Unified Approach to Bulk/SOI/UTB/s-DG MOSFET Compact Modeling

Xing Zhou[1], *Karthik Chandrasekaran*[1], *Siau Ben Chiah*[2], *Wangzuo Shangguan*[1], *Zhaomin Zhu*[1], *Guan Huei See*[1], *Shesh Mani Pandey*[2], *Guan Hui Lim*[1], *Subhash Rustagi*[3], *Michael Cheng*[2], *Sanford Chu*[2], *and Liang-Choo Hsia*[2]

[1]Nanyang Technological University
[2]Chartered Semiconductor Manufacturing
[3]Institute of Microelectronics
Singapore

(exzhou@ntu.edu.sg)

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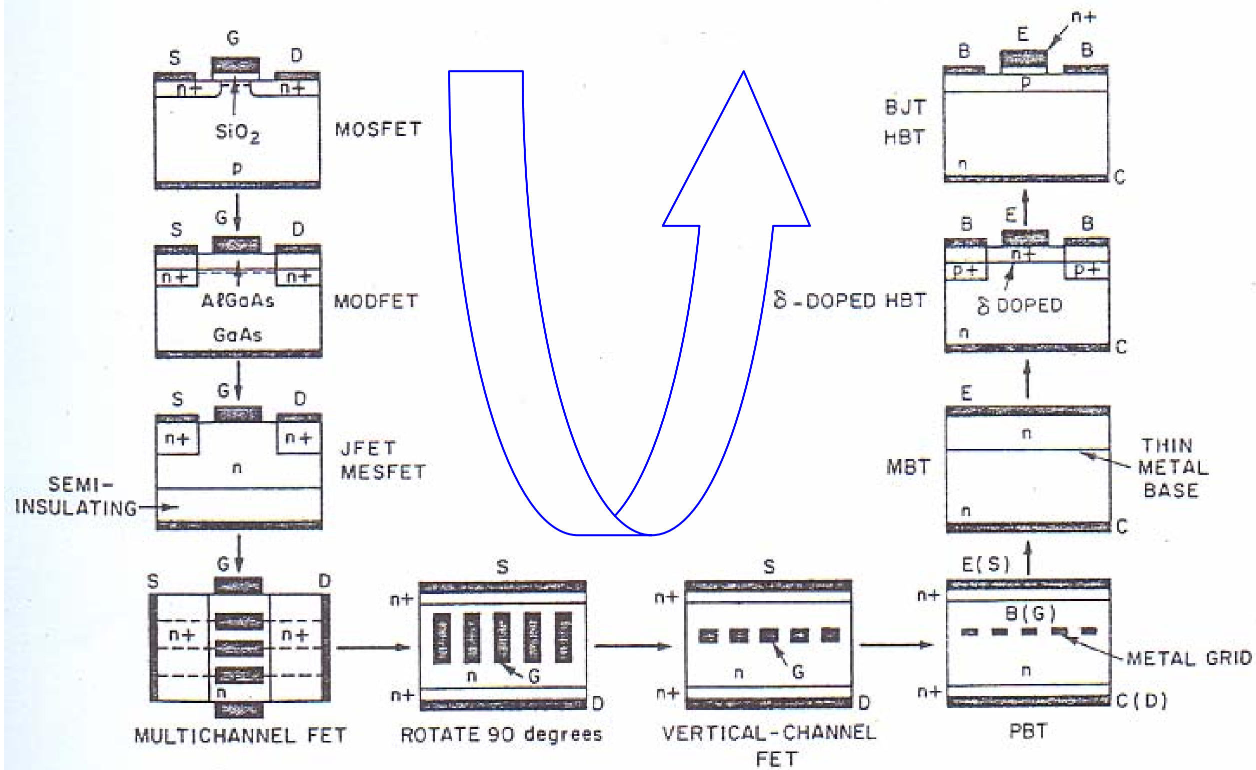
Presentation Outline

- **Introductory question:** best models and approaches to various MOS structures and operations?
- **Unified view and unification of MOS models**
- **Unified regional approach**
- **Application and results**
  - Strained-Si heterostructure channel
  - Doped symmetric-DG
  - Undoped DG/SOI
  - *Latest*: Doped asymmetric-DG
- **Summary and conclusions**

Continuum Transformation: FET to BJT

Field effect → **Potential effect**

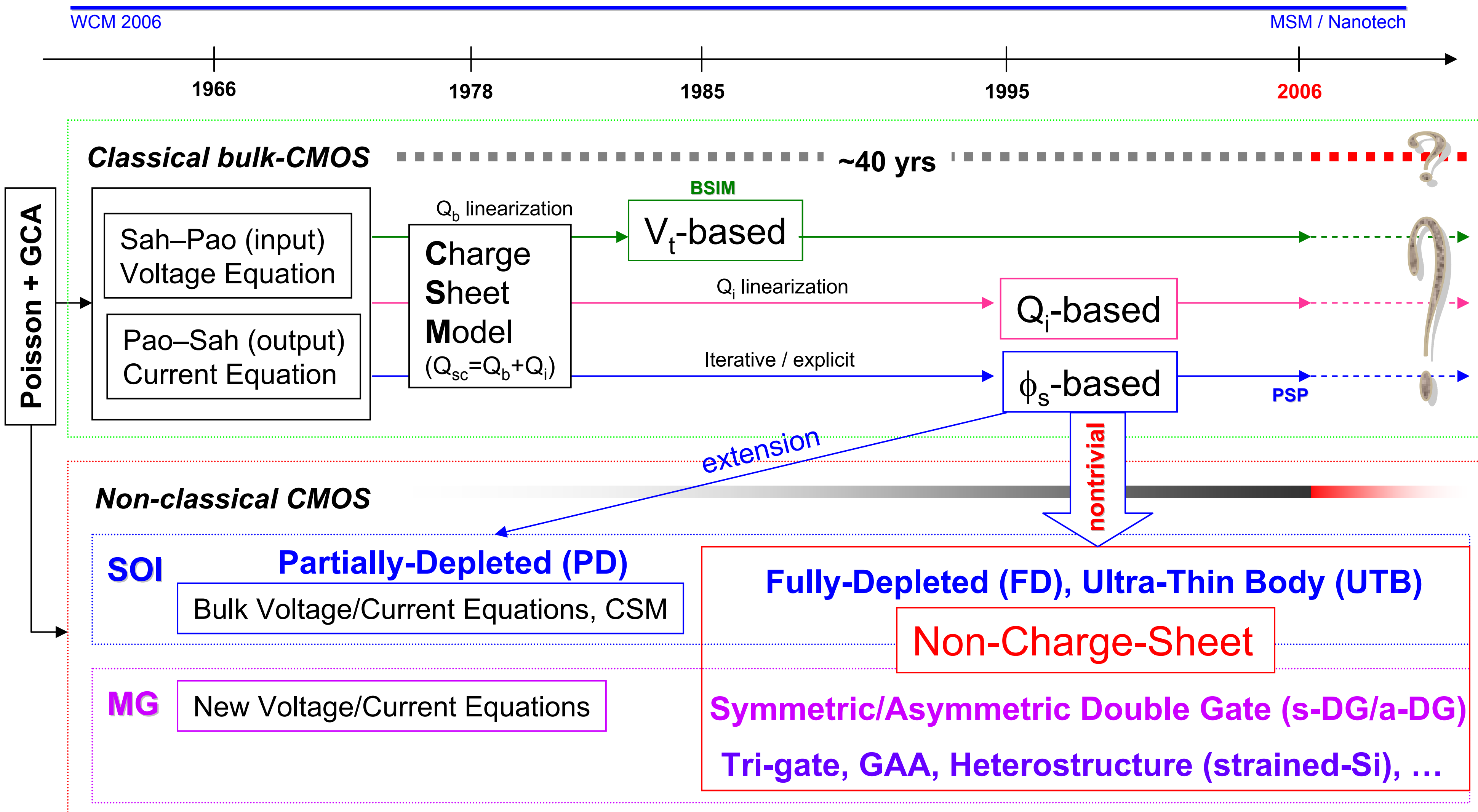


Continuum transformation of device configurations.

Courtesy: S. M. Sze, *High-speed semiconductor devices*, Wiley, 1990.

Similar transformation from classical bulk-MOS to non-classical SOI/MG MOSFETs?

MOSFET Compact Models: History and Future



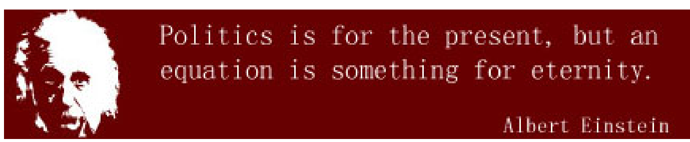
Motivation: Unification of MOSFET Models

- **After ~40 years, bulk-MOS compact modeling 'goes back' to the original (ϕ_s) formulation/solution, mainly because "V_t" approach cannot meet the requirement of current technologies.**

- **As bulk-CMOS scaling is approaching its limit** (<<40yrs?) **and non-classical CMOS emerges, do we want to '*re-start*' from new formulations due to non-extendable bulk formulation? Or, do we want to build non-classical models '*in parallel*' with bulk models?**

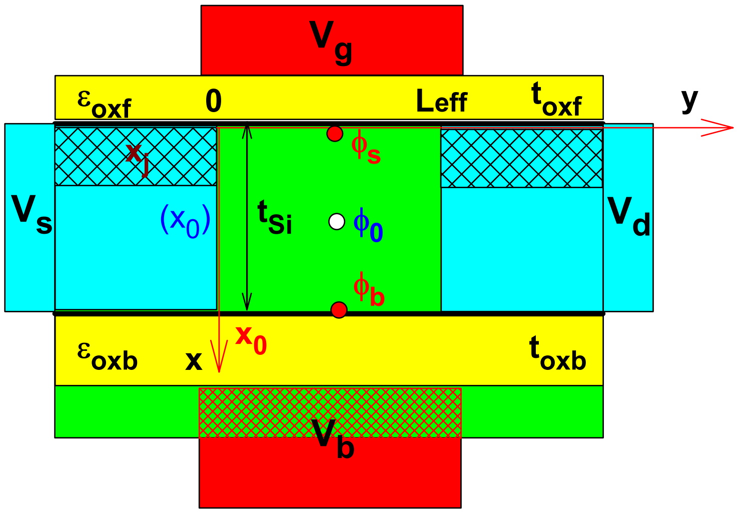
- **As a device** (geometry/layer) **dimensions and** (physical/electrical) **parameters vary, its operations change seamlessly; so should the models describing its characteristics be.**

