Transitioning from BSIM4 to BSIM6

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Outline

- CMC – An Introduction
- Physics of BSIM6
- BSIM6 results
- Summary

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CMC Members

EDA Vendors, Foundries, IDMs, Fabless, Research Institutions/Consortia

Accelicon	**Cypress Semiconductor**	**Mentor Graphics**	**STARC**
Agilent Technologies	**Elpida Memory**	**ProPlus Design Solutions**	**ST Microelectronics**
AIST	**Fujitsu Semiconductor**	**Qualcomm**	**Synopsys, Inc.**
Analog Devices	**GLOBALFOUNDRIES**	**Renesas Electronics**	**Texas Instruments Inc.**
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AWR	**Intel**	**Samsung**	**TSMC**
Broadcom	**LEAP**	**Silvaco**	**United Microelectronics**
Cadence	**LSI Corporation**	**Soitec**	
Denso	**Magma**	**Sony**	

CMC History and Purpose

- CMC was formed in 1996 as a collaboration of foundries, fabless companies, IDMs, and EDA vendors

Foundry or IDM's Fab → Commercial or In-House Circuit Simulator → Fabless or IDM IC Designer

- Compact models provide the connections.
- Standard compact models enable efficiencies in this process.

IDM – Integrated Device Manufacturer

CMC Charter

To promote the international, nonexclusive standardization of compact model formulations and the model interfaces

CMC Vision

- Standardized compact models for all major technologies so that customer communication and efficiency can be enhanced.

- Standard interfaces so that models can be tested faster and implemented easier.

- Better compact models for the latest technologies, allowing leading edge design development cycles to shorten.

CMC Strategy

- Examine, promote and standardize compact modeling efforts based upon business needs.
- Encourage developers to dwell on current and near-term problems that will advance compact modeling.
- Provide industry resources for monitoring and mentoring compact model development
- Provide a standardization process to the compact model developers

CMC standard models

- 1996 BSIM3
- 2000 BSIM4
- 2002 BSIMSOI
- 2004 MEXTRAM
- 2004 HICUM
- 2005 R2_CMC
- 2006 PSP
- 2007 HiSIM_HV
- 2007 R3_CMC
- 2008 MOSVAR
- 2009 Diode_CMC
- 2011 HiSIM2

- 2012+
  - BSIM-CMG Multi-Gate MOSFET Model
  - BSIM6 MOSFET Model
  - HiSIM-SOI DDSOI MOSFET Model
  - ETSOI MOSFET Model
    - BSIM-IMG & HiSIM models are candidates

CMC Models DO NOT remain static

- Most enhancements are requested by members but they can also come from the developer
- CMC decides which enhancements they want to pursue
- CMC members test enhancements before they are released as a standard

CMC Member Benefits

- Influence selection and enhancements of standards

- Regular interactions with modeling experts from other companies and universities.

- Full access to CMC website: www.geia.org/CMC---Council
  - Most information produced since 2007 is only available to members.
    - ✓ Quarterly meeting minutes and presentations
    - ✓ Subcommittee activity reports
    - ✓ Some standard model codes
- University-supported standard model codes are available to members and non-members.

  The developer grants users a perpetual, irrevocable, worldwide, non-exclusive, royalty-free license with respect to the software. Users are granted the right to modify, copy and redistribute the software and documentation.

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BSIM6: Charge based MOSFET model

- BSIM6 is the next BSIM Bulk MOSFET model
- Charge based core derived from Poisson's solution
- Physical effects (SCE, CLM etc.) taken from BSIM4
- Parameter names matched to BSIM4 parameters
- Gummel Symmetry (symmetric @ $V_{DS}=0$)
- AC Symmetry
  - Capacitances/derivatives are symmetric @$V_{DS}=0$
- Continuous in all regions of operations
- Physical Capacitance model
  - Short channel CV–Velocity saturation & other effects
- No glitches – smooth current and capacitance behavior

Physics of BSIM6 Model

- Using linearization approach and normalization

Other models ignored circled terms

$$2q_i + \ln(q_i) + \ln\left[\frac{2n_q}{\gamma}\left(\frac{2n_q}{\gamma}q_i + 2\sqrt{-2q_i + \psi_p}\right)\right] = \psi_p - 2\phi_f - v_{ch}$$

- No approximation to solve the charge equation

- We solved the charge equation using first & second order Newton-Raphson technique to obtain analytical expression of q_i

Drain current expression

- Drain current

$$I_D = I_{drift} + I_{diff} = \mu W\left(-Q_i \frac{d\Psi_S}{dx} + V_T \frac{dQ_i}{dx}\right)$$

- Second order mobility model

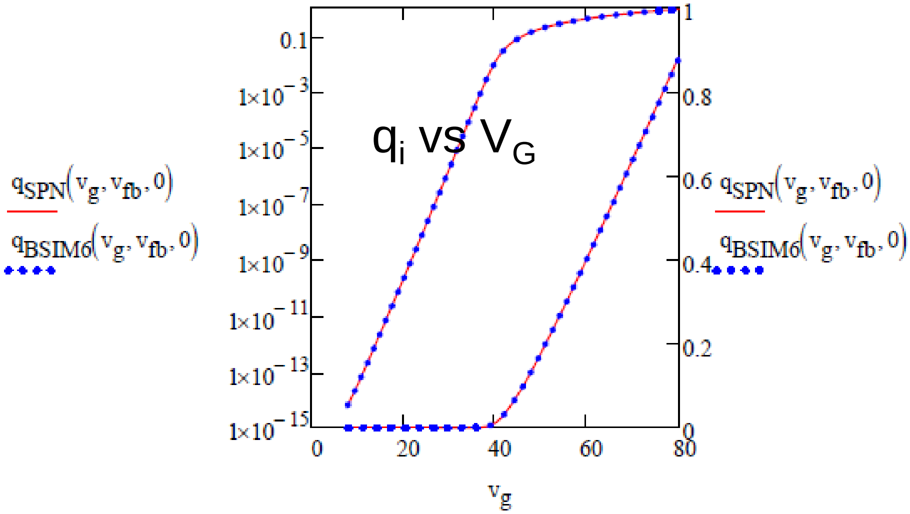
$$I_D = \frac{\mu_v}{\sqrt{1+\left(\frac{\mu_v}{v_{sat}}\left|\frac{d\Psi_S}{dx}\right|\right)^2}} W\left(-Q_i \frac{d\Psi_S}{dx} + V_T \frac{dQ_i}{dx}\right)$$

