Global Geometrical Scaling in BSIM6

Y. S. Chauhan[1,2], M. Chalkiadaki[3], S. Venugopalan[2], M. A. Karim[2], N. Paydavosi[2], S. Jandhyala[2], J. P. Duarte[2], C. Enz[3], A. Niknejad[2] and C. Hu[2]

[1]IIT Kanpur, India

[2]UC Berkeley, USA

[3]EPFL Switzerland

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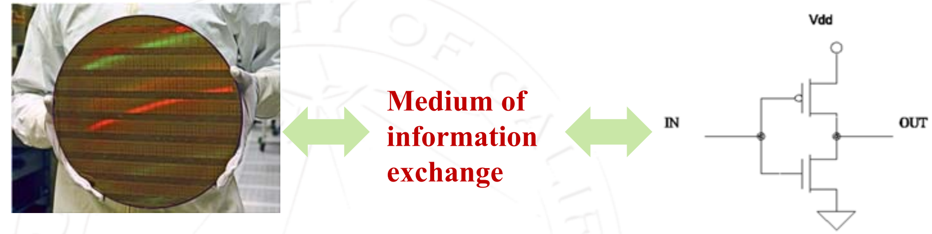
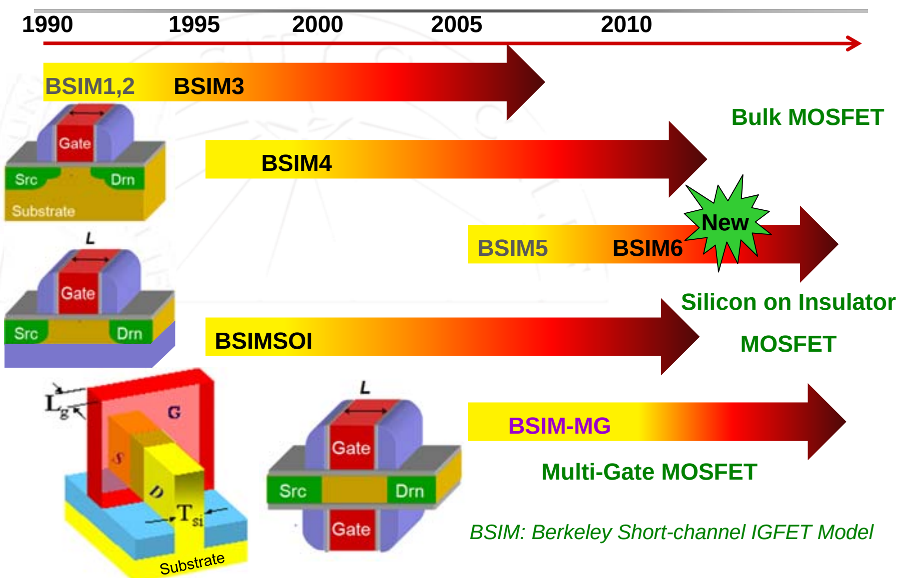
MOS-AK San Francisco

SPICE Transistor Modeling



- **Simulation Time**
  - ~ 10µs per DC data point
  - No complex numerical method allowed
- **Accuracy requirements**
  - ~ 1% RMS Error after fitting
- **Excellent Convergence**
- **Example: BSIM-CMG**
  - 5,000 lines of VA code
  - 50+ parameters
  - Open-source software implemented in major EDA tools

BSIM Family of Compact Device Models



BSIM: Berkeley Short-channel IGFET Model

BSIM6: Charge based MOSFET model

- BSIM6 – Next BSIM Bulk MOSFET model
  - Charge based core derived from Poisson's solution
  - Real device effects (SCE, CLM etc.) from BSIM4
  - *Parameter names matched to BSIM4*
- Physical Capacitance model
  - Short channel CV–Velocity saturation & CLM
- *Symmetry*
  - Currents & derivatives are symmetric @ VDS=0
  - Capacitances & derivatives are symmetric @VDS=0
  - Provide accurate results in Harmonic Distortion simulation
- Continuous in all regions of operations
- Better Statistical Modeling using physical parameters