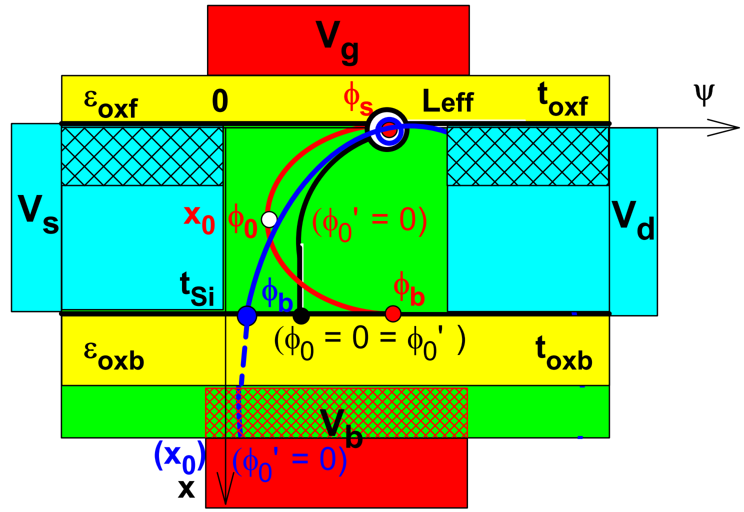
- **Motivation: A 'unified' MOS model with *seamless* transitions across device types and operations.**



The best of Einstein's theory is not only a brand *new* theory, but one that includes *old* (Newton's) theory as a special case.

Unified View of a MOSFET with Two Gates





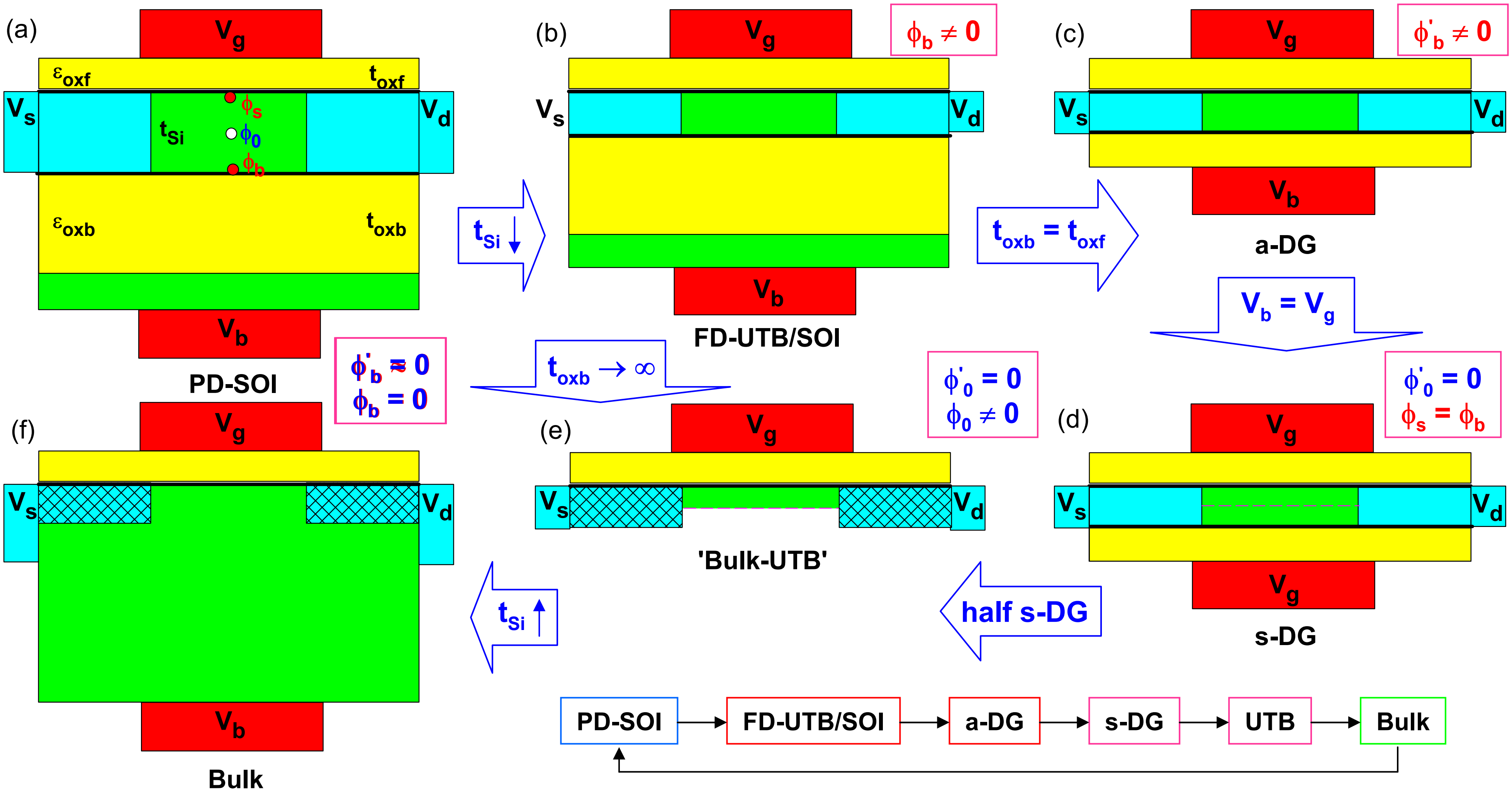
Key physical parameters

- Channel thickness (t_{Si}) and doping (N_{ch})
- Front/back oxide thickness (t_{oxf}/t_{oxb})
- Front/back gate dielectric constant ($\varepsilon_{oxf}/\varepsilon_{oxb}$) and flat-band ($V_{FBf}/V_{FBb}$)
- Others: channel length (L_{eff}), junction depth (x_j), over/under-lap (ΔL), and doping (N_{sd})

Different structures/operation

- Bulk: $\phi_b = 0$, $\phi'_b = 0$
- PD-SOI: $\phi_b = 0$, $\phi'_b \approx 0$
- FD-SOI: $\phi_b \neq 0$, $\phi'_b \neq 0$
- a-DG: $\phi_b \neq 0$, $\phi'_b \neq 0$
- s-DG: $\phi_0 \neq 0$, $\phi'_0 = 0$

Seamless Transformation and Unification of MOSFETs



Generic Voltage Equations for DG/SOI/Bulk MOSFET

- **Poisson Equation**

$$\frac{d^2\psi}{dx^2} = -\frac{\rho}{\varepsilon_{Si}} = -\frac{q(p-n+N_D-N_A)}{\varepsilon_{Si}} = \frac{q}{\varepsilon_{Si}}(n-p+N_A-N_D)$$

$$= \frac{qN_A}{\varepsilon_{Si}}\left[e^{(\psi-2\phi_F-V_c)/v_{th}} - e^{-\psi/v_{th}} + 1 - e^{-(2\phi_F+V_c)/v_{th}}\right] \equiv \frac{qN_A}{\varepsilon_{Si}} G(\psi, V_c)$$

↓ (First integral)

- **Field Equation**

$$E_s^2 = E_0^2 + F_s^2$$

+

$$F_s(\phi_s, \phi_0, V_c) = \pm\sqrt{2qN_A/\varepsilon_{Si}}\left[\int_{\phi_0}^{\phi_s} G(\psi, V_c)\, d\psi\right]^{1/2} \qquad (\varphi = \phi/v_{th})$$

$$= \pm\sqrt{2qN_A/\varepsilon_{Si}}\left\{v_{th}\left[e^{-\varphi_s} - e^{-\varphi_0} + (\varphi_s - \varphi_0)\right] + v_{th} e^{-(v_c - 2\varphi_F)}\left[e^{\varphi_s} - e^{\varphi_0} - (\varphi_s - \varphi_0)\right]\right\}^{1/2}$$

(p) (N_A) (n) (N_D)

- **Gauss' Law (boundary conditions)**

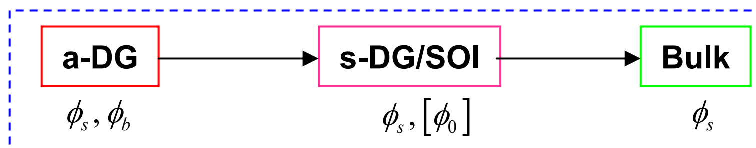
$$E_s = -\phi_s' = -\frac{\varepsilon_{oxf}}{\varepsilon_{Si}}\frac{V_{gf}-\phi_s}{t_{oxf}}, \quad (V_{gf} \equiv V_g - V_{FBf})$$

$$E_0 = E_b = -\phi_b' = +\frac{\varepsilon_{oxb}}{\varepsilon_{Si}}\frac{V_{bf}-\phi_b}{t_{oxb}}, \quad (V_{bf} \equiv V_b - V_{FBb})$$