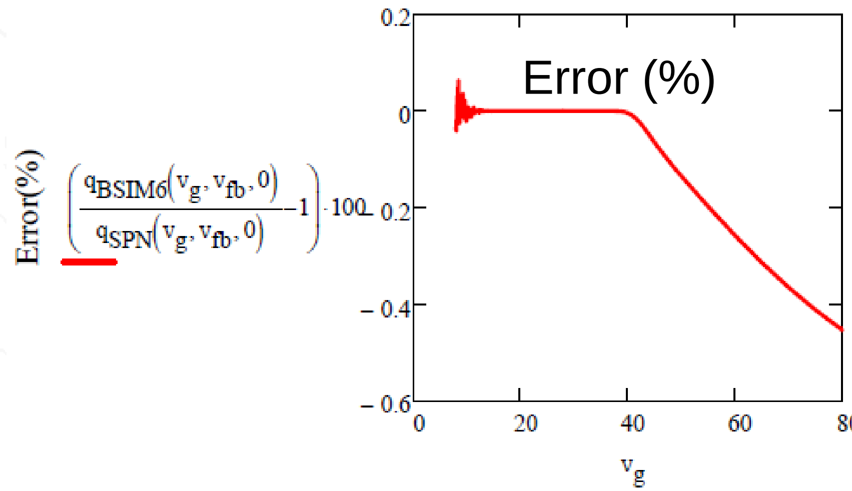
- Using charge linearization & normalization

$$-\frac{Q_i}{C_{ox}} = n_q\left(\Psi_P - \Psi_S\right), q = \frac{-Q_i}{2n_q C_{ox} V_T}, i_d = \frac{I_D}{2n_q \frac{W}{L}\mu_v C_{ox} V_t^2}, \lambda_c = \frac{2\mu_v V_t}{v_{sat} L}$$

$$i_d = \frac{\left(q_s^2 + q_s\right) - \left(q_d^2 + q_d\right)}{\frac{1}{2}\left(1+\sqrt{1+\left[\lambda_c\left(q_s - q_d\right)\right]^2}\right)}$$

