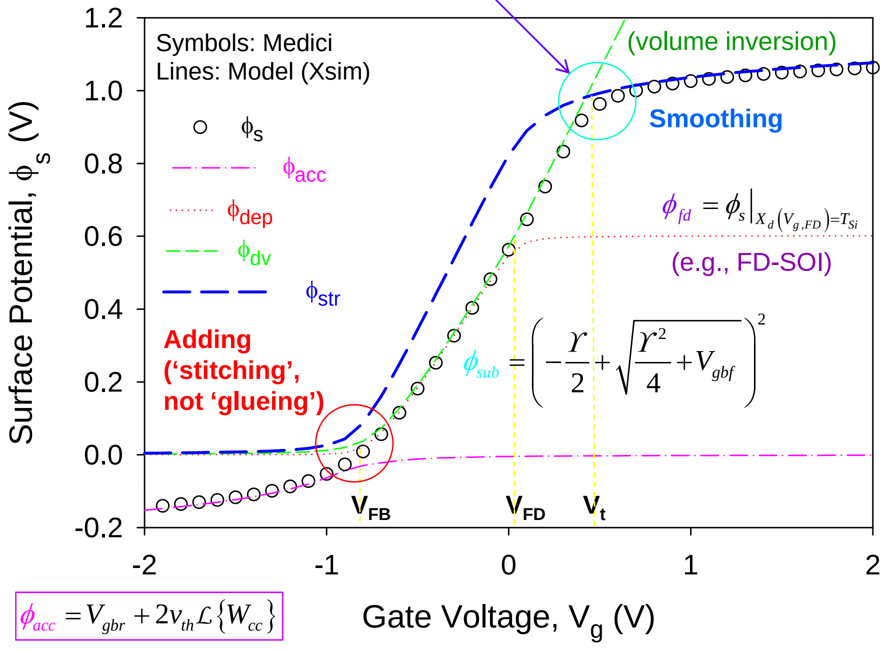
$$\boxed{\phi_{ds} = \vartheta_{eff}\{\phi_{sub}, \phi_{str}; \delta_\phi\}} \qquad \boxed{\phi_{sa} = \phi_{acc} + \phi_{sub}} \qquad \boxed{\phi_{seff} = \phi_{acc} + \phi_{ds}}$$

The Surface Potential: Unified Regional Modeling (URM)

$\phi_{ds} = \vartheta_{eff}\left\{\phi_{dv}, \phi_{str}; \delta_{\phi}\right\}$

$\phi_{dv} = V_g - V_{FB} + \Upsilon\sqrt{\phi_{dep}}$

$\boxed{\phi_{seff} = \phi_{acc} + \phi_{ds}}$ Single piece



$\phi_{fd} = \phi_s\big|_{X_d(V_{g,FD})=T_{Si}}$

(e.g., FD-SOI)

$\phi_{sub} = \left(-\frac{\Upsilon}{2} + \sqrt{\frac{\Upsilon^2}{4} + V_{gbf}}\right)^2$

$\phi_{acc} = V_{gbr} + 2v_{th}\mathcal{L}\left\{W_{cc}\right\}$

$\phi_{str} = V_{gbf} - 2v_{th}\mathcal{L}\left\{W_{ss}\right\}$

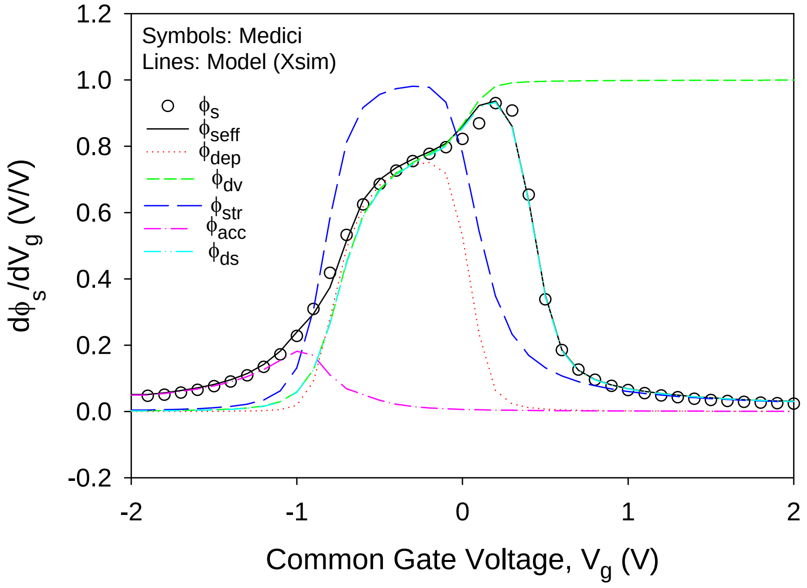
$V_{cb}(y)$ dependent

$\phi_{dep} = \vartheta_{eff}\left\{\phi_{sub}, \phi_{fd}; \delta_d\right\}$

T_{Si} and N_A dependent

ϕ_s at $V_{gb} = V_{FB}$ is not solved exactly, but two pieces are "**stitched**" (rather than "**glued**") to form a single-piece (ϕ_{seff}) seamlessly. "Glued"/iterative solution requires retaining all the terms in the voltage equation.