II

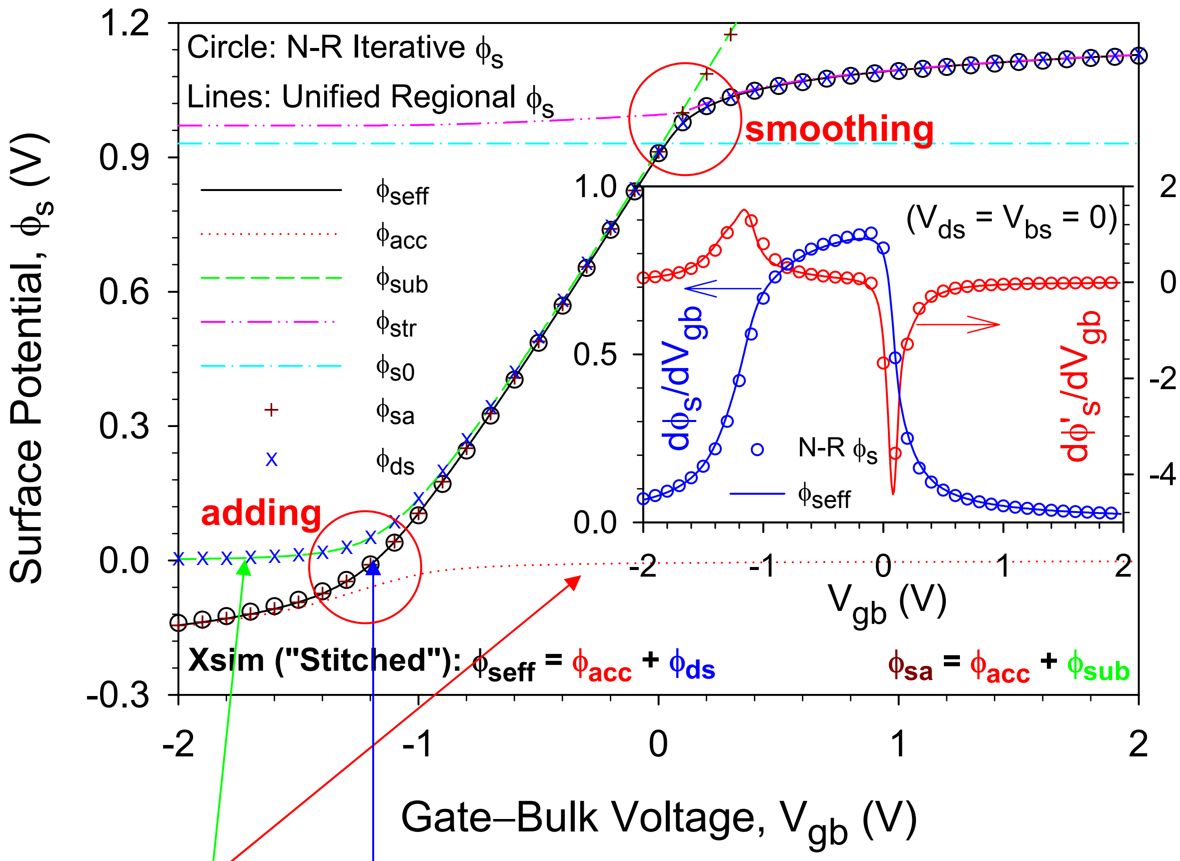
$$\psi(0,y) = \phi_s(y), \quad E_x(0,y) = E_s(y) = -\phi_s'(y)$$

$$\psi(x_0,y) = \phi_0(y), \quad E_x(x_0,y) = E_0(y) = -\phi_0'(y)$$



- **Voltage Equations (second integral not possible for *doped* channel)**

Essence of the Unified Regional Approach



$$\phi_s \approx \begin{cases} \phi_{cc} = V_{gb} - V_{FB} + 2v_{th}\mathcal{L}\{w\} & V_{gb} < V_{FB} \\ \phi_{dd} = \left(-\frac{\gamma}{2} + \sqrt{\frac{\gamma^2}{4} + V_{gb} - V_{FB}}\right)^2 & V_{FB} < V_{gb} < V_t \\ \phi_{ss} = \phi_{s0} + V_{cb} + \Delta & V_{gb} > V_t \end{cases}$$

$$\phi_{s,eff} = \begin{cases} \phi_{acc} = V_{gbr} + 2v_{th}\mathcal{L}\{w\} & V_{gb} < V_{FB} \\ \phi_{sub} = \left(-\frac{\gamma}{2} + \sqrt{\frac{\gamma^2}{4} + V_{gbf}}\right)^2 & V_{FB} < V_{gb} < V_t \\ \phi_{str} = \phi_{s0} + V_{cb} + \Delta_{eff} & V_{gb} > V_t \end{cases}$$

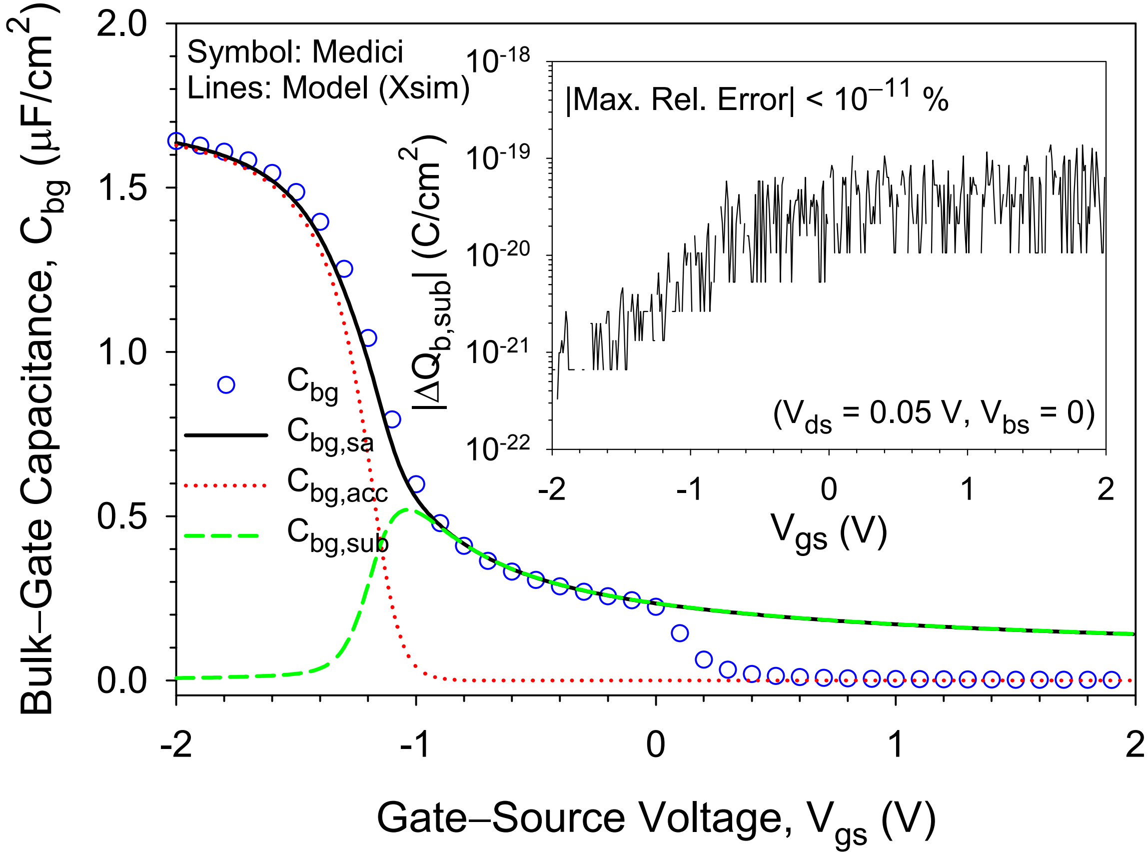
ϕ_s at $V_{gb} = V_{FB}$ is not solved exactly, but two pieces are “**stitched**” (rather than “**glued**”) to form a single-piece (ϕ_{seff}) seamlessly

“Pulled” to zero – no effect outside the region

“Glued”/iterative solution requires to maintain all the terms in the equation

Unified Regional Bulk-Charge Model

Other CSM: Right-hand side valid for $V_{gb} \geq V_{FB}$



$$\left|\Delta Q_{b,sub}\right| = \left|Q_{b,sub} - Q_{b,sub1}\right|$$

Difference between the left-hand and right-hand side of the voltage equation

$$V_{gb} - V_{FB} \equiv V_{gbr} + V_{gba} \qquad \phi_{sa} = \phi_{acc} + \phi_{sub}$$

$$Q_{sc} = -C_{ox}\left(V_{gb} - V_{FB} - \phi_{sa}\right)$$

$$= -C_{ox}\left[\underbrace{\left(V_{gbr} - \phi_{acc}\right)}_{Q_{b,acc}} + \underbrace{\left(V_{gba} - \phi_{sub}\right)}_{Q_{b,sub1}}\right]$$

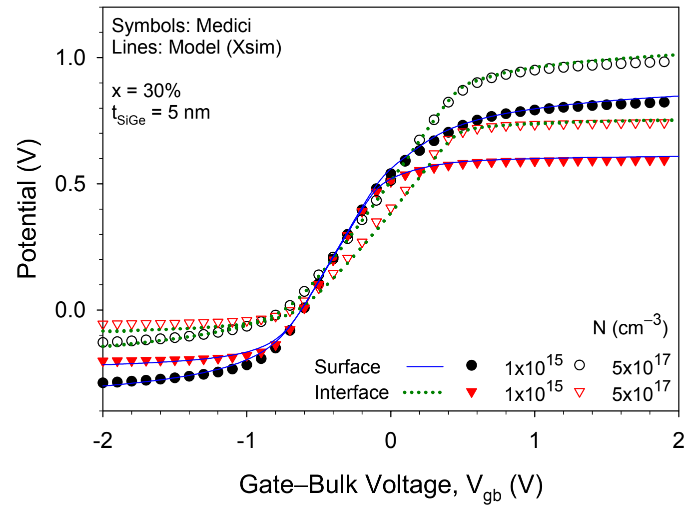
$$= Q_{b,acc} + Q_{b,sub}$$

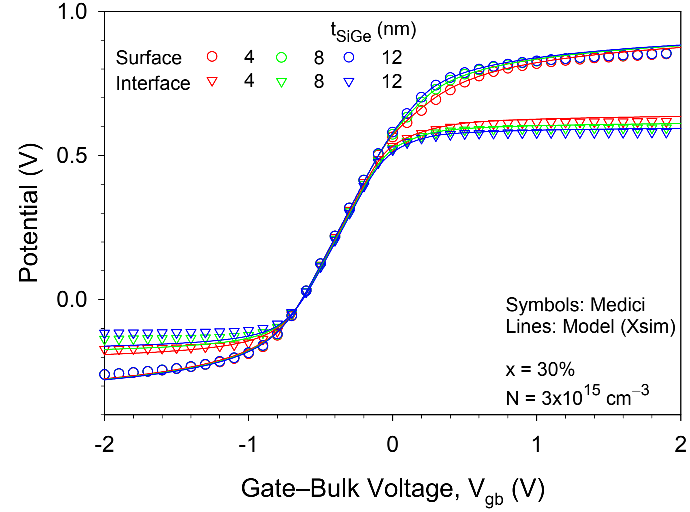
$$Q_{b,acc} \equiv -C_{ox}\left(V_{gbr} - \phi_{acc}\right)$$