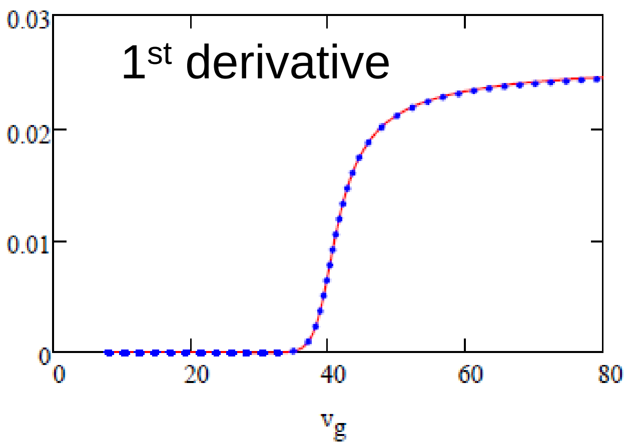
Normalized Q_i-V_G & derivatives

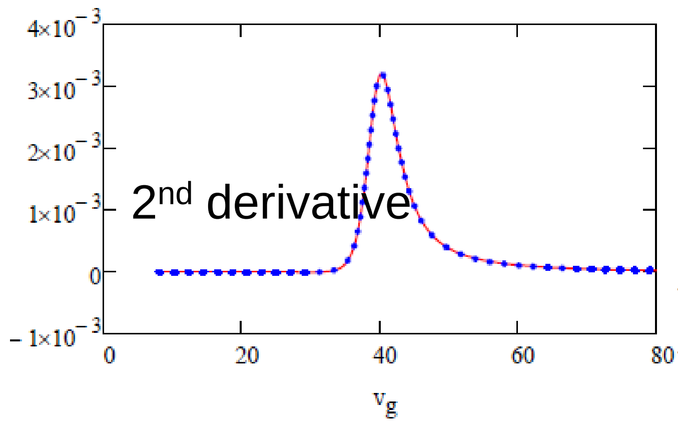


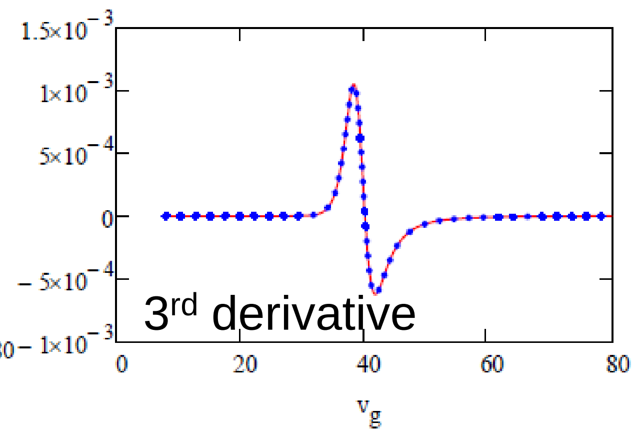


Red – Numerical Surf. Pot. model

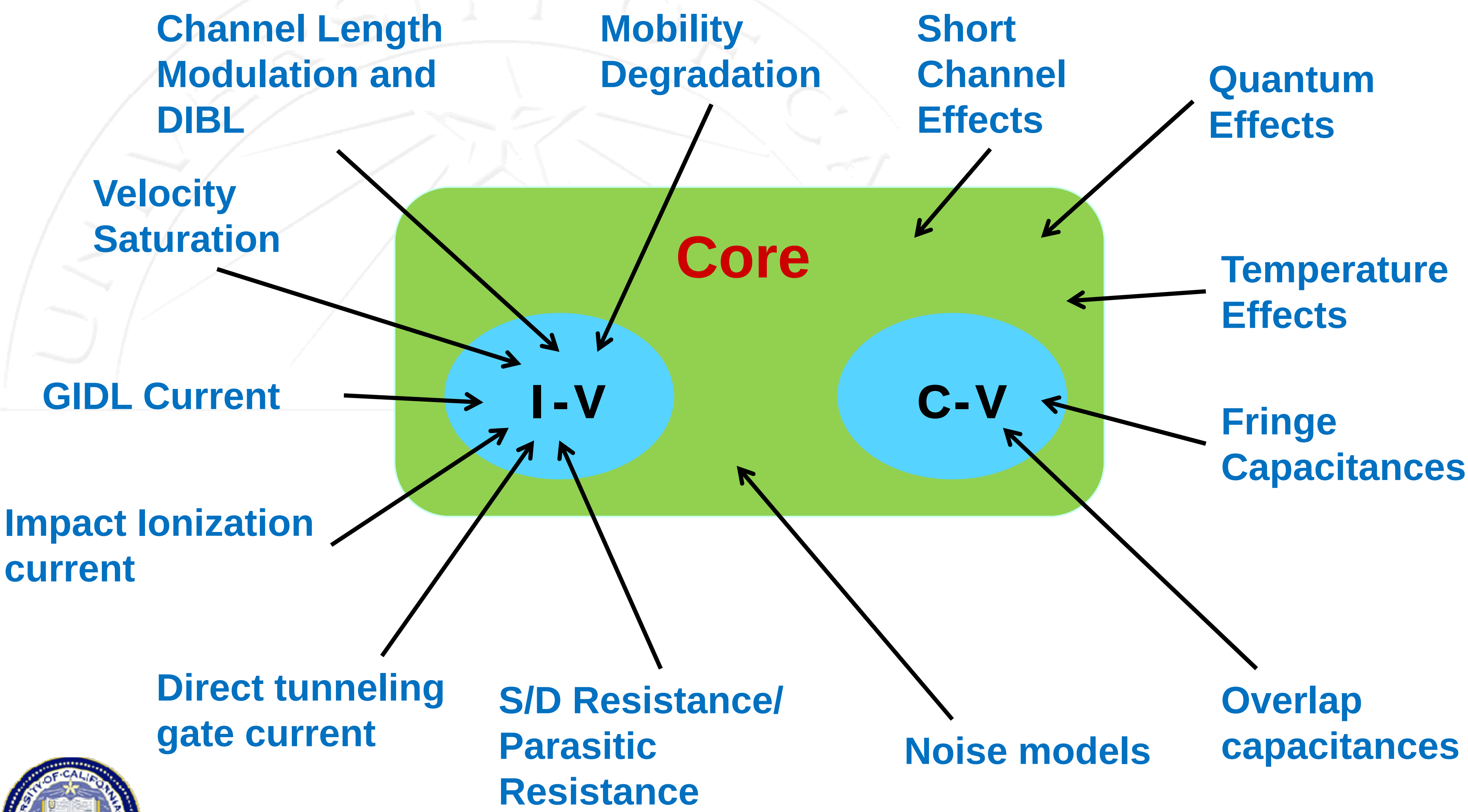
Blue – BSIM6 model







BSIM6 Model Development



All effects incorporated in BSIM6.

Mobility Model

- Mobility model has been adopted from BSIM4

$$\mu_{eff} = \frac{U0}{1 + (UA + UC \cdot V_{bsx}) \cdot E_{eff}^{EU} + \dfrac{UD}{\left[\dfrac{1}{2}\left(1 + \dfrac{q_{is}}{q_{bs}}\right)\right]^{UCS}}}$$

where

$$\eta = \begin{cases} \frac{1}{2} \cdot ETAMOB & \text{for NMOS} \\ \frac{1}{3} \cdot ETAMOB & \text{for PMOS} \end{cases}$$

$$E_{effs} = 10^{-8} \cdot \left(\frac{q_{bs} + \eta \cdot q_{is}}{\epsilon_{ratio} \cdot Tox} \right)$$