Surface-Potential Derivatives and Regional Components

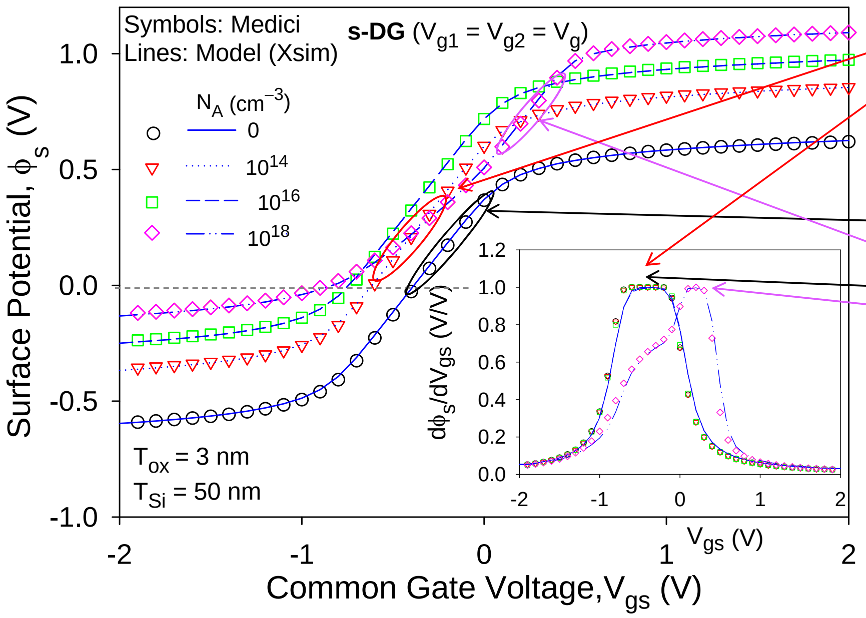


- ☐ **Regional solutions scale with body doping (N_A), body thickness (T_{Si}), oxide thickness (T_{ox}), and all terminal biases**
- ☐ **Smooth higher-order derivatives**
- ☐ **Regional charge model – key to physically-based parameter extraction**
- ☐ **Foundation to unification of MOS compact models (bulk/SOI/DG/NW/SB/DSS)**

X. Zhou, *et al.*, (invited review article), J. Comput. Electron., Mar. 2011.

http://www.springerlink.com/content/x8t0742r3m051650/

Doping-Dependent ϕ_s: "Depletion" vs. Volume Inversion



"Depletion" ($N_A = 10^{14}$)

Slope ≈ 1

$$\frac{d\phi_s}{dV_g} = 1 - \frac{\Upsilon}{2\sqrt{\Upsilon^2/4 + V_{grf}}} \approx 1$$

Volume inversion (undoped $N_A = 0$, or beyond full-depletion)

Slope = 1

- ❑ **"Low-doping depletion" and "zero-doping volume inversion" have similar behaviors but different physics**
- ❑ **Full-doping scaling (zero to high) is only possible to be modeled by the URM**

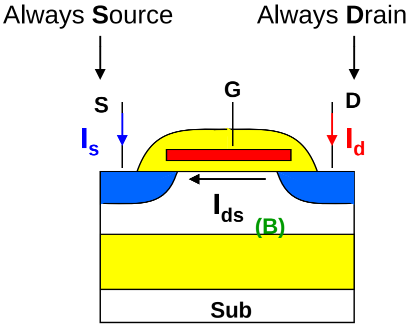
Paradigm Shift: B/G-reference and Source/Drain by Label

❑ **S/D by convention** (nMOS)

- $V_d > V_s$: $I_{ds} > 0$ ('D' → 'S')
- $V_d < V_s$: $I_{ds} > 0$ ('D' ↔ 'S')

- By convention, nMOS I_{ds} always flows from 'D' to 'S'
- Terminal swapping for $-V_{ds}$: involving $|V_{ds}|$ in model

❑ **S/D by label (layout)**



- $V_d > V_s$: $I_{ds} > 0$ (D → S)
- $V_d < V_s$: $I_{ds} < 0$ (S → D)

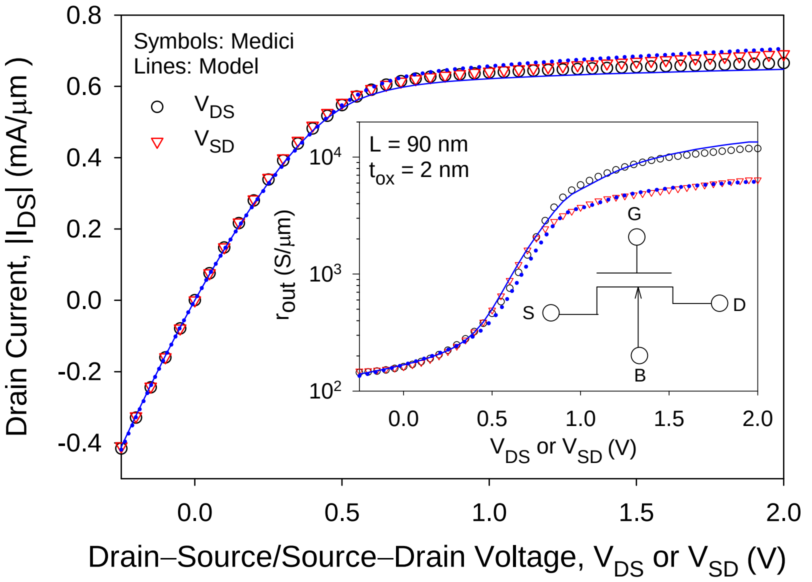
❑ **Effective drain–source voltage ($V_{ds,eff}$)**

FB: $\boxed{V_{ds,eff} = V_{d,eff} - V_{s,eff}}$ BC: $\boxed{V_{ds,eff} = V_{db,eff} - V_{sb,eff}}$

$$\boxed{\begin{aligned} I_{ds} &= \overline{\beta}\left(\overline{q_i} + \overline{A_b}v_{th}\right)V_{ds,eff} = I_d - I_s \\ &= \overline{\beta}\left(\overline{q_i} + \overline{A_b}v_{th}\right)V_{db,eff} - \overline{\beta}\left(\overline{q_i} + \overline{A_b}v_{th}\right)V_{sb,eff} \end{aligned}}$$

- ➢ **Key**: **Bulk/Ground-reference** — auto switch to B/G-ref when body-contact is biased or floating
- ➢ Intrinsic I_{ds} is an exact odd function of V_{ds}
- ➢ Physical modeling of asymmetric MOS (nontrivial with "terminal swapping" for negative V_{ds})