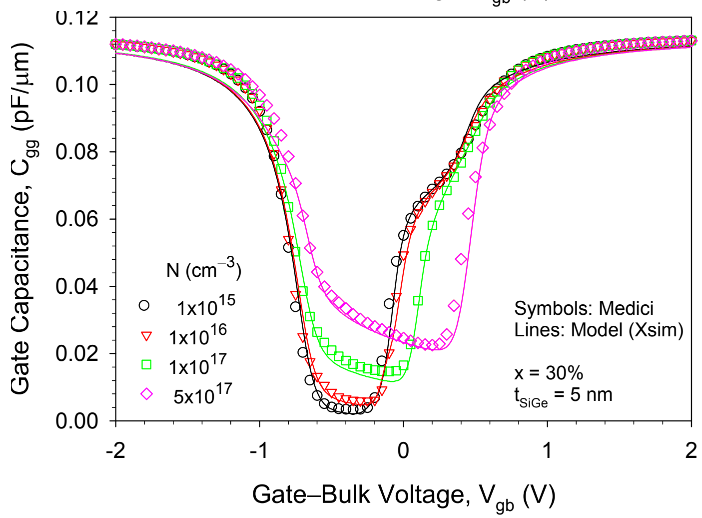
$$Q_{b,sub} \equiv -C_{ox}\left(V_{gba} - V_{gbf} + \gamma\sqrt{\phi_{sub}}\right)$$

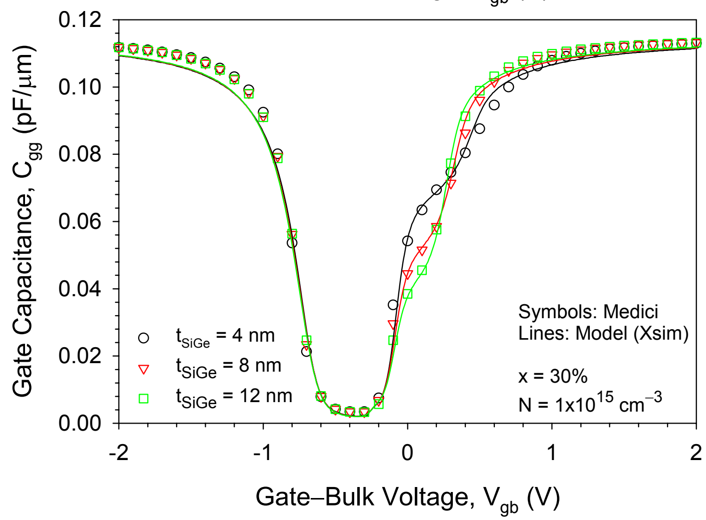
Extending to strained-Si/SOI/DG …

Unified Regional Approach Applied to Strained-Si

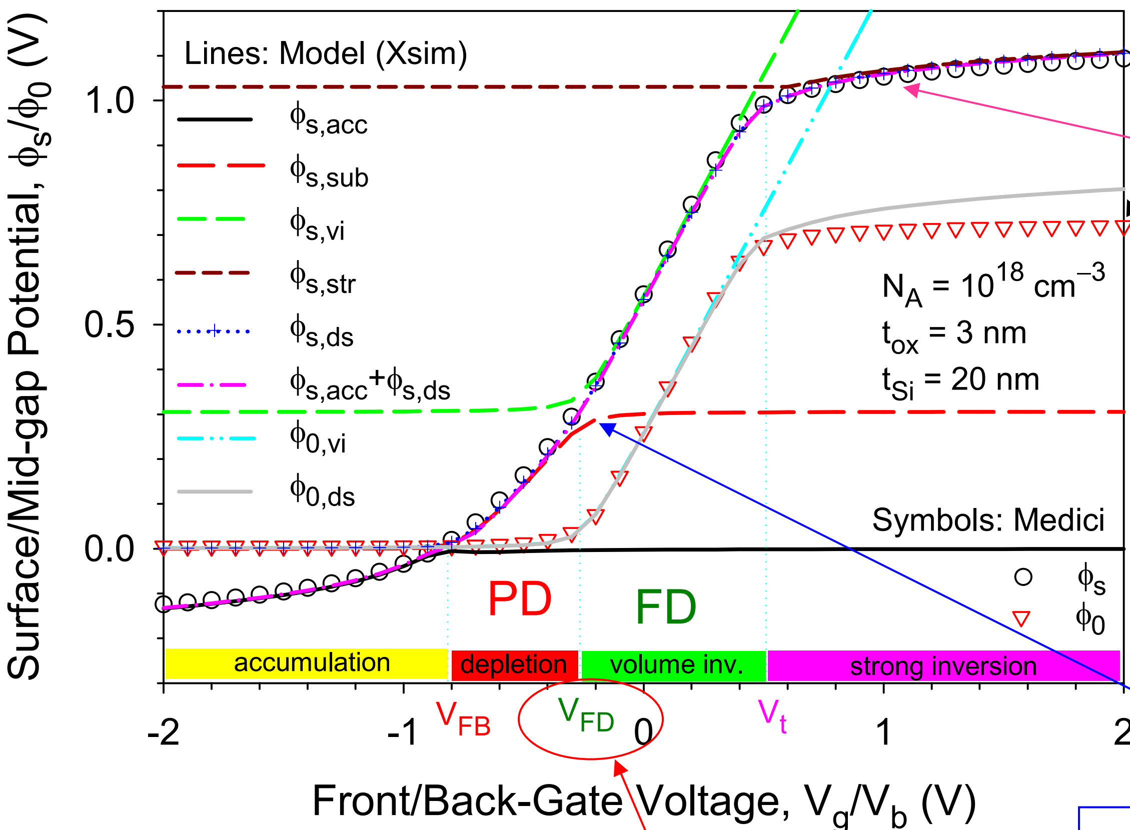








Doped s-DG: Explicit Unified Regional Solutions



'Strong-inversion' regional solution assuming channel full depletion

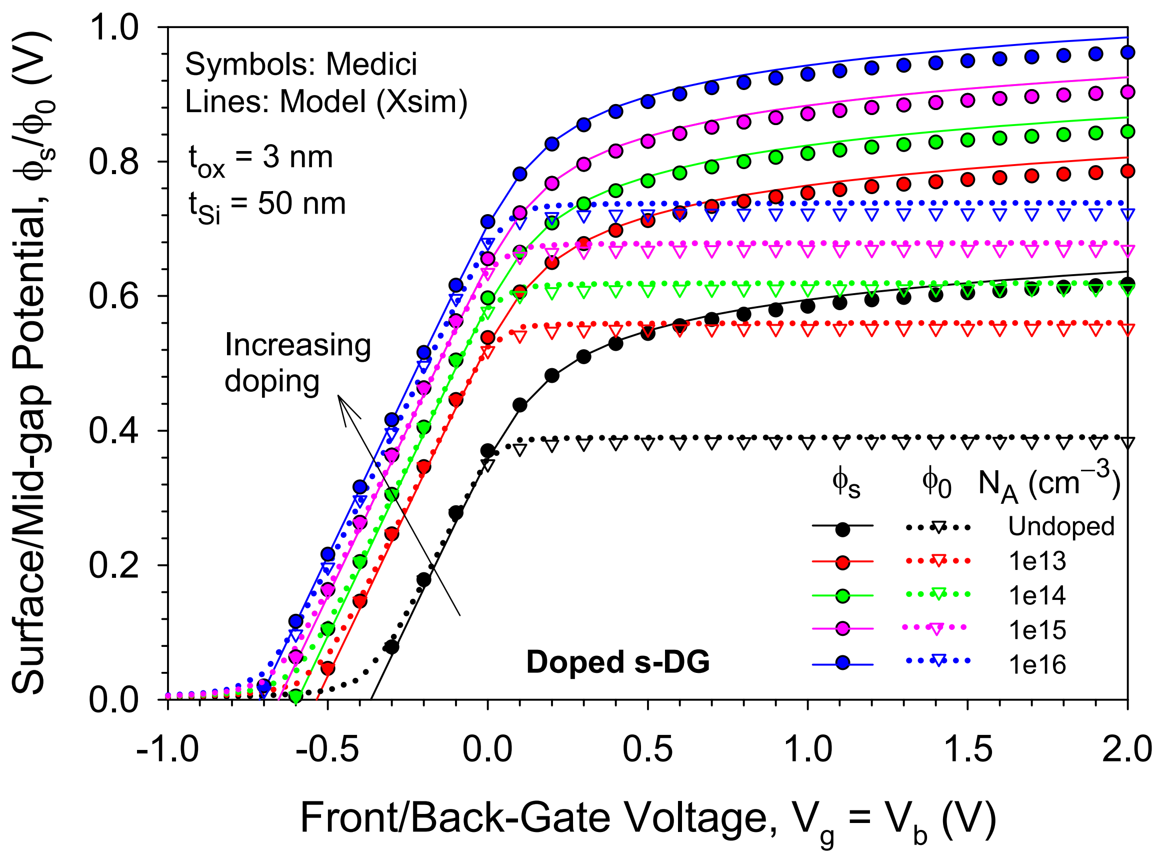
Inaccuracy in mid-gap potential has minimum effect on ϕ_s

Unified regional solutions from 'depletion' to 'volume inversion'