MV/cm

$$V_{dsx} = \sqrt{V_{ds}^2 + 0.01} - 0.1$$

$$V_{bsx} = -\left[V_s + \frac{1}{2}(V_{ds} - V_{dsx}) \right]$$

Output conductance

- DIBL Effect (from BSIM4)

$$PVAGfactor = \begin{cases} 1 + PVAG \cdot \frac{q_{im}}{E_{sat}L_{eff}} & \text{for } PVAG > 0 \\ \frac{1}{1 - PVAG \cdot \frac{q_{im}}{E_{sat}L_{eff}}} & \text{for } PVAG < 0 \end{cases} \tag{3.104}$$

$$\theta_{rout} = \frac{0.5 \cdot PDIBL1}{cosh\left(DROUT \cdot \frac{L_{eff}}{L_{t0}}\right) - 1} + PDIBL2 \tag{3.105}$$

$$V_{ADIBL} = \frac{q_{ia} + 2kT/q}{\theta_{rout}} \cdot \left(1 - \frac{V_{dsat}}{V_{dsat} + q_{ia} + 2kT/q}\right) \cdot PVAGfactor \cdot \frac{1}{1 + PDIBLCB \cdot V_{bsx}} \tag{3.106}$$

$$M_{DIBL} = \left(1 + \frac{V_{ds} - V_{dseff}}{V_{ADIBL}}\right) \tag{3.107}$$

CV Model

- Physical CV Model (including poly-depletion effect)

$$v_{gpqm} = v_g - v_{fb} - \psi_p$$

$$\chi_s = \sqrt{0.25 + \frac{v_{gpqm} + 2 \cdot q_s}{\gamma_g^2}}$$

$$\chi_d = \sqrt{0.25 + \frac{v_{gpqm} + 2 \cdot q_{deff}}{\gamma_g^2}}$$

$$T_1 = \frac{v_{gpqm} + 2 \cdot q_s}{1 + 2 \cdot \chi_s}$$

$$T_2 = \frac{v_{gpqm} + 2 \cdot q_{deff}}{1 + 2 \cdot \chi_d}$$

$$T_4 = \frac{(q_s - q_{deff})^2}{3(\chi_s + \chi_d)^3}$$

$$T_7 = \frac{0.8 \cdot \left[(\chi_s + \chi_d)^2 + \chi_s \cdot \chi_d\right]}{1 + q_s + q_{deff}} + \frac{2}{\gamma_g^2}$$

$$Q_b = T_1 + T_2 + \left[T_4 \cdot T_7 - n_q \cdot \left(q_s + q_{deff} + \frac{(q_s - q_{deff})^2}{3(1 + q_s + q_{deff})}\right)\right]$$

$$Q_s = \frac{n_q}{3}\left[2 \cdot q_s + q_{deff} + \frac{1 + 0.8 \cdot q_s + 1.2 \cdot q_{deff}}{2}\left(\frac{q_s - q_{deff}}{1 + q_s + q_{deff}}\right)^2\right]$$

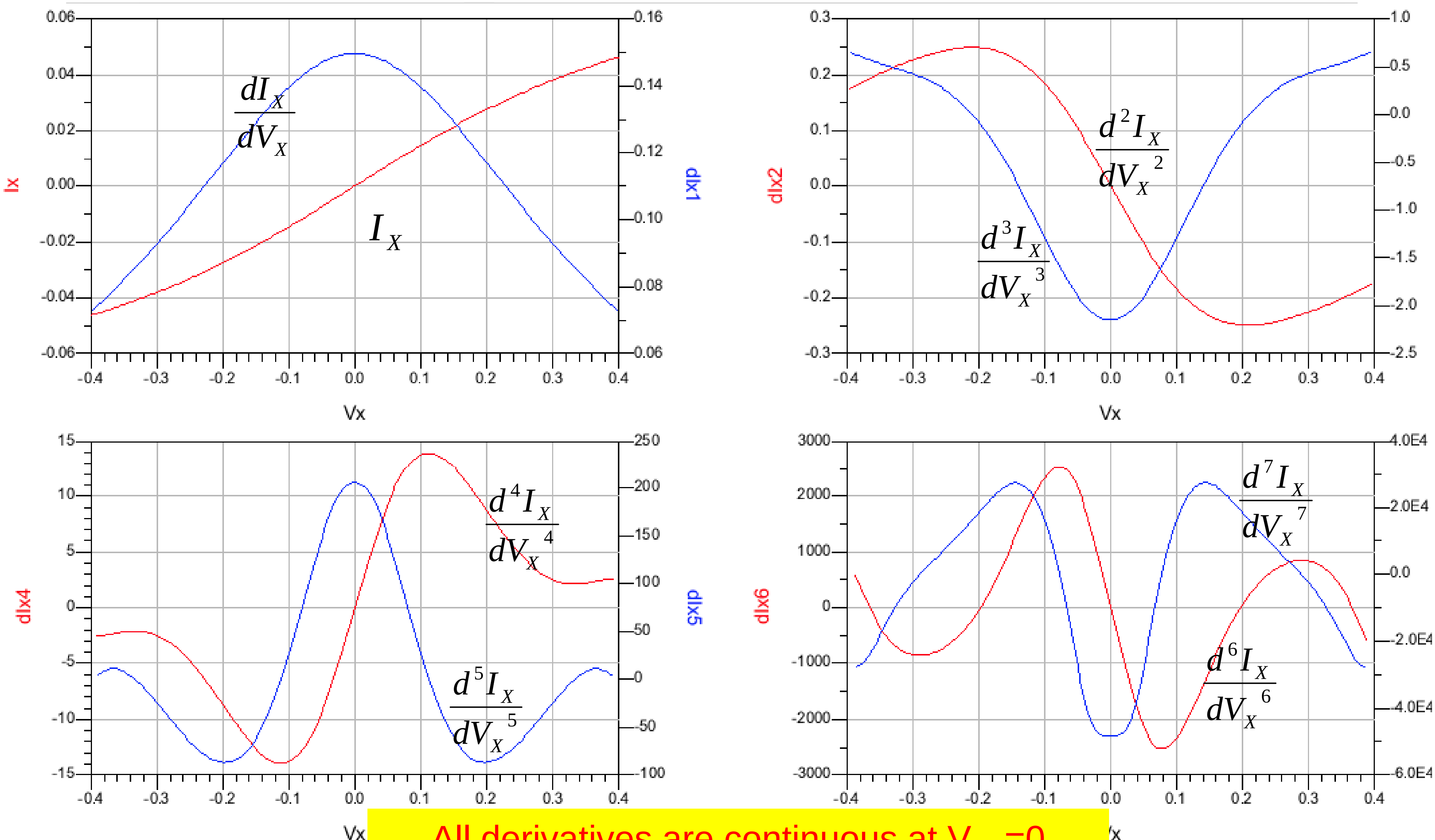
$$Q_d = \frac{n_q}{3}\left[q_s + 2 \cdot q_{deff} + \frac{1 + 1.2 \cdot q_s + 0.8 \cdot q_{deff}}{2}\left(\frac{q_s - q_{deff}}{1 + q_s + q_{deff}}\right)^2\right]$$

