BSIM4.3.0 Model

Enhancements and Improvements Relative to BSIM4.2.1

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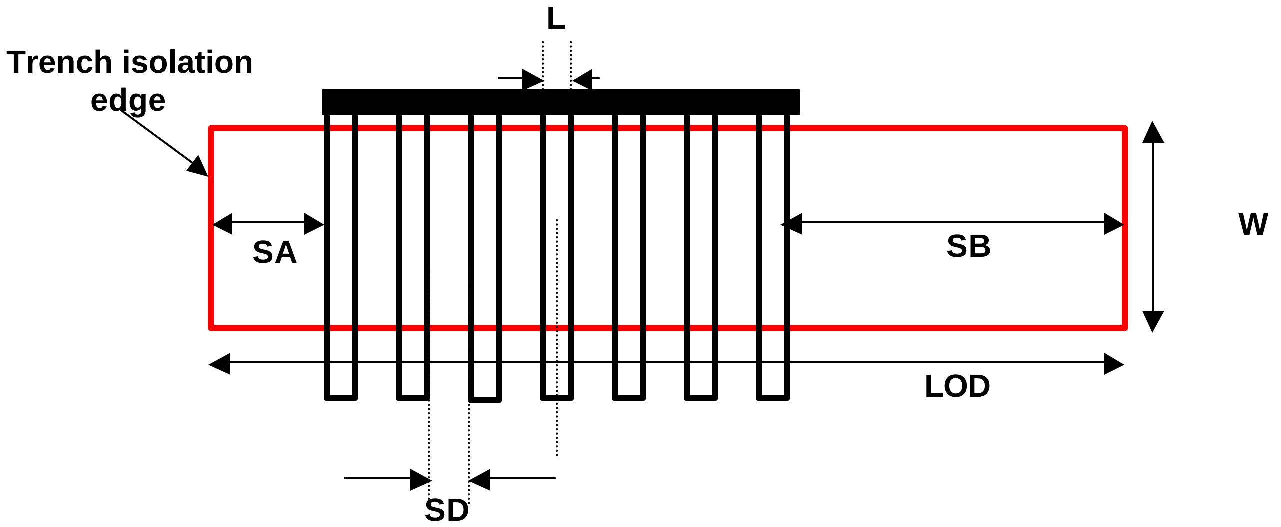
OUTLINE

New Features of BSIM4.3.0 beta’ release

- ❖Stress effect model
- ❖New temperature model
- ❖Holistic noise model enhancement
- ❖Unified current saturation model
  - ❑Velocity saturation
  - ❑Velocity overshoot
  - ❑Source injection thermal velocity limit
- ❖New document for multi-layer gate tunneling
- ❖Forward body bias

Model for Isolation-induced Stress Effects



Instance parameters added: SA, SB, SD

SD is neighbour finger distance which is constant throughout all the fingers.

Stress effect calculation only if: 1) both SA and SB are given and are larger than 0 for finger number NF=1; 2) SA, SB and SD are all given and are larger than 0 for NF >1

Intermediate geometry definitions :

$$LOD = SA + SB + NF \cdot L + (NF - 1) \cdot SD$$

Mobility Model With STI Stress

Define :

$$r_{m_{eff}} = \Delta m_{eff} / m_{effo} = (m_{eff} - m_{effo}) / m_{effo}$$

$$= \frac{m_{eff}}{m_{effo}} - 1$$ (relative mobility change due to stress)

So, $$\frac{m_{eff}}{m_{effo}} = 1 + r_{m_{eff}}$$ (Vth insensitive to Lod, SA and/or SB)

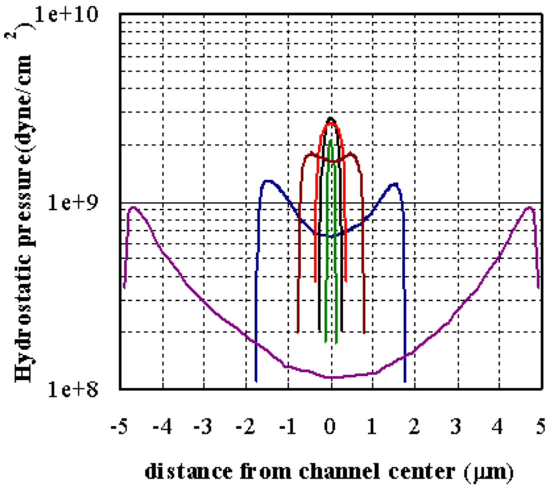
Stress Effects Model-1/LOD Model

- Simple stress distribution function: 1/(SA+L/2), 1/(SB+L/2)
- $r_{m_{eff}}$ expression with LOD, L, W, and T dependence

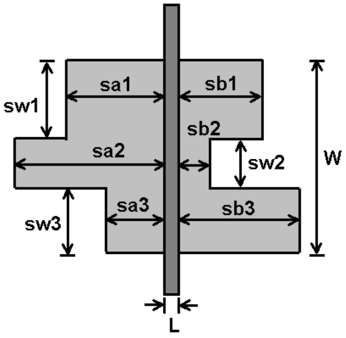
$$r_{meff} = \frac{ku0}{Kstress\_u0} \cdot (Inv\_sa + Inv\_sb)$$

$$Inv\_sa = \frac{1}{SA + 0.