Modeled physically

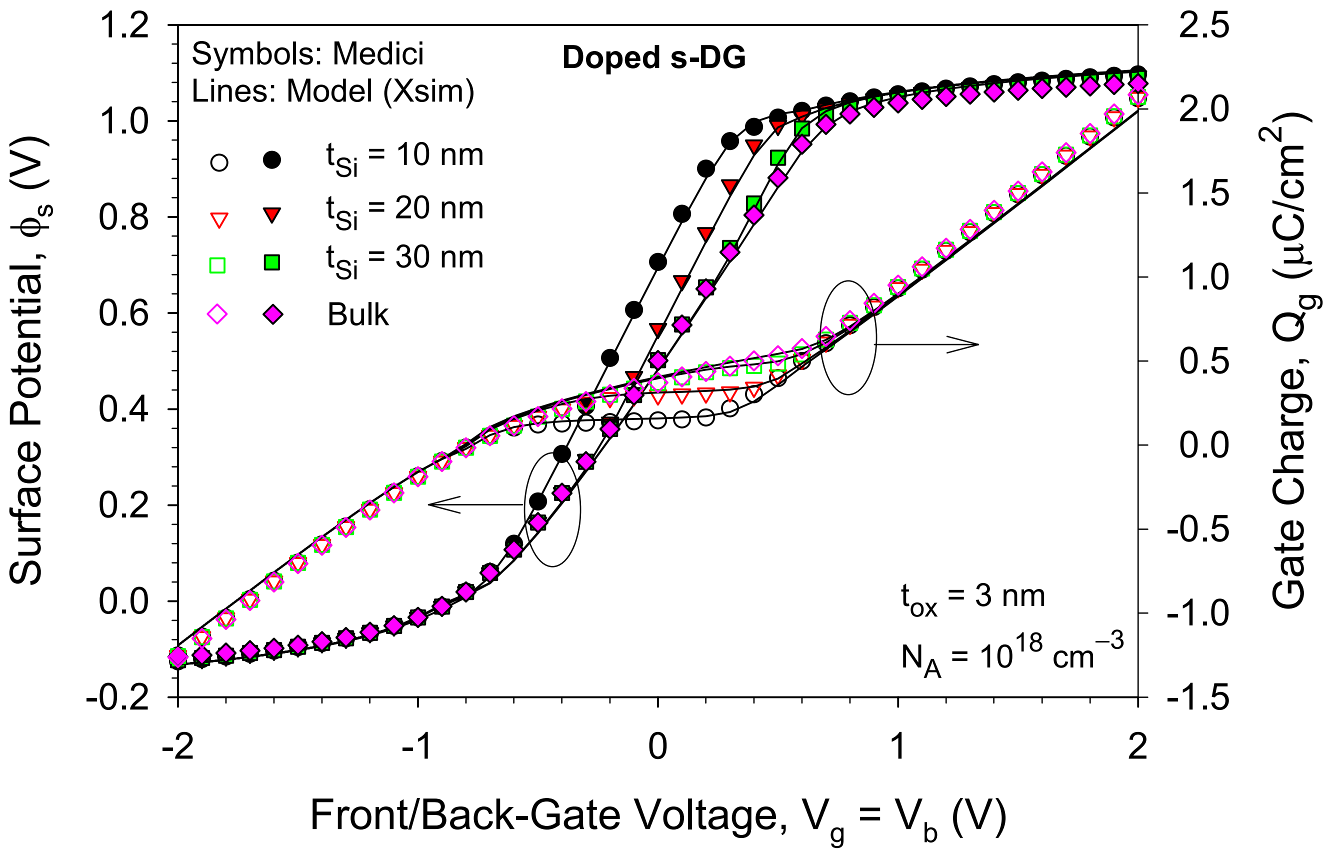
(See: WCM2006 poster by Karthik)

Doped s-DG: Doping Scaling – Doped to Undoped



- **Continuous and seamless scaling with channel doping**
- **Essential for accurate modeling for 'undoped' channel – with low 'unintentional' doping which, if not modeled, will lead to mV error in ϕ_s**

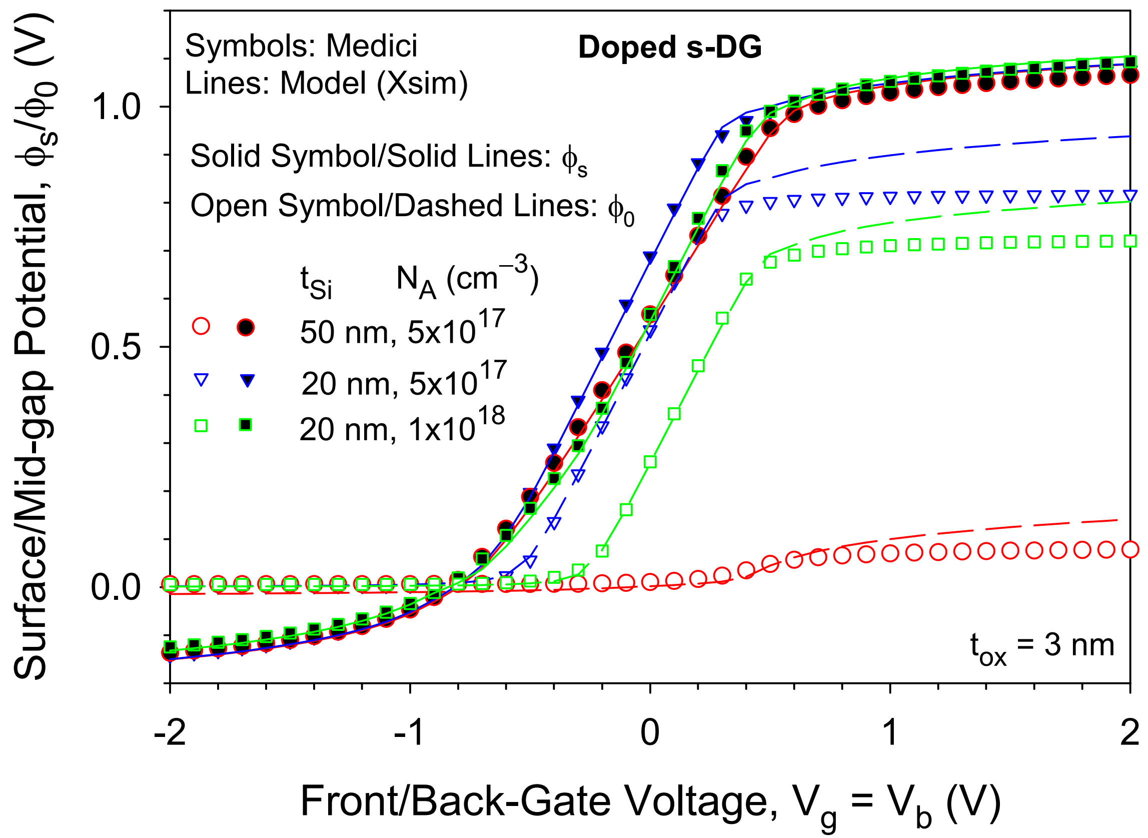
Doped s-DG: Channel Thickness Scaling – UTB to Bulk



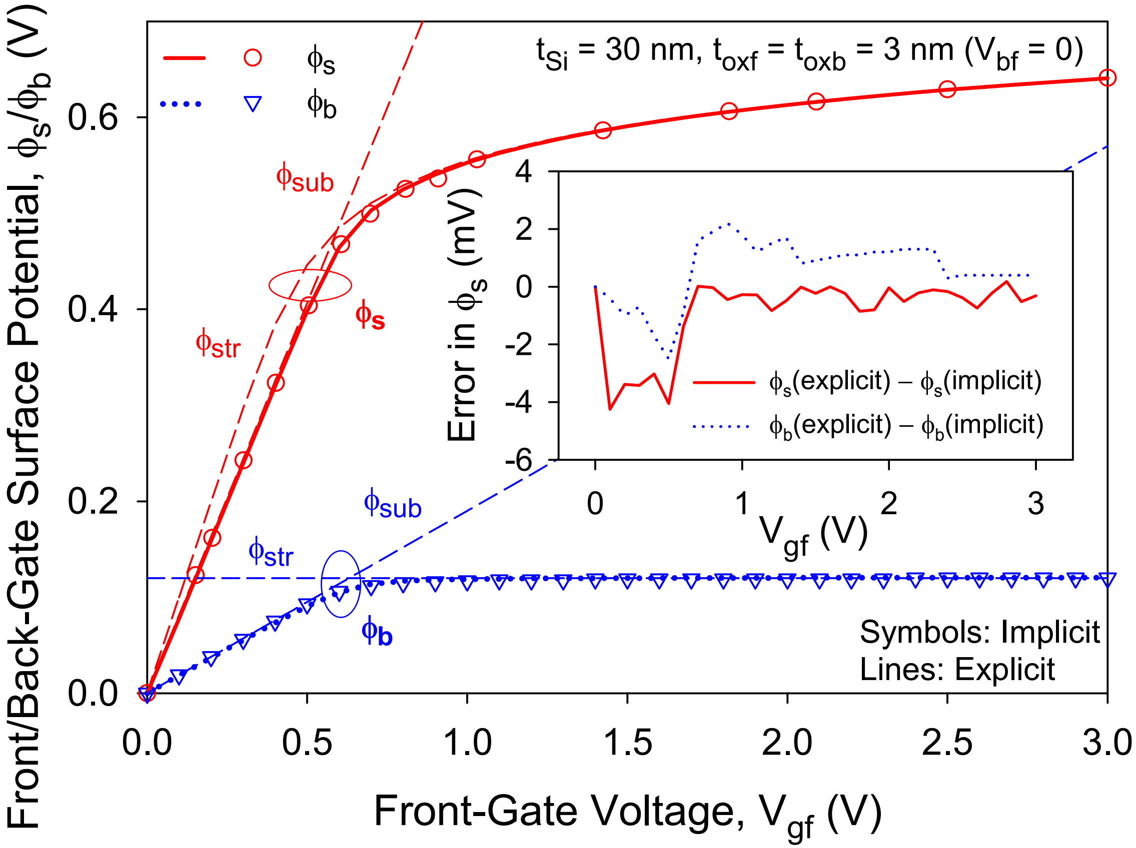
- **Continuous scaling with channel thickness**
- **Unified model with seamless transition from UTB/DG to bulk MOSFETs**

Doped s-DG: Doping & Channel Thickness Variations

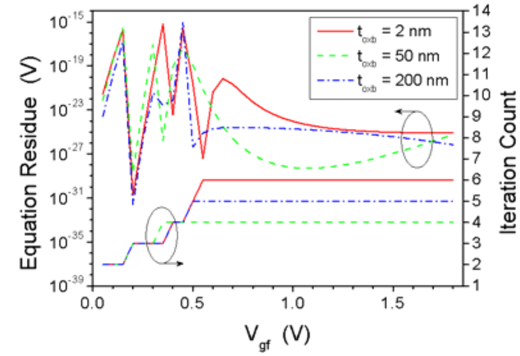
Comparison for t_{Si} (circle/triangle) and N_A (triangle/square) variations