Short Channel CV Model has been added in BSIM6.0.0 Beta5

I_{DS}-V_X Gummel Symmetry

I_{DS} vs V_X

(V_D=V_X & V_S=-V_X)

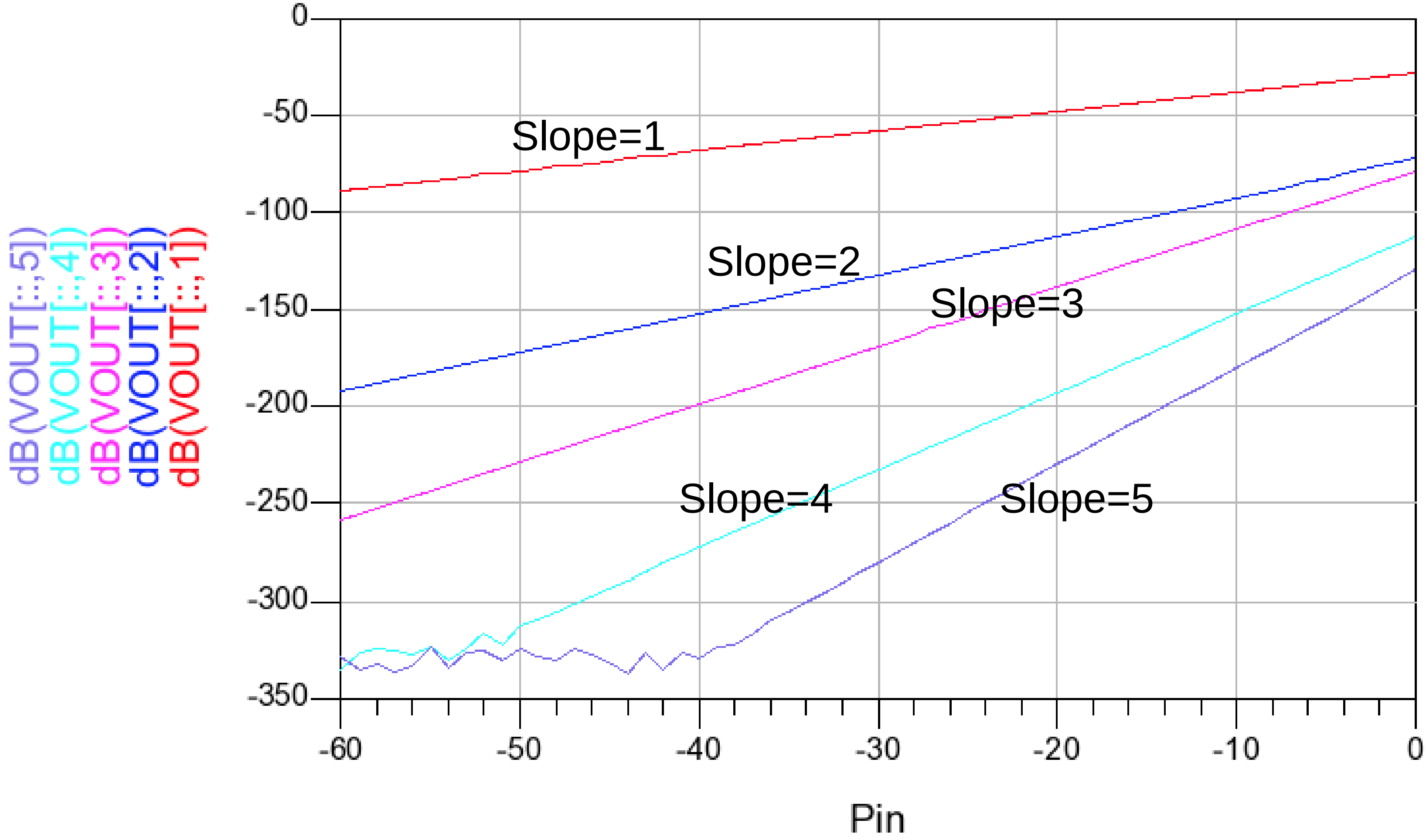


All derivatives are continuous at V_{DS}=0

(N+1 derivatives exist, where N=DELTA)