Modeling Asymmetric Source/Drain MOSFET



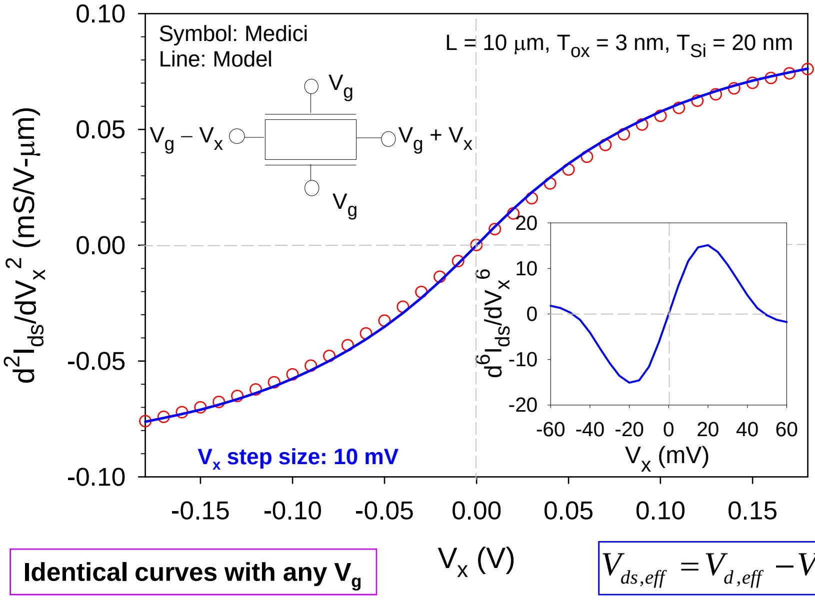
$X_{j,s}$ = 80 nm, $N_{D,s} = 10^{19}$ cm^{-3}; $X_{j,d}$ = 30 nm, $N_{D,d} = 10^{18}$ cm^{-3}

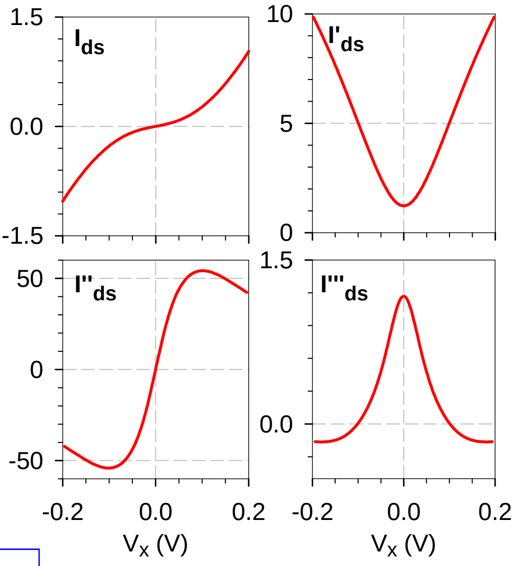
G. H. See, *et al.*, T-ED, 55(2), p. 624, Feb. 2008.

- ❑ **"Source" and "Drain" by label (rather than by MOS convention); i.e., V_{DS} and V_{SD} are different**
- ❑ **Structural asymmetry (e.g., X_j, N_D) can be captured by refitting physical parameters (e.g., $v_{sat,s}$ and $v_{sat,d}$)**
- ❑ **Models based on S/D terminal swapping for negative V_{ds} at circuit level can never model asymmetric device easily (need to have two sets of symmetric model parameters)**

Gummel Symmetry Test on Undoped s-DG Without BC

"Floating body" (without body contact): **<u>Key</u> – "ground-referenced" model**





Identical curves with any V_g

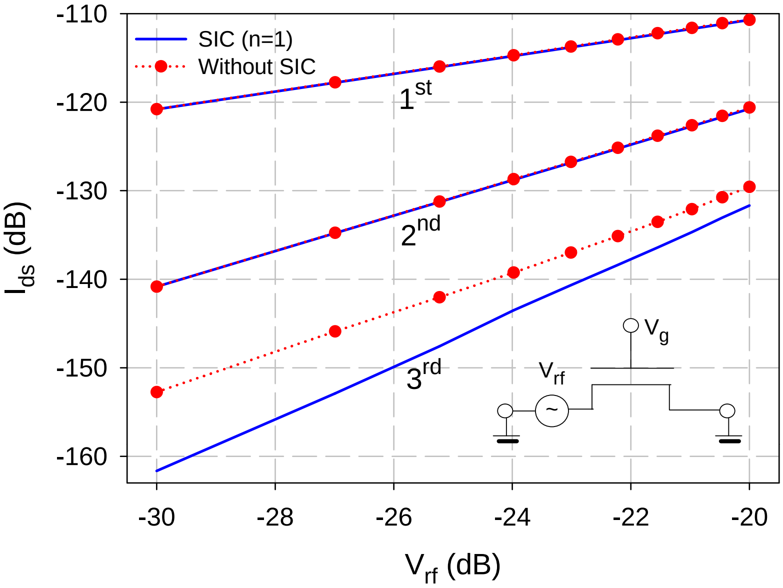
$$V_{ds,eff} = V_{d,eff} - V_{s,eff}$$

G. J. Zhu, *et al.*, T-ED, 55(9), p. 2526, 2008.

Harmonic-Balance Simulation

SIC: Symmetric Imref Correction

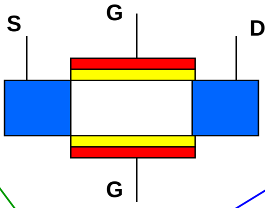
$$\phi_o = n v_{th}\left[\ln 2 - \ln\left(e^{-V_s/n v_{th}} + e^{-V_d/n v_{th}}\right)\right]$$



Undoped-Body DG FinFET vs. GAA SiNW

- **FinFET (DG)**

$$\frac{d^2\phi}{dx^2} = \frac{q n_i}{\varepsilon_{Si}} e^{(\phi - V_c)/v_{th}}$$



- **First integration**

$$\boxed{V_{gf} - \phi_s = \Upsilon_i \sqrt{v_{th}\left(e^{(\phi_s - V_c)/v_{th}} - e^{(\phi_o - V_c)/v_{th}}\right)}}$$

Ignore the ϕ_o term

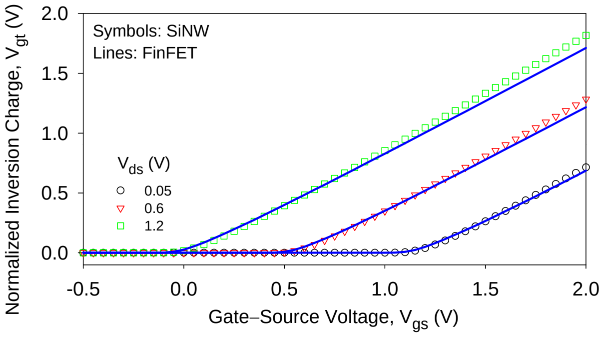
$$\boxed{\phi_s\left[V_c(y)\right] = V_{gf} - 2 v_{th}\mathcal{L}\left\{\frac{\Upsilon_i}{2\sqrt{v_{th}}} e^{\left(V_{gf} - V_c\right)/2 v_{th}}\right\}}$$