Undoped DG: Explicit Unified Regional Solutions



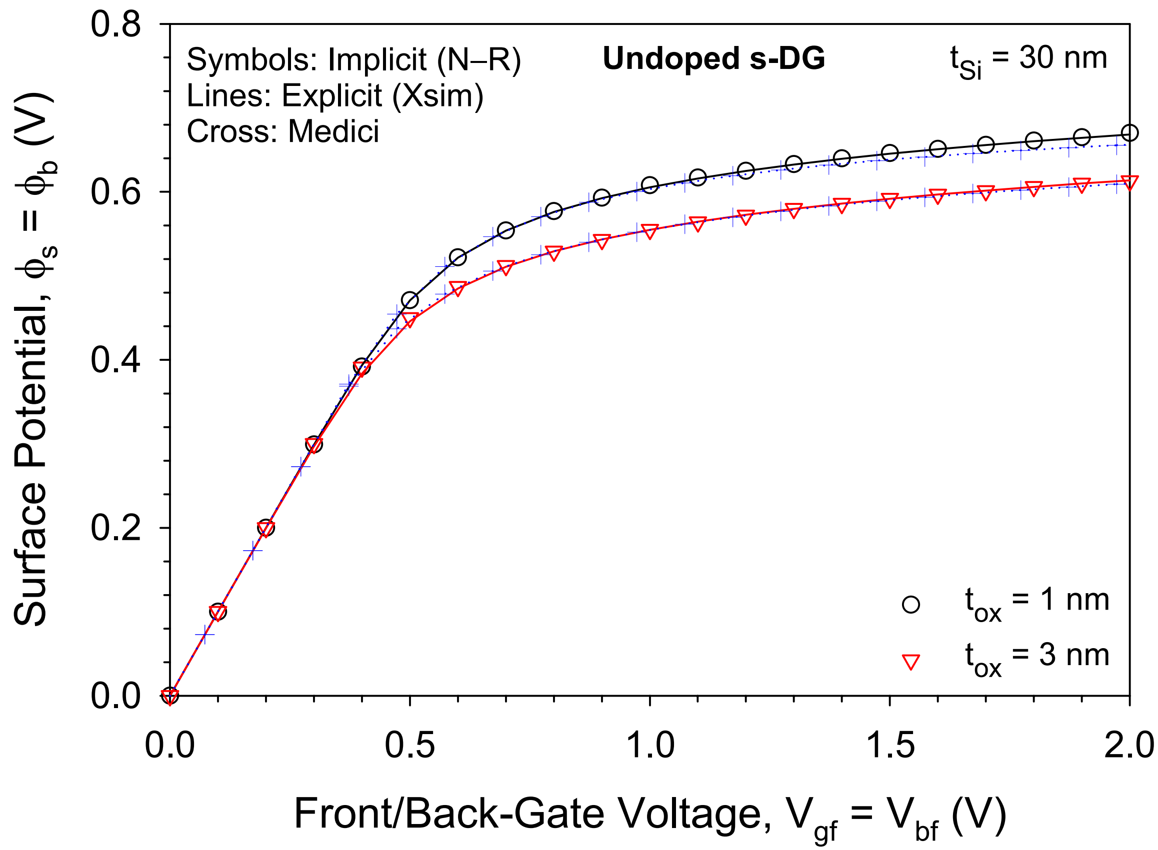
Explicit regional solutions scalable with layer/bias



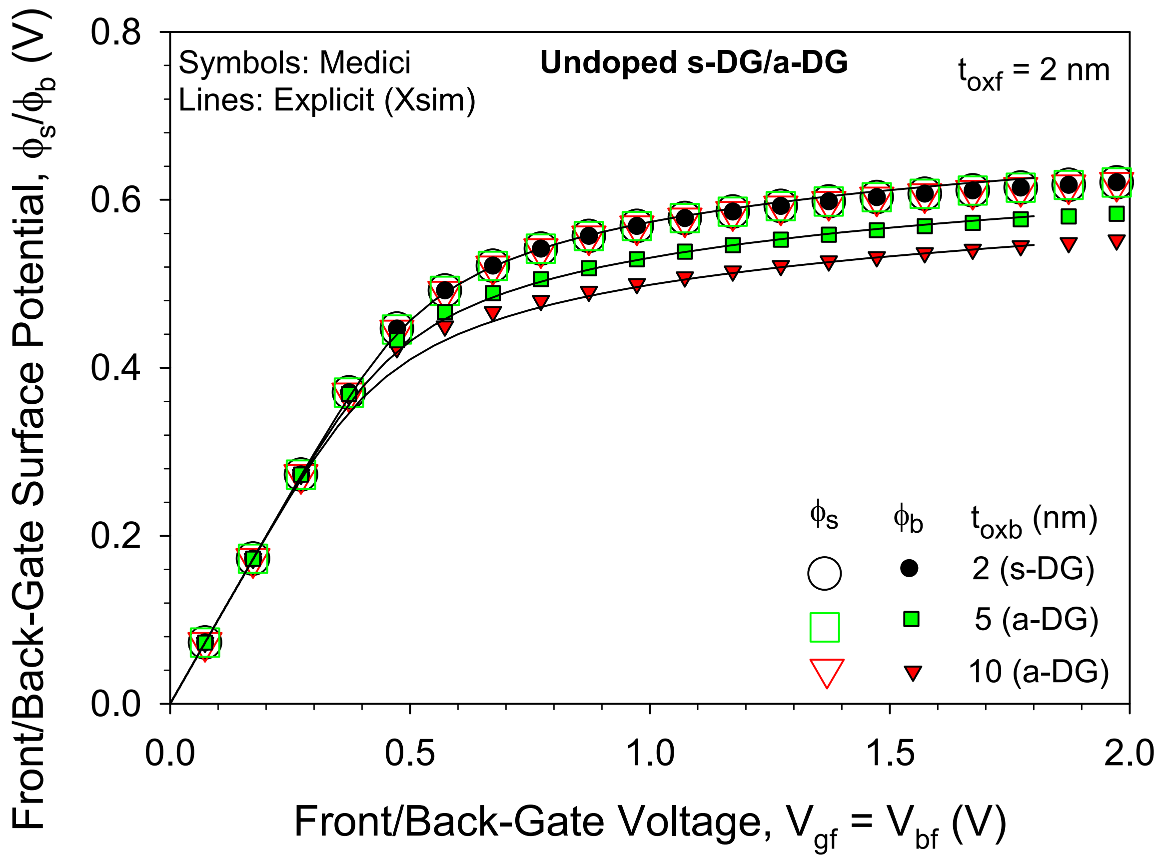
- **Implicit <u>generic</u> DG solutions are available**
- **Our Newton–Raphson solutions need 2~6 iterations to reach femto-V accuracy**
- **Explicit <u>regional</u> solutions are derived with mV accuracy**