Harmonic Balance Simulation

- BSIM6 gives correct slope for all harmonics



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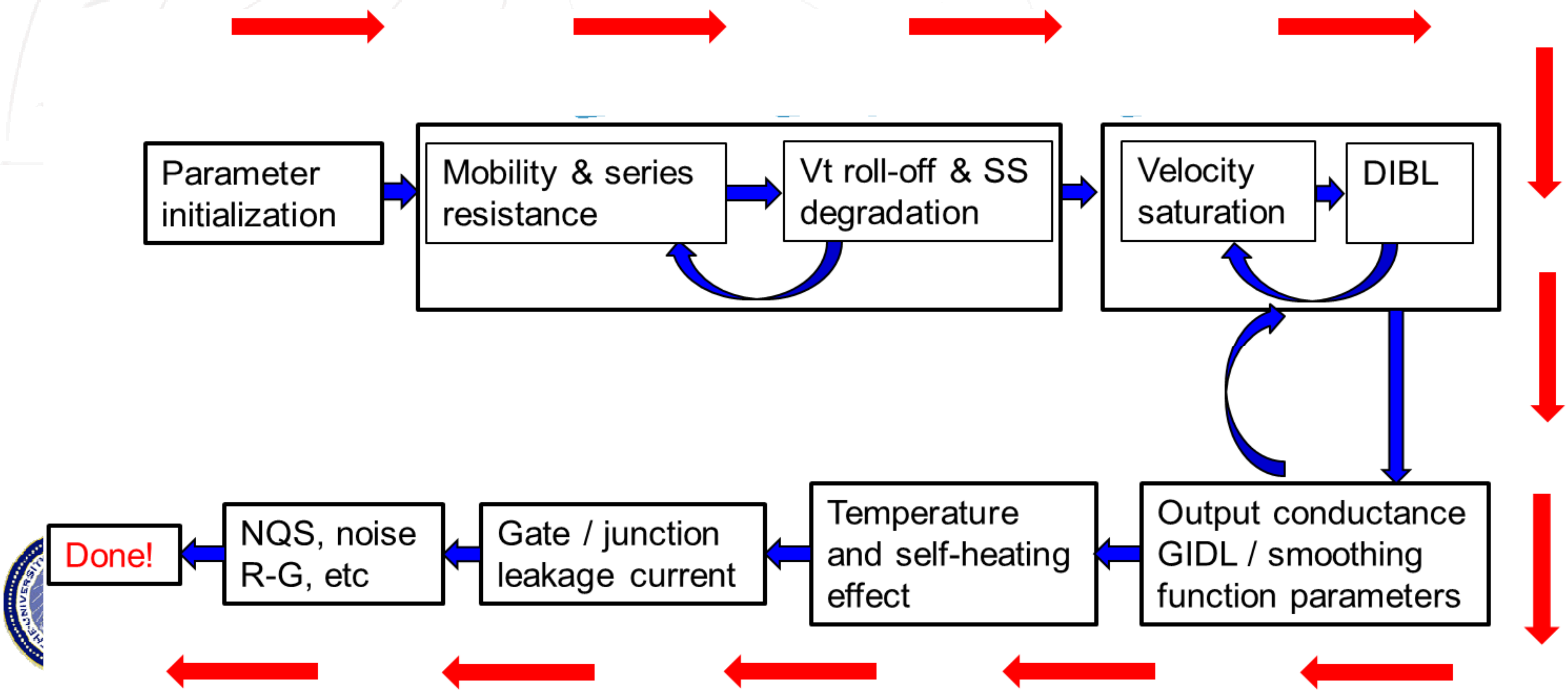
Global Extraction Procedure

- Single set of parameters for entire range of length
- Accurate evaluation of next technology nodes
- Global extraction procedure has been developed
  - 200+ parameters can't be extracted using optimizer
  - Step by step approach needed



BSIM6 Model Validation: $I_{DS}V_{GS}$ at V_{DS}=0.05V for different V_{BS}

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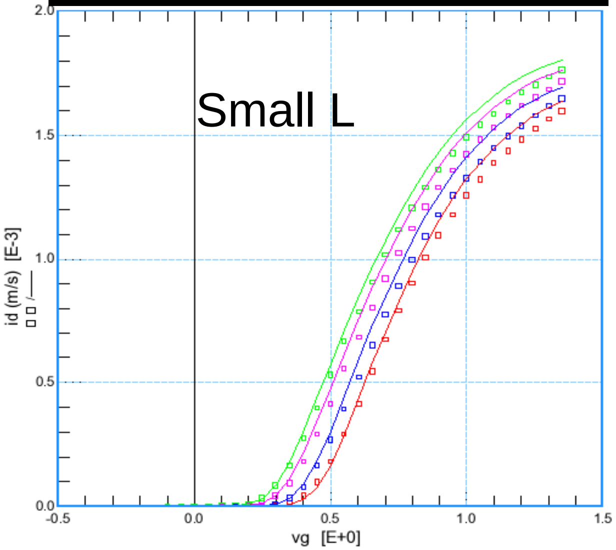

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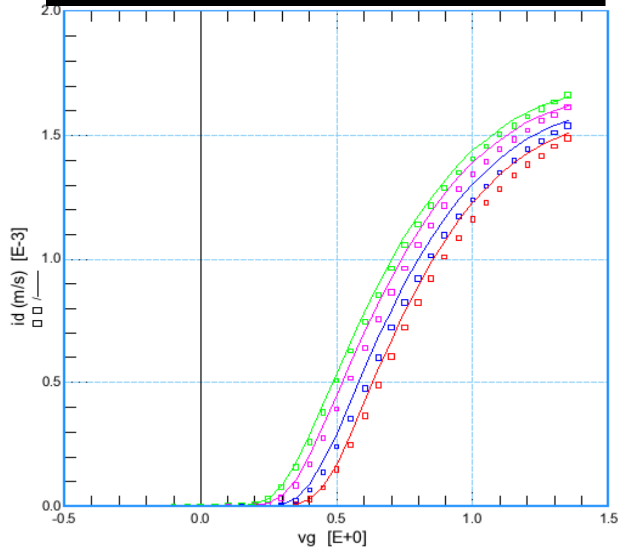