Physics of BSIM6 Model

- Gauss' Law

$$V_G - V_{FB} - \Psi_S = -\frac{Q_{si}}{C_{ox}} = -\frac{Q_i + Q_b}{C_{ox}}$$

- Poisson's solution for long channel MOSFET

$$\frac{Q_{si}}{\Gamma C_{ox}\sqrt{V_t}} = \mp\sqrt{e^{-\frac{\Psi_S}{V_t}} + \frac{\Psi_S}{V_t} - 1 + e^{-\frac{2\Phi_F + V_{ch}}{V_t}}\left(e^{\frac{\Psi_S}{V_t}} - \frac{\Psi_S}{V_t} - 1\right)}$$

- Bulk charge density is given by

$$\frac{Q_b}{\Gamma C_{ox}\sqrt{V_t}} = \mp\sqrt{e^{-\frac{\Psi_S}{V_t}} + \frac{\Psi_S}{V_t} - 1}$$

- Combining these, we have

$$V_G - V_{FB} - \Psi_S = -\frac{Q_i}{C_{ox}} \pm \Gamma\sqrt{V_t\left(e^{-\frac{\Psi_S}{V_t}} + \frac{\Psi_S}{V_t} - 1\right)}$$

Physics of BSIM6 Model

- Defining Pinch-off potential $\Psi_P = \Psi_S$, when $Q_i=0$

$$V_G - V_{FB} - \Psi_P = sign(\Psi_P)\Gamma\sqrt{V_t\left(e^{-\frac{\Psi_P}{V_t}} + \Psi_P - 1\right)}$$

$$-\frac{Q_i}{\Gamma C_{ox}\sqrt{V_t}} = \sqrt{\frac{\Psi_S}{V_t} + e^{\frac{\Psi_S - 2\Phi_F - V_{ch}}{V_t}}} - \sqrt{\frac{\Psi_S}{V_t}}$$

Ψ_P is evaluated from implicit equation

- For Ψ_S> few V_t, we have

$$-\frac{Q_i}{C_{ox}} = n_q(\Psi_P - \Psi_S)$$

n_q is the slope factor

- Inversion Charge linearization

*Ref.: Tsividis book & J.M. Sallese et al., Solid State Electronics

Physics of BSIM6 Model

- Using linearization approach and normalization

ACM/EKV/BSIM5 ignored the circled term

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

- No approximation to solve the charge equation compared to other models.
- Solved the charge equation analytically

Drain current with velocity saturation

- Drain current

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

- Mobility model (ensures symmetry)

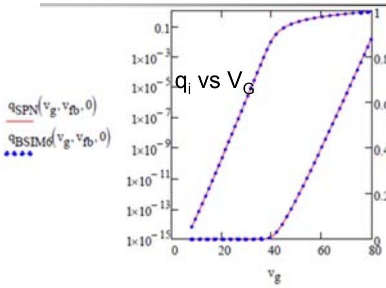
$$I_D = \frac{\mu_v}{\sqrt{1 + \left(\frac{\mu_v}{v_{sat}}\left|\frac{d\Psi_S}{dx}\right|\right)^2}}W\left(-Q_i\frac{d\Psi_S}{dx} + V_T\frac{dQ_i}{dx}\right)$$

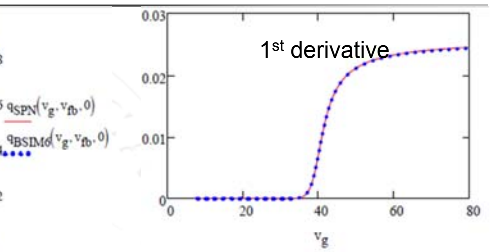
$$-\frac{Q_i}{C_{ox}} = n_q(\Psi_P - \Psi_S), q = \frac{-Q_i}{2n_q C_{ox} V_T}, i_d = \frac{I_D}{2n_q\frac{W}{L}\mu_v C_{ox} V_t^2}, \lambda_c = \frac{2\mu_v V_t}{v_{sat} L}$$