Undoped s-DG: Explicit – Implicit – Numerical

Comparison of explicit solution with iterative and numerical solutions

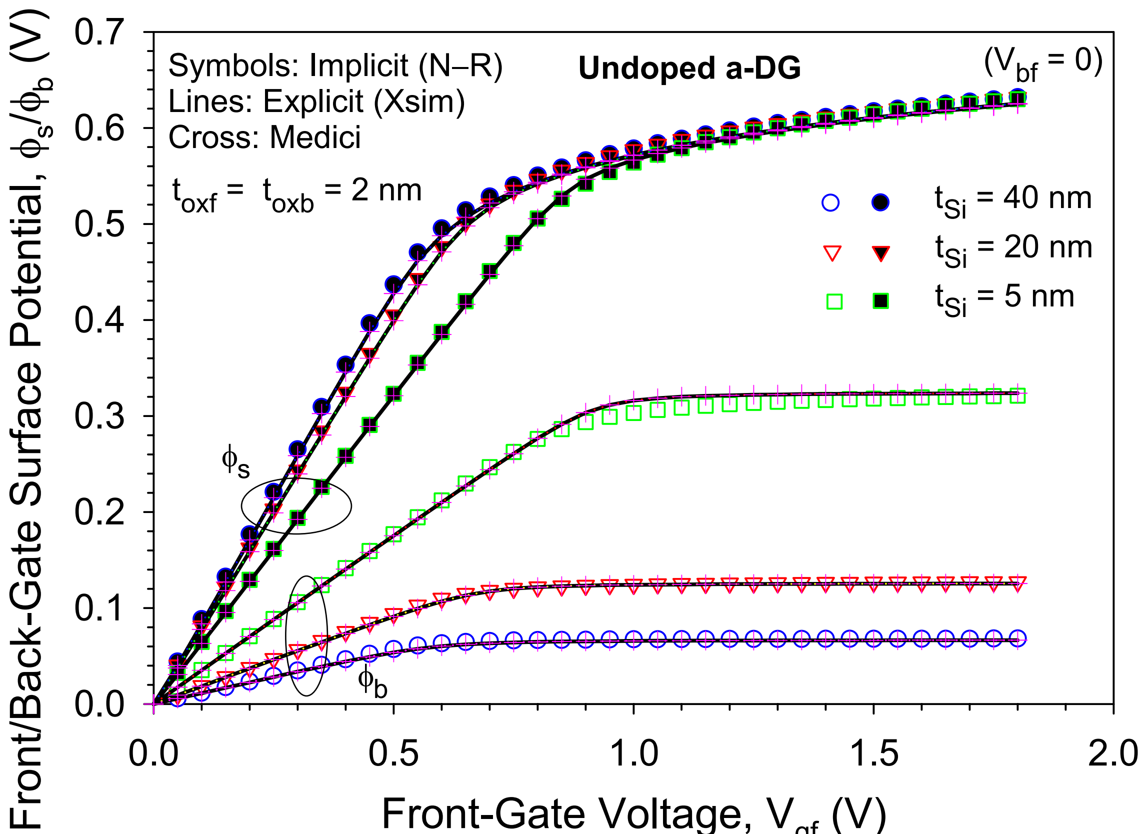


Undoped s-DG: Back Oxide Scaling – s-DG to a-DG



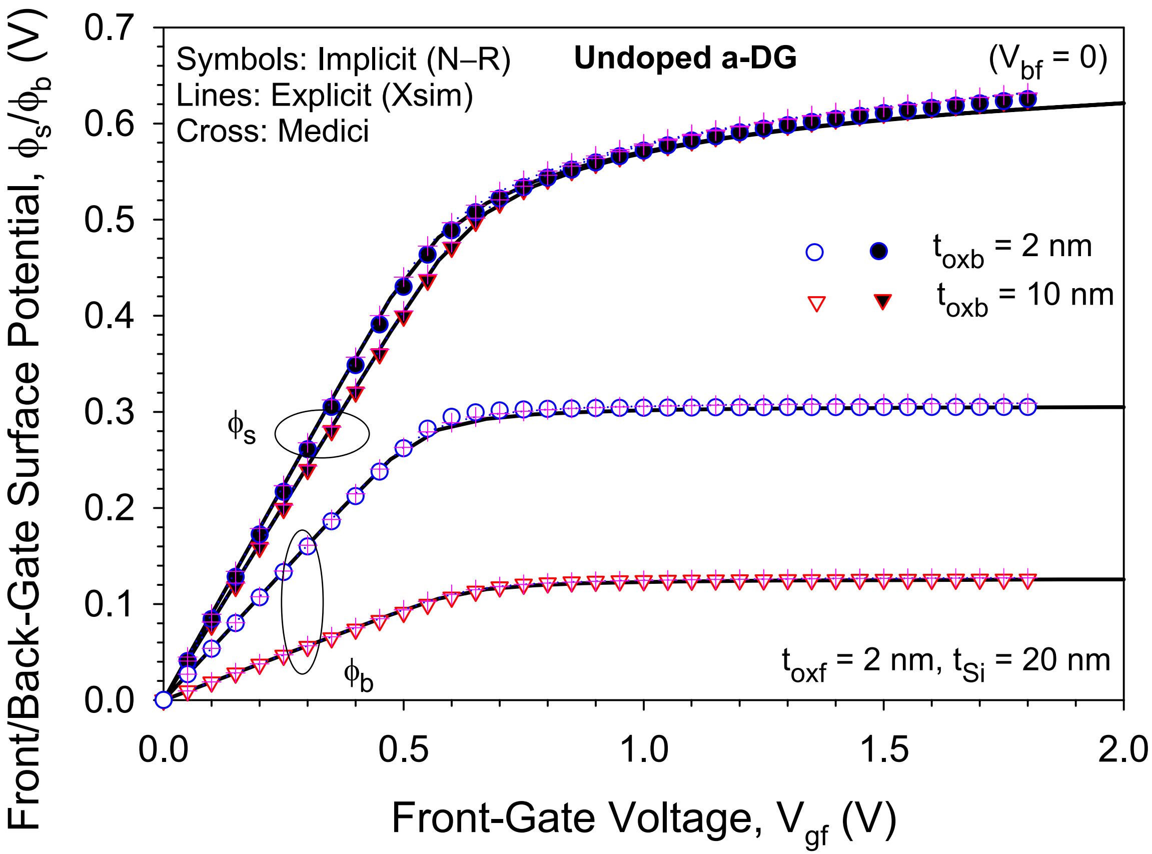
- **Continuous scaling and transition from symmetric to asymmetric DG**
- **Asymmetry due to back-gate oxide thickness (t_{oxb}) variation ($V_g = V_b$)**
- **Comparison with numerical (Medici) solutions**

Undoped a-DG: Channel Thickness Scaling



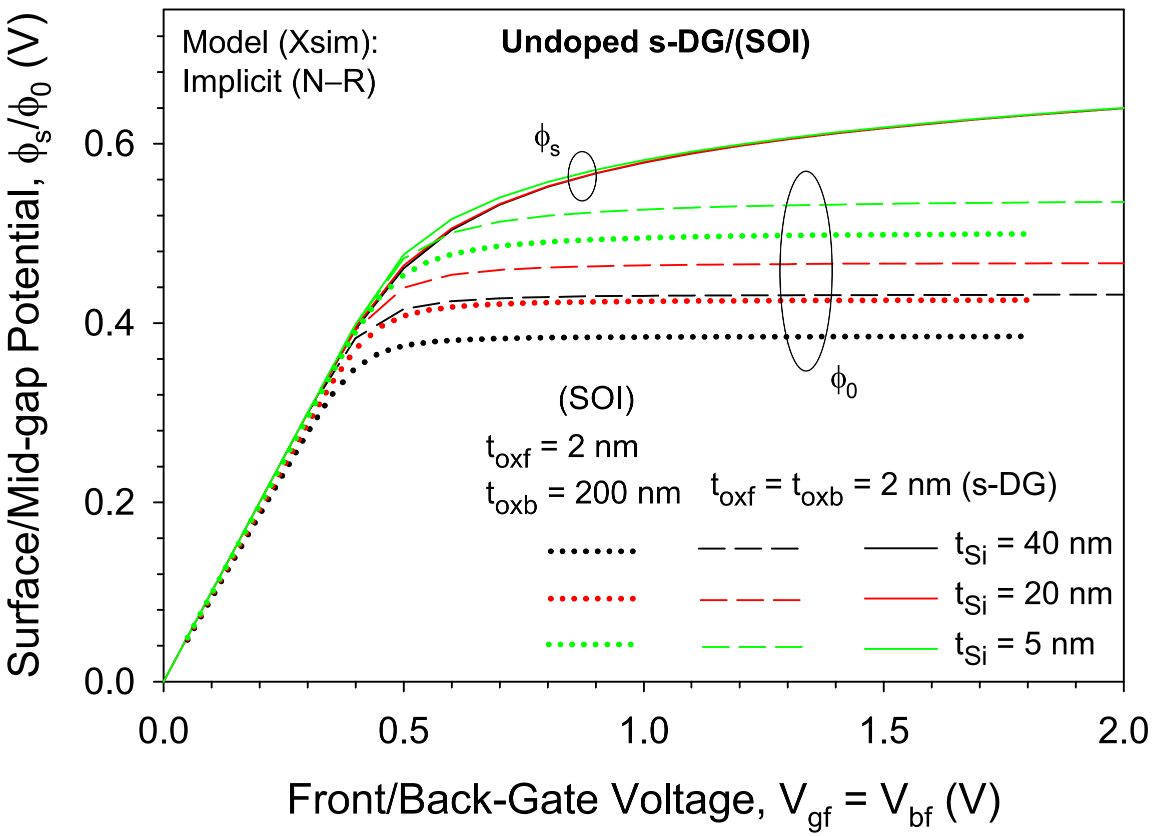
- **Continuous channel thickness scaling**
- **Asymmetry due to single-gate bias (V_g) sweeping ($V_{bf} = 0$)**
- **Explicit solution compared with implicit and numerical solutions**

Undoped a-DG: Back Oxide Thickness Scaling



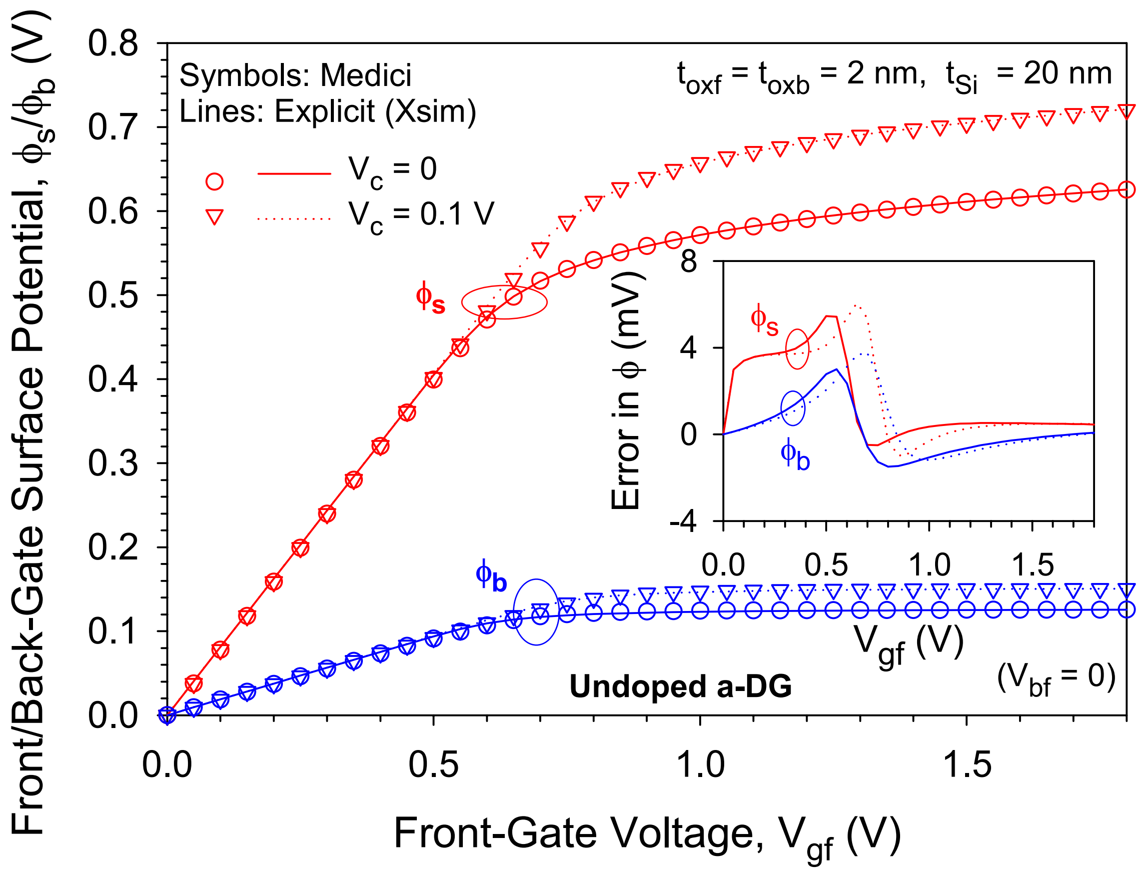
- **Continuous back-gate oxide thickness scaling**
- **Asymmetry due to single-gate bias (V_g) sweeping ($V_{bf} = 0$)**
- **Explicit solution compared with implicit and numerical solutions**

Undoped s-DG: Channel Thickness Scaling – s-DG to SOI



- **Continuous channel thickness scaling**
- **Comparison between s-DG and 'SOI'**
- **Implicit N–R solution (difficult to converge as t_{oxb} approaches t_{oxf})**