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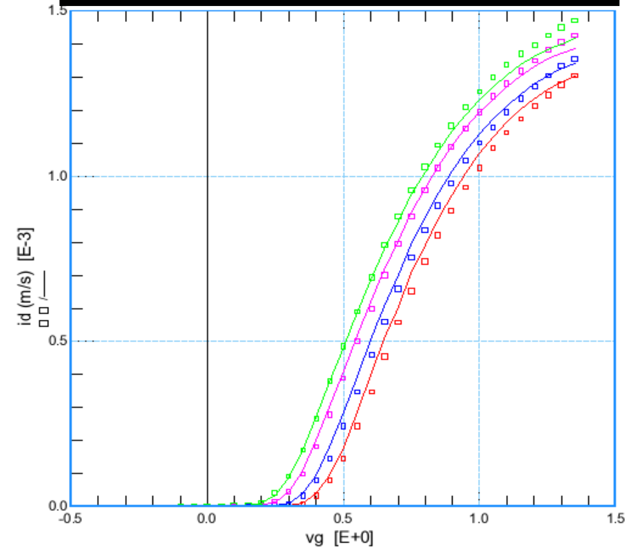

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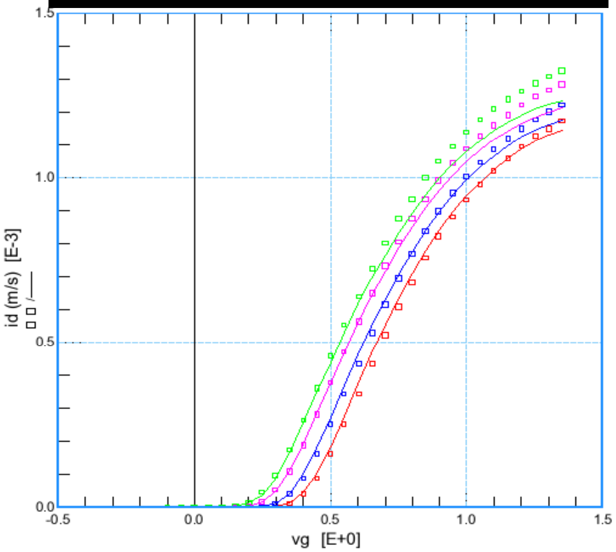

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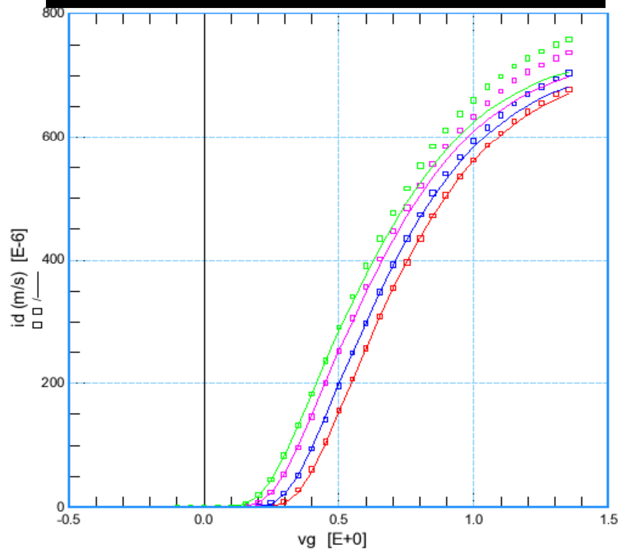

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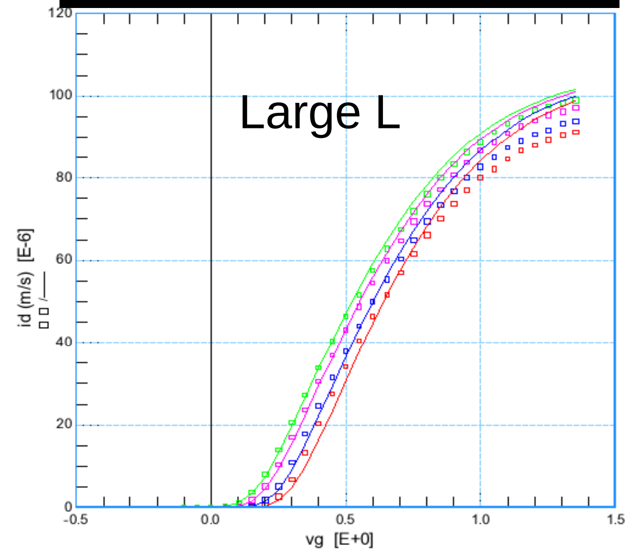

BSIM6 Model Validation: Width Scaling

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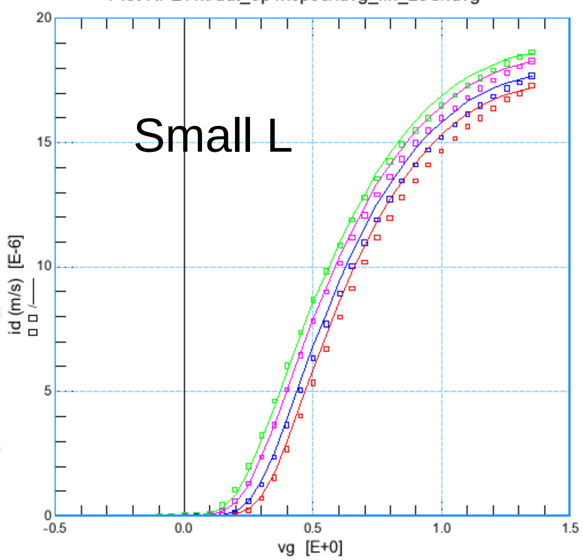