- Using charge linearization & normalization

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

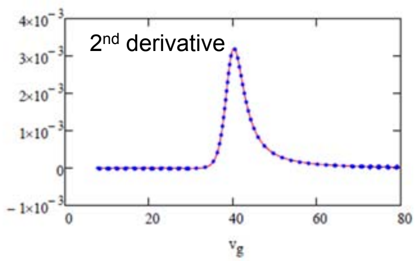
Normalized Q_i-V_G & derivatives

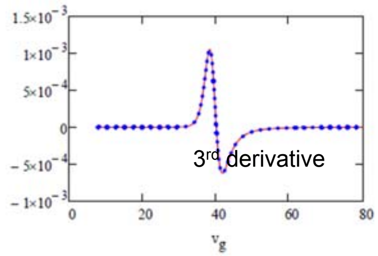




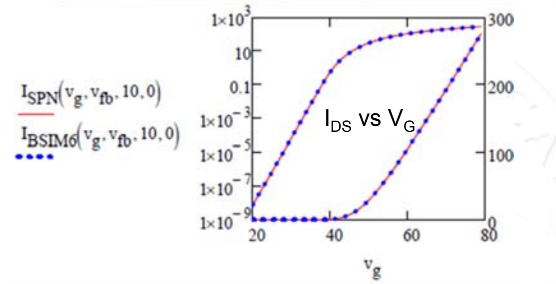
Red – Numerical Surf. Pot. model

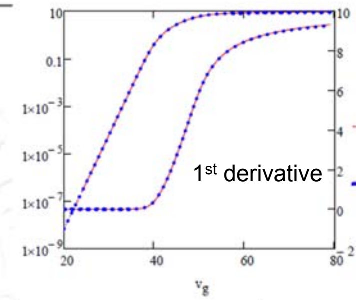
Blue – BSIM6 model

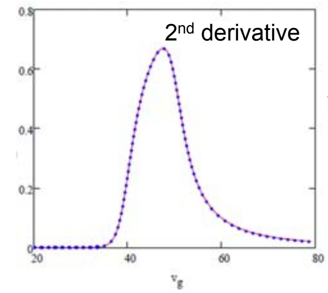




Normalized I_{DS}-V_{GS} & derivatives







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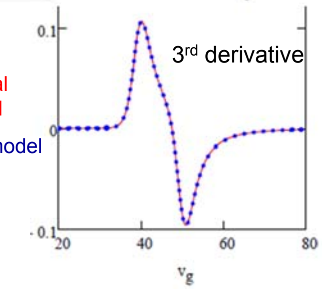


Mobility Model

- Mobility model has been adopted from BSIM4

BSIM4

$$\mu_{eff} = \frac{U0 \cdot f(L_{eff})}{1+(UA+UC\cdot V_{bseff})\left[\frac{V_{gsteff}+C_0\cdot(VTH0-VFB-\Phi_s)}{TOXE}\right]^{EU}+UD\left(\frac{V_{th}\cdot TOXE}{V_{gsteff}+2\sqrt{V_{th}^2+0.0001}}\right)}$$