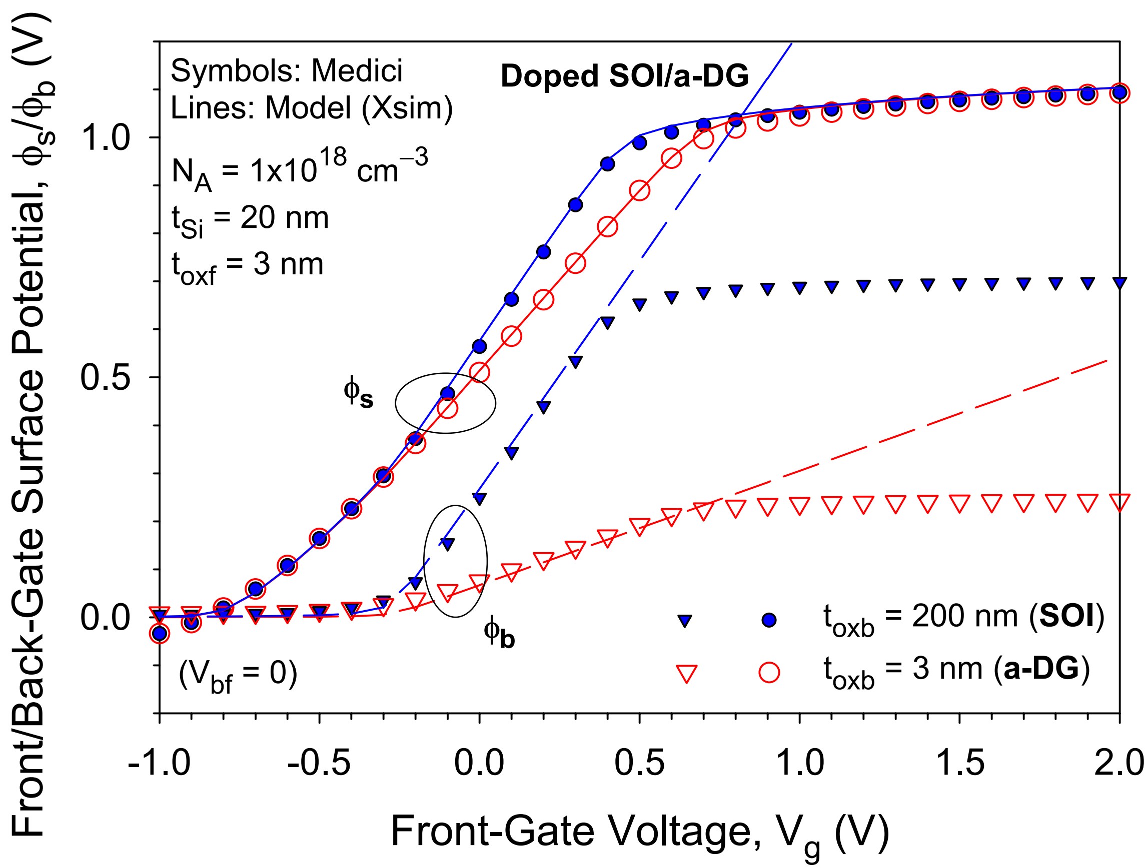
Undoped a-DG: Channel Voltage Variation for MOSFETs



- Undoped a-DG with non-zero channel voltage ($V_c \neq 0$)
- Accurate ϕ_s and ϕ_b solutions needed for **MOSFET terminal current** evaluated at the source $\phi(V_s)$ and drain $\phi(V_d)$ ends
- **Explicit** solution compared with **numerical** solution, showing **~mV** error for application to MOSFETs

Doped a-DG/UTB-SOI: Regional Solutions

Seamless transition from a-DG to SOI

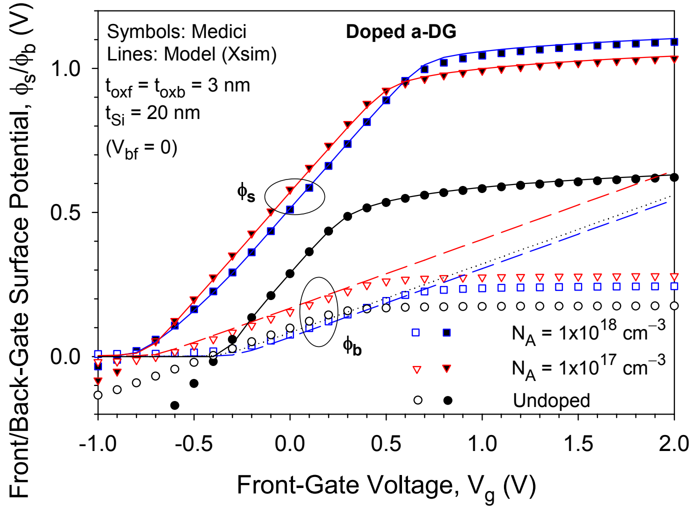


- The most challenging case: **doped a-DG** & **UTB/SOI** (known to be **non-integrable**!)
- Demonstrated physical/ regional solutions in ***depletion*** and ***volume inversion*** regions, with **seamless** transitions in t_{oxb}, t_{Si}, N_A, V_b variations, validated by Medici
- Final challenge: **accurate ϕ_b solution** in ***strong inversion***!

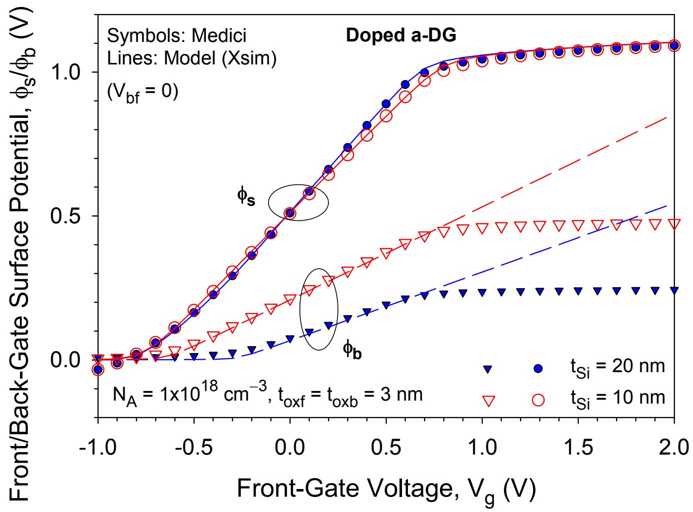
Seamless Transitions: Doping, Thickness, Bias Scaling

WCM 2006 — MSM / Nanotech

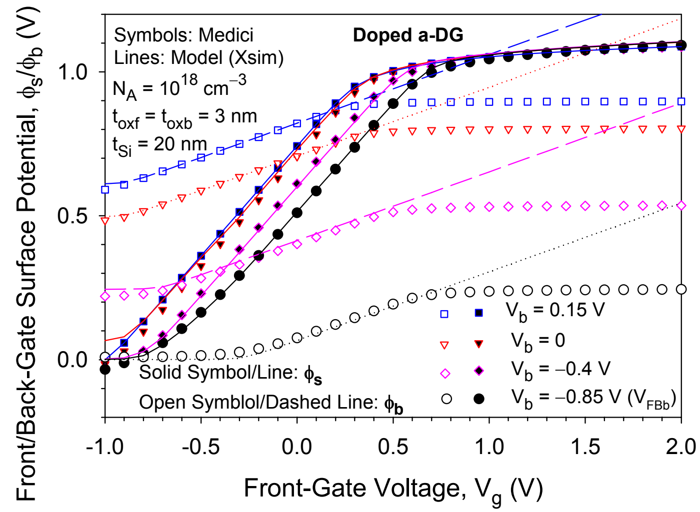
Doped to undoped



DG: FD to PD



Back-bias scaling



Latest results → conclusion / vision

- **Unified regional solution: the only 'solution' to *future* generation *non-classical* MOSFETs?**
- **Close to the 'final' ultimate solution: Unification of MOS models**

Summary and Conclusions

- **What is the best modeling approach?** — from historical bulk-MOS development to future generation non-classical MOS structures/operations
- **Classical bulk ϕ_s-based formulation** — non-extendable to DG/non-CSM
- **Unified regional solutions** — feasible for constructing complete solutions for non-classical MOS with structural/operational variations and seamless transitions, which also includes bulk-MOS (and converges to the simplest V_t-based formulations)
- **Model development** — to tackle the ‘future’ problem, now; rather than re-starting or getting around or doubling the efforts. ***Key***: the approach
- **Goals and Vision** — ***Unification*** of MOS models with the *unified regional approach* within one model infrastructure and seamless transitions across device types and operations

Acknowledgment and References

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- ***Institute of Microelectronics/A*STAR***: ARC HN/OCL/103/0105/IME

❑ **Related publications**

- "Surface-potential Solution for Generic Undoped MOSFETs with Two Gates," submitted for publication.
- "Explicit Unified Regional Surface Potential for Asymmetric Undoped Double-Gate MOSFETs," submitted for publication.
- "Compact Modeling of Doped Symmetric DG MOSFETs with Regional Approach," ***Proc. WCM-Nanotech 2006***, Boston, May 2006.
- "Effect of Substrate Doping on the Capacitance–Voltage Characteristics of Strained-silicon pMOSFETs," ***IEEE Electron Device Lett.***, Vol. 27, No. 1, pp. 62–64, Jan. 2006.
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- "Physics-based single-piece charge model for strained-Si MOSFETs," ***IEEE Trans. Electron Devices***, Vol. 52, No. 7, pp. 1555–1562, July 2005.
- "A Compact Model for Future Generation Predictive Technology Modeling and Circuit Simulation," (*Invited Paper*), ***Proc. MIXDES 2005***, Kraków, June 2005, pp. 881–886.
- "Unified Regional Charge-based Versus Surface-potential-based Compact Modeling Approaches," (*Invited Paper*), ***Proc. WCM-Nanotech 2005***, Anaheim, May 2005, pp. 25–30.
- "Single-piece polycrystalline silicon accumulation/depletion/inversion model with implicit/explicit surface-potential solutions," ***Appl. Phys. Lett.***, Vol. 86, No. 20, 202111, May 2005.