- **Second integration** $C_{ox} = \varepsilon_o K_{ox}/T_{ox}$

$$\boxed{V_{gt,c}(V_c) = \Upsilon_i \sqrt{v_{th} e^{\frac{\phi_s(V_c) - V_c}{v_{th}}}} \sin\left(\frac{\Upsilon_i C_{ox}}{\varepsilon_{Si}} \frac{T_{Si}}{4 v_{th}} \sqrt{v_{th} e^{\frac{\phi_o(V_c) - V_c}{v_{th}}}}\right)}$$

- **SiNW (GAA)**

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\phi}{dr}\right) = \frac{q n_i}{\varepsilon_{Si}} e^{(\phi - V_c)/v_{th}}$$



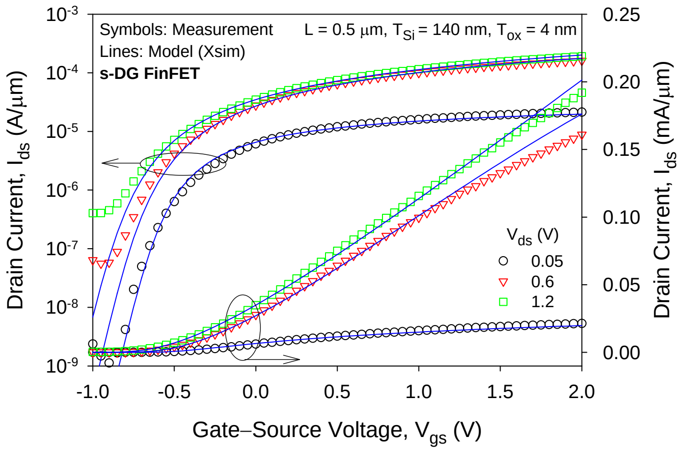
$C_{ox} = \varepsilon_o K_{ox}/R\ln\left(1 + T_{ox}/R\right)$

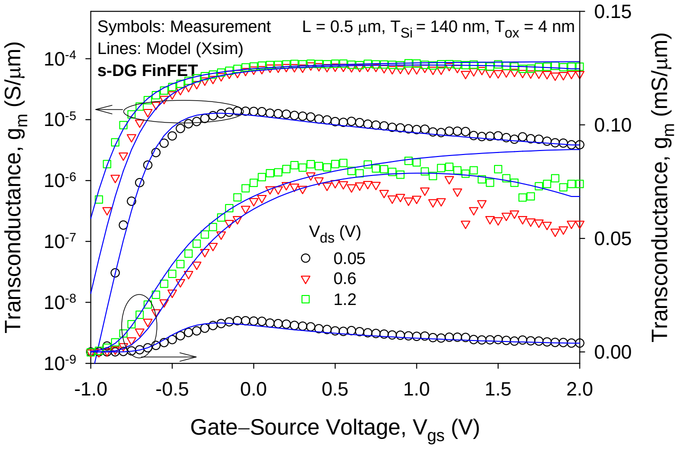
$$\boxed{V_{gt,c}(V_c) = \frac{R q n_i}{2 C_{ox}} e^{(\phi_s + \phi_o - 2V_c)/2 v_{th}}}$$

s-DG/FinFET: Short-Channel Transfer Characteristics

Transfer Ids–Vgs

Transfer gm–Vgs





Symmetric-DG FinFET model comparison with Measurement.

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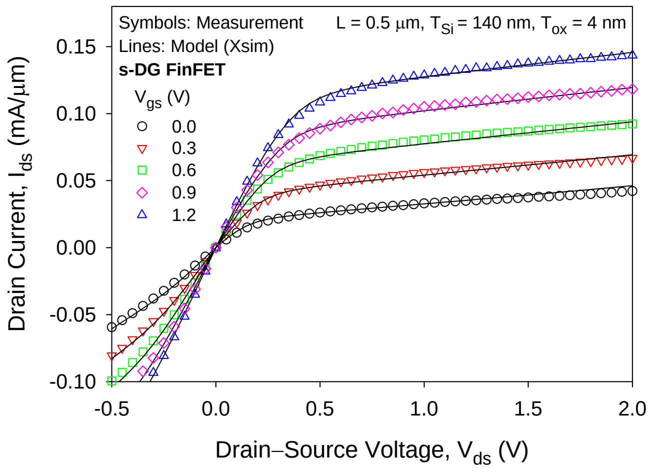
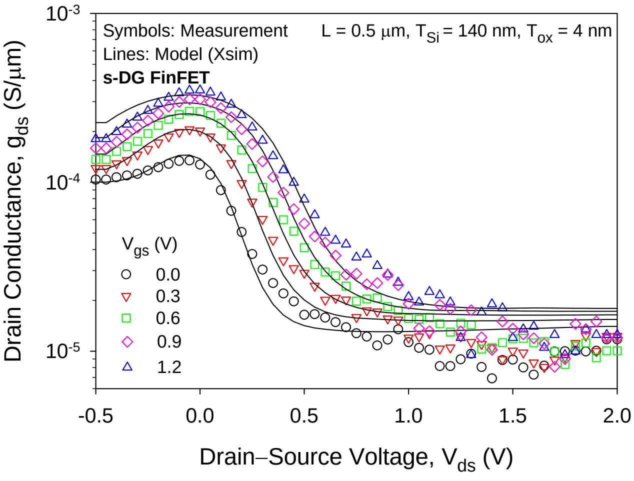
s-DG/FinFET: Short-Channel Output Characteristics