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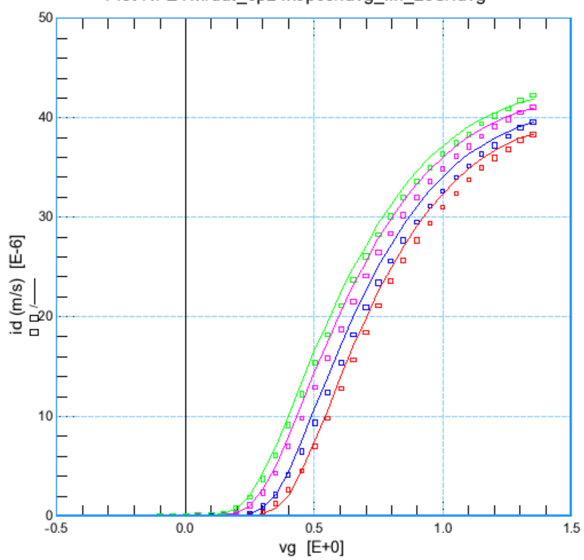

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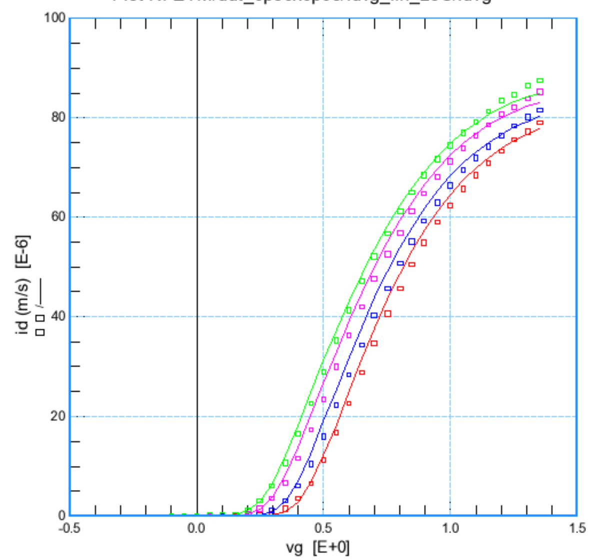

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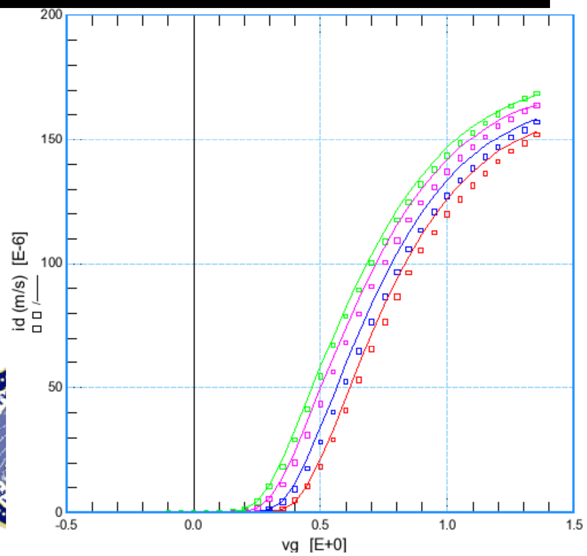

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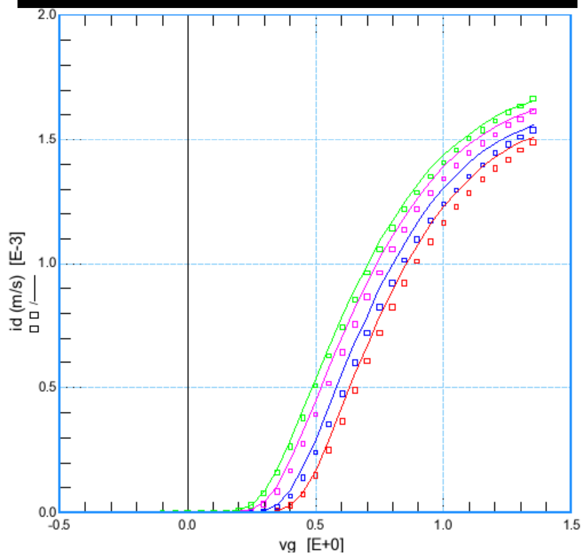

Conclusion

- Rapid development
  - BSIM6.0.0 Beta7 released on 28th Feb. 2012
  - From scratch to production level in 15 months!
- Charge based physical compact model
  - Physical effects & Parameter names matched to BSIM4 → No new training required for engineers
  - Smooth charge/current/capacitance & derivatives
- Model is symmetric and continuous around $V_{DS}=0$
  - Fulfills Gummel symmetry and AC symmetry
  - Shows accurate slope for harmonic balance simulation
- BSIM4's extraction methodology can be easily used for BSIM6 → fast deployment & lower cost
- Under standardization review at CMC

Acknowledgement

- Cadence
- Synopsys
- Accelicon
- ADI
- TI
- IBM
- ST
- Magma
- All CMC Members

BSIM-EPFL Collaboration

BSIM and EPFL groups have agreed to collaborate on the long-term development and support of BSIM6 as an open-source MOSFET SPICE models for worldwide use. This is an exciting opportunity to leverage the long history and large user base of the BSIM model with the long experience and active role of EPFL for furthering charge-based compact model.