BSIM6

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

where

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

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

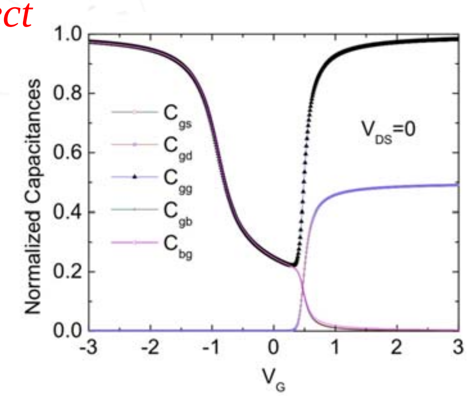
MV/cm

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

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

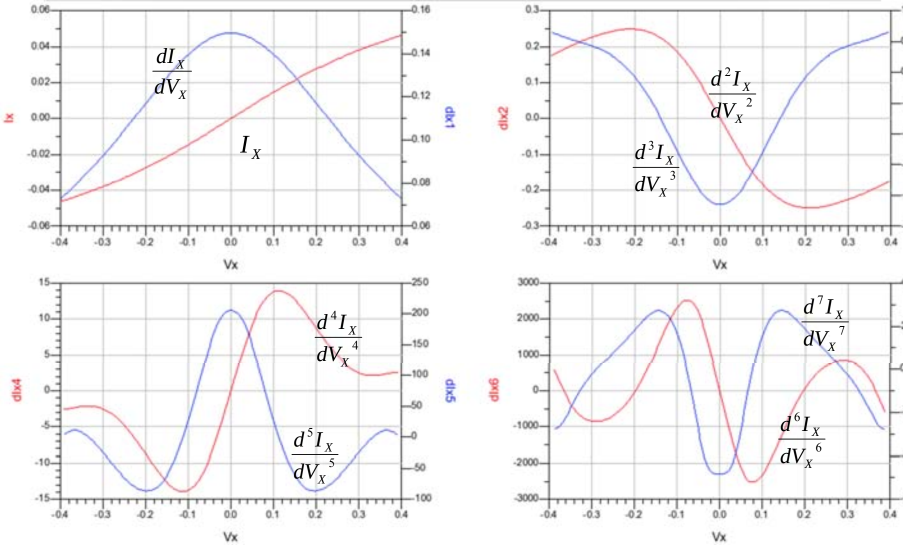
CV Model

- Physical Capacitance Model
- Poly-depletion & *Quantum Mechanical Effect*
- Channel Length Modulation
- *Velocity Saturation Effect*
- Charge conservation



I_X vs V_X (V_D=V_X & V_S=-V_X)

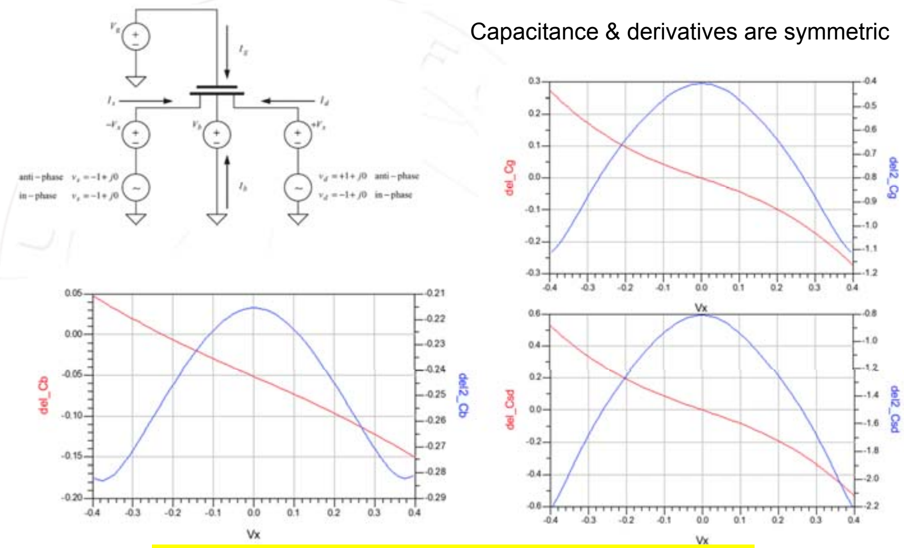
I_{DS}-V_X Gummel Symmetry



All derivatives are continuous at V_{DS}=0

AC Symmetry test

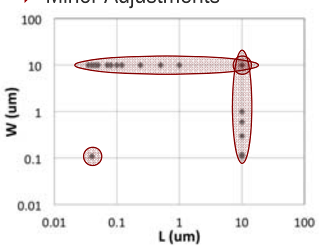
(C. McAndrew, IEEE TED, 2006)



Capacitances and derivatives are continuous at V_{DS}=0

General Information

- BSIM6 is validated against ST 40nm Bulk CMOS Technology Measurements
- Almost the same Parameter Extraction Procedure with BSIM4 is followed
  - Minor Adjustments