Output Ids–Vds

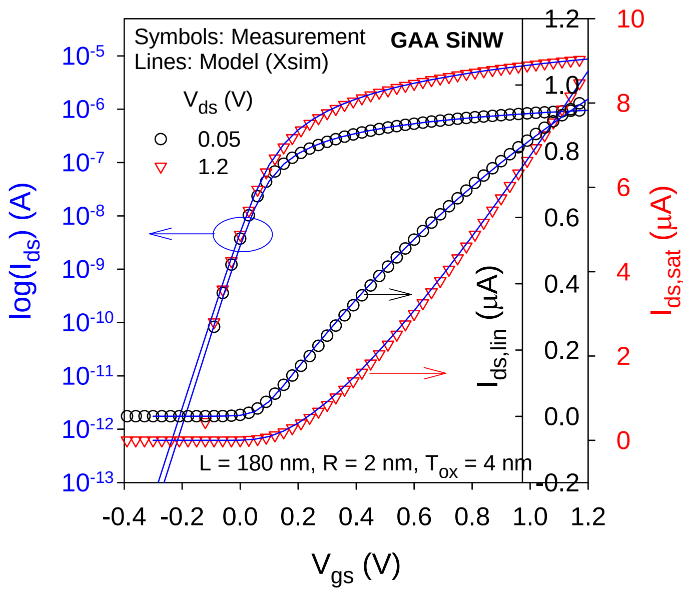
Output gds–Vds

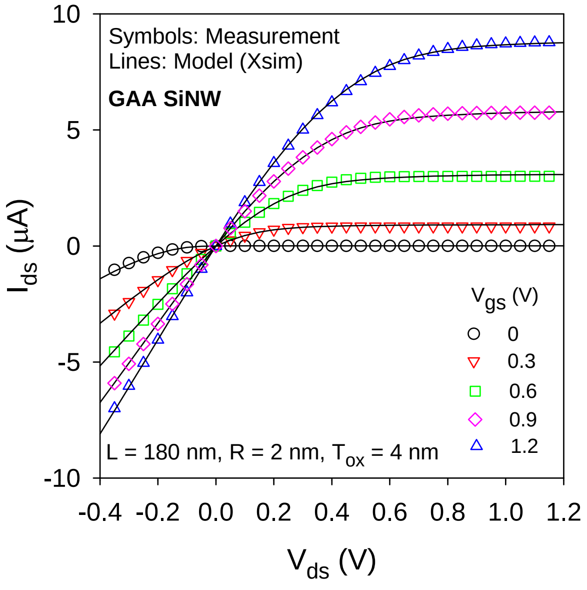




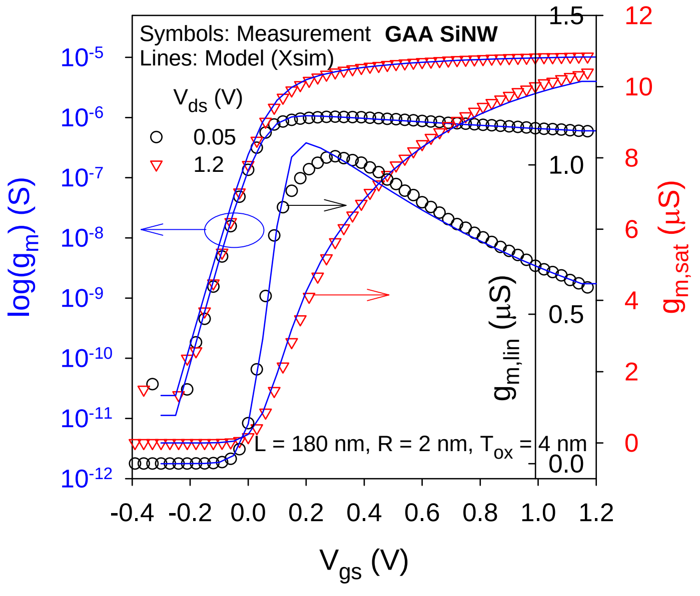
Symmetric-DG FinFET model comparison with Measurement.

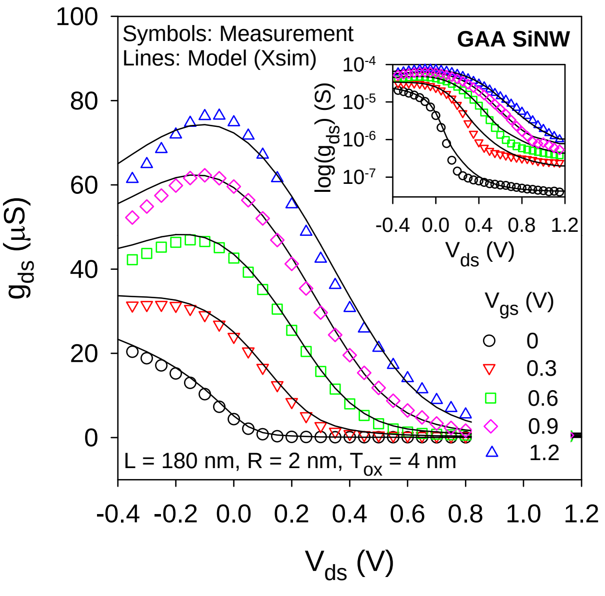
GAA: Model Comparison with Measurement



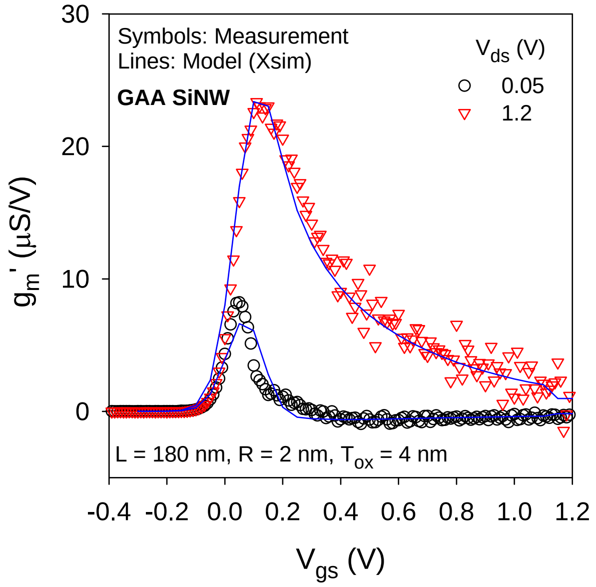


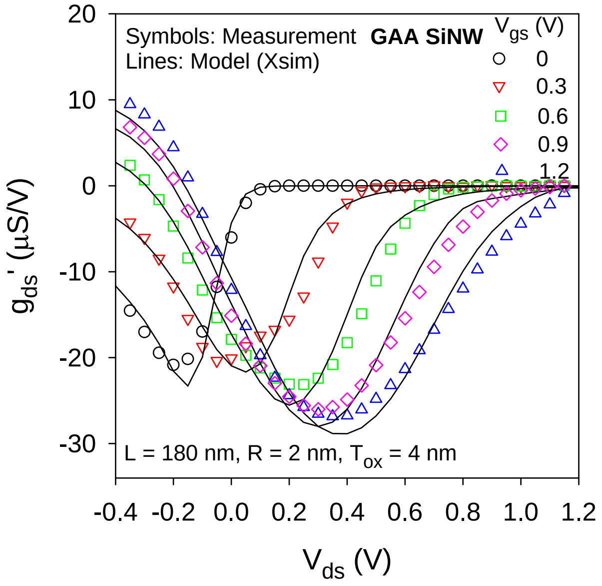
GAA: Model Comparison with Measurement (1st Derivative)



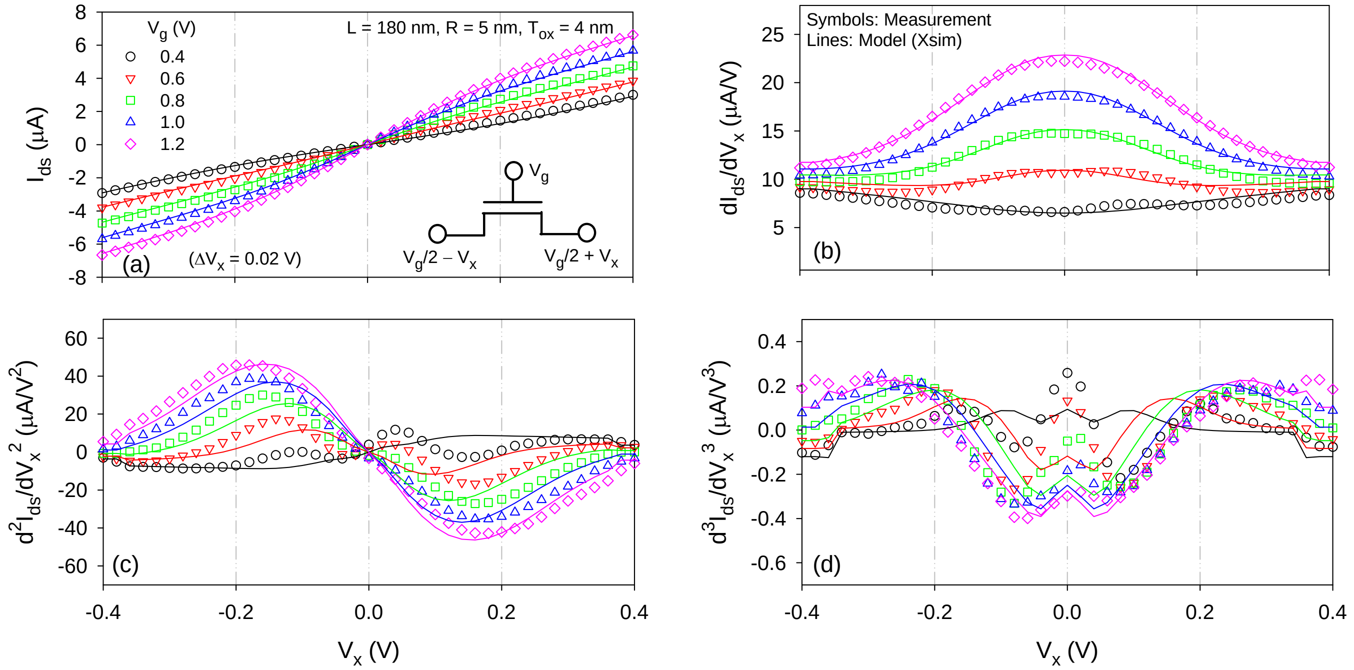


GAA: Model Comparison with Measurement (2nd Derivative)