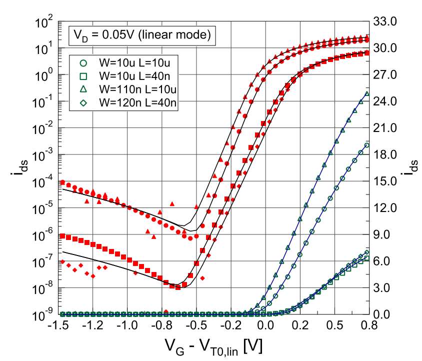
- The results are in form of Normalized Quantities

$$i_{ds} = \frac{I_{DS}}{I_{spec}}, \quad g_m = \frac{G_m}{G_{spec}}, \quad g_{ds} = \frac{G_{ds}}{G_{spec}}$$

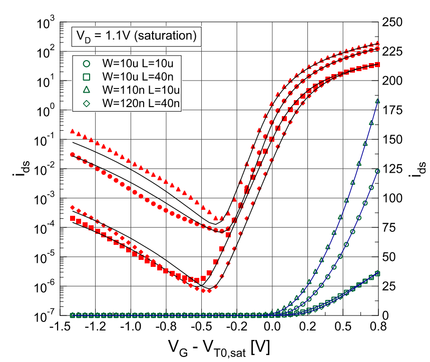
$$G_{spec} = \frac{I_{spec}}{U_T}$$

Evaluation of the Model for the Corner DUTs – 1/3

$i_{ds,lin}$ vs. $V_G - V_{T0,lin}$

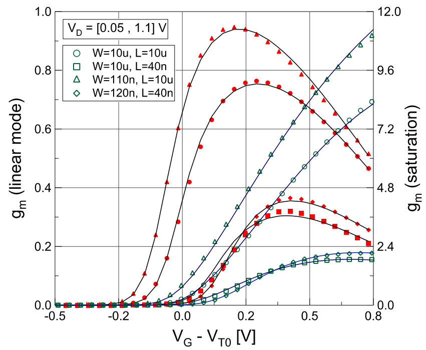


$i_{ds,sat}$ vs. $V_G - V_{T0,sat}$

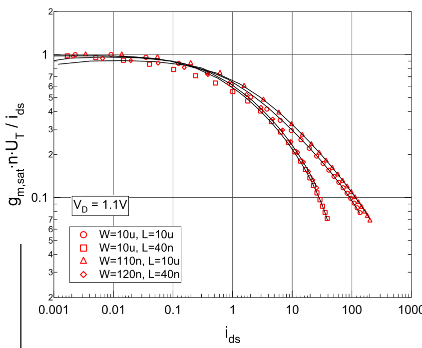


Evaluation of the Model for the Corner DUTs – 2/3

$g_m\ vs.\ V_G - V_{T0}$



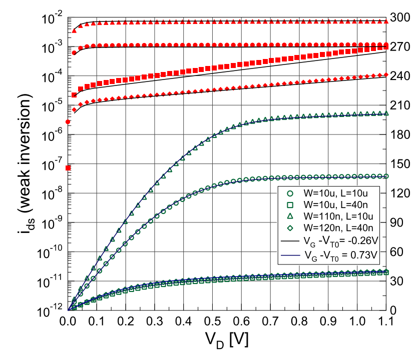
$ng_{m,sat}/i_{ds}\ vs.\ i_{ds}$



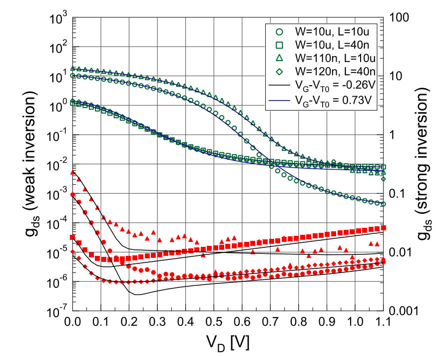
$$\frac{nG_mU_T}{I_D} = \frac{\frac{nG_{m,sat}}{I_{spec}}U_T}{\frac{I_{DS}}{I_{spec}}} = \frac{ng_{m,sat}}{i_{ds}}$$