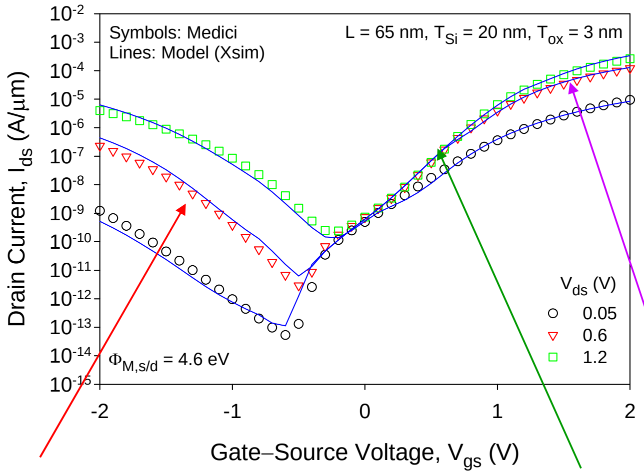


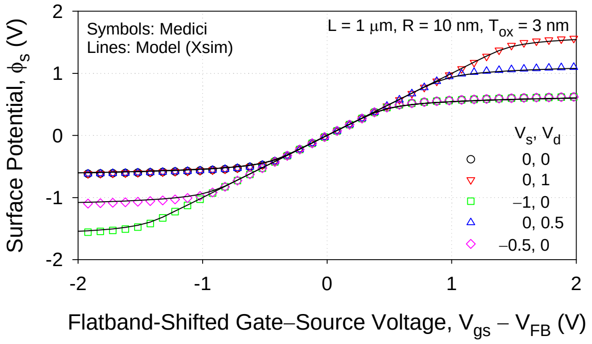


GAA: Measured Gummel Symmetry Test



Schottky-Barrier MOSFET: Ambipolar Current

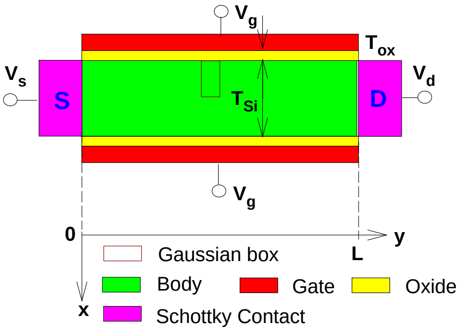




Hole tunneling

Electron thermionic

Electron tunneling

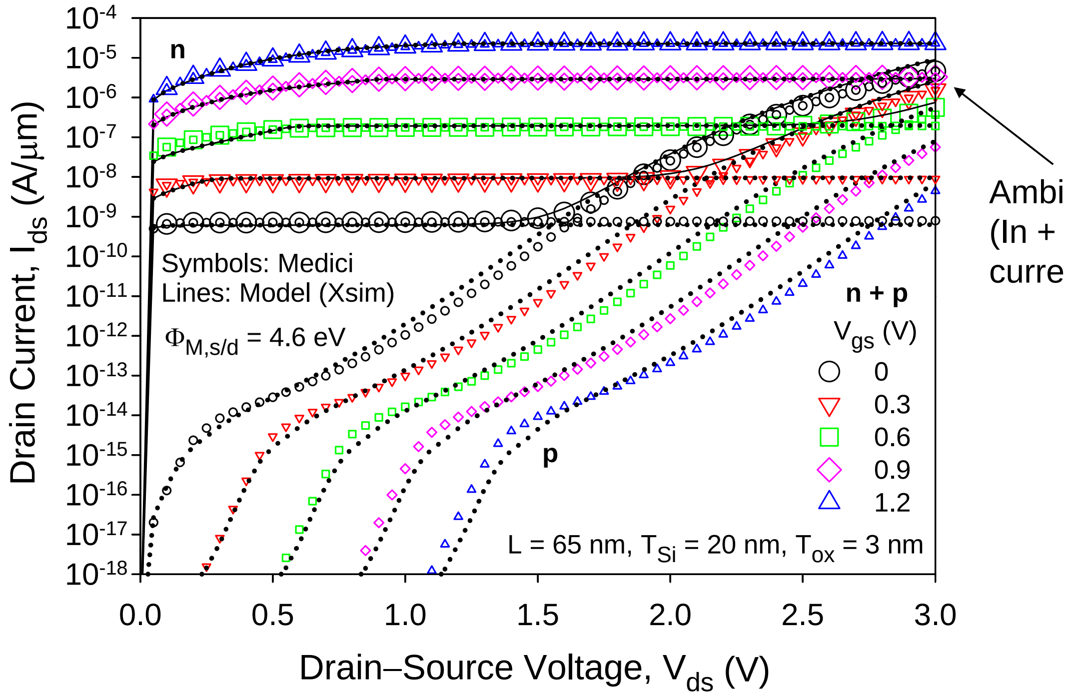


No drift-diffusion!

Ambipolar possible in undoped SB-MOS with mid-gap $\Phi_{M,s/d}$

- Medici: two-carrier
- Xsim: sum of two unipolar ($I_{ds,n} + I_{ds,p}$)

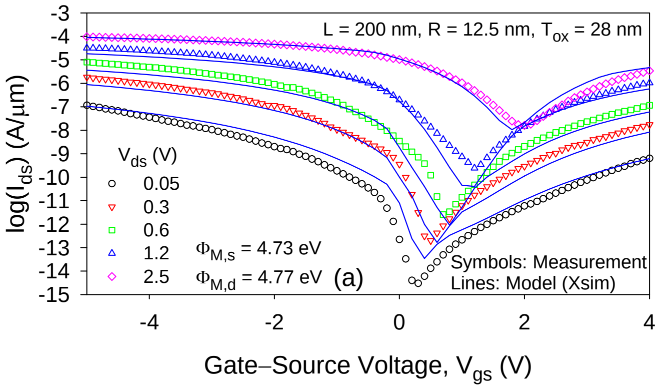
SB-MOS: Total Current = (Electron + Hole) Currents



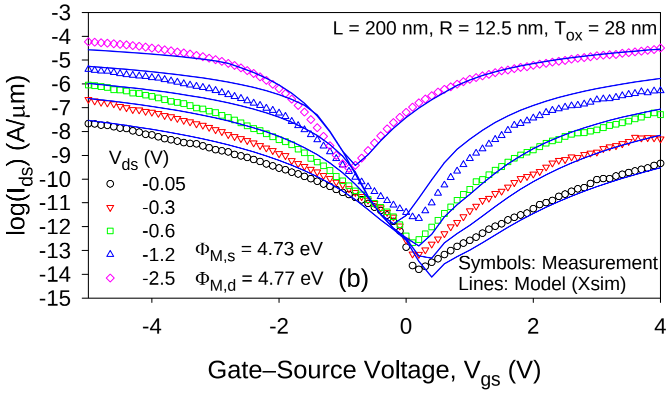
Ambipolar (In + Ip) current

SB-MOS: Model Applied to Measured SB-MOS

nMOS operation (+Vds)



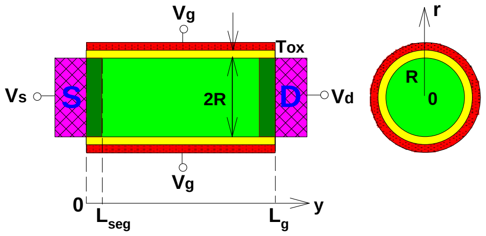
pMOS operation (–Vds)



SB-MOS model comparison with Measurement.
(Same model and same device with different bias)

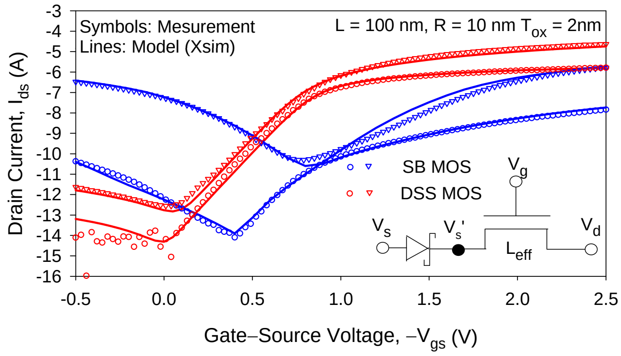
G. J. Zhu, *et al*., T-ED, 56(5), p. 1100, May 2009.