Evaluation of the Model for the Corner DUTs – 3/3

$i_{ds}\ vs.\ V_D$



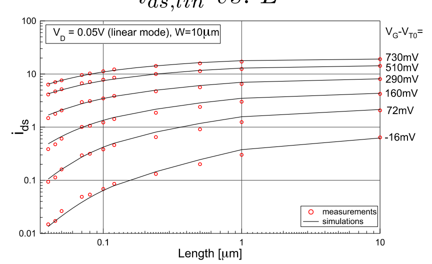
$g_{ds}\ vs.\ V_D$



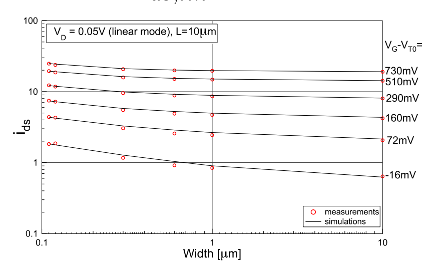
Correct Behavior for the Corner Geometries

Evaluation of the Model's Scalability – 1/2

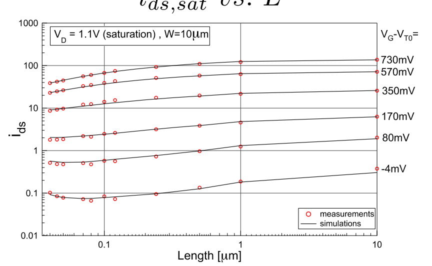
$i_{ds,lin}\ vs.\ L$



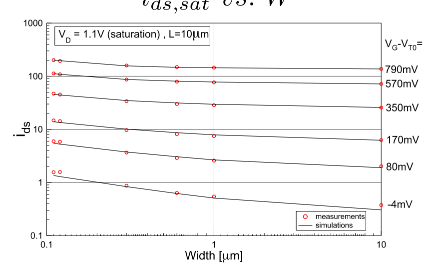
$i_{ds,lin}\ vs.\ W$



$i_{ds,sat}\ vs.\ L$



$i_{ds,sat}\ vs.\ W$



Study of the Model's Symmetry

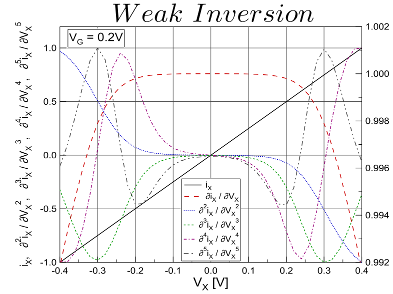
- Gummel Symmetry Test (GST) in Weak & Strong Inversion
- Test BSIM6 for I_X Current and its Derivatives up to 5[th] Degree

$$I_X = I_D - I_S\ vs.\ V_X = V_D - V_S,\ when\ V_D = -V_S$$

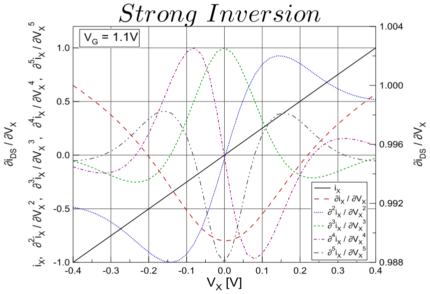
- Quantities are Normalized to their Maximum Values

$$i_X = \frac{I_X}{max(I_X)} \quad and \quad \frac{\partial^n i_X}{\partial V_X^n} = \frac{(\partial^n I_X)/\partial V_X^n}{max(\partial^n I_X/\partial V_X^n)}$$

Weak Inversion



Strong Inversion



Smooth behavior around V_{DS}=0V

BSIM6 model summary

- Rapid development: Released **BSIM6.0.0-beta8B in Sept. 2012**
- Charge based physical compact model
  - Physical effects & Parameter names matched to BSIM4
  - Smooth charge/current/capacitance & derivatives
- 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 in CMC

Acknowledgement

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  - Pragya Kushwaha
  - Chadan Yadav
  - Shantanu Agnihotri
- SOITEC
- LETI
- ST Microelectronics
- Analog Devices
- Texas Instruments
- IBM
- TSMC
- Global Foundries
- All other CMC Members

BSIM6 References

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