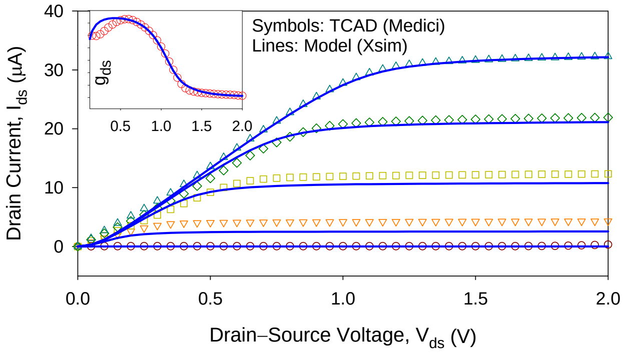
DSS-SiNW: Subcircuit Model



Dopant-Segregated Schottky (DSS) SiNW:

- Thermionic/tunneling (TT) + drift-diffusion (DD)
- The unique **convex** curvature in I_{ds}–V_{ds} can only be modeled by a subcircuit model: SBD (TT) + MOS (DD)

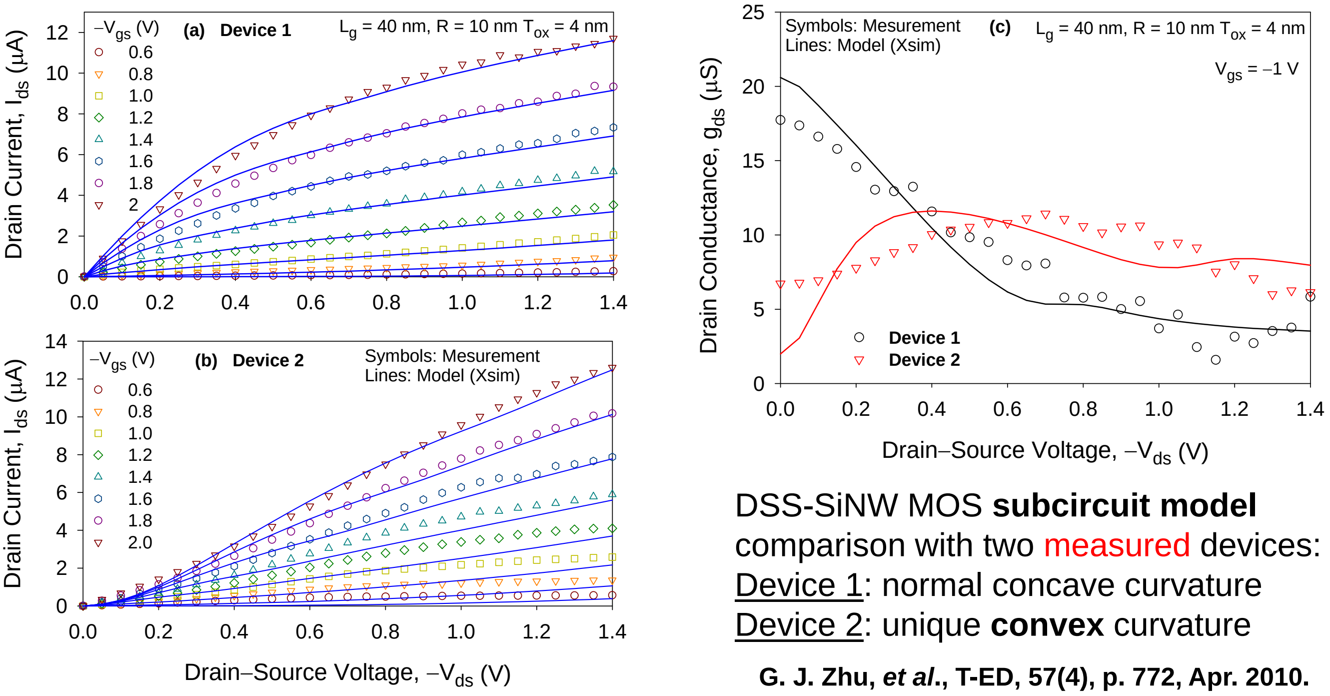




DSS-SiNW MOS **subcircuit model** comparison with Measurement.

G. J. Zhu, *et al*., SSDM, p. 402, Oct. 2009; T-ED, 57(4), p. 772, Apr. 2010.

DSS-SiNW: Subcircuit Model for Two Measured Devices



DSS-SiNW MOS **subcircuit model** comparison with two measured devices:

Device 1: normal concave curvature

Device 2: unique **convex** curvature

G. J. Zhu, *et al*., T-ED, 57(4), p. 772, Apr. 2010.

Xsim: Basic Bulk-MOS Model Parameters

Total: 33 basic parameters

(less for DG/GAA)

- ❑ **Physical parameters [6]**
  - Oxide thickness (T_{ox}), S/D junction depth (X_j)
  - Doping: channel (N_{ch}), gate (N_{gate}), S/D (N_{sd}), overlap (N_{ov})
- ❑ **AC/Poly/QM parameters [8]**
  - Bulk charge sharing (BCS): channel (λ_c), gate (λ_p), overlap (λ_{ov})
  - Potential barrier lowering (PBL): accumulation (α_{acc}), depletion/inversion (α_{ds})
  - Extrinsic: lateral spread (σ), inversion/bulk charge factor (ν_i, ν_b)
- ❑ **DC parameters [19]**
  - Mobility: vertical-field mobility (μ, μ_2, μ_3, ν)
  - Effective field: vertical (ζ_n, ζ_b), lateral (δ_L)
  - PBL: accumulation (α_{acc}), depletion/inversion (α_{ds}), long-channel DIBL (α_{dibl})
  - BCL/lateral-doping: BCL (λ), halo-peak (κ), halo-spread (β), halo-centroid (l_μ)
  - Series resistance: bias-dependent (υ), bias-independent (ρ)
  - Velocity saturation (v_{sat}), velocity overshoot (ξ), effective D/S voltage (δ_s)
- ❑ **Smoothing parameters** — internal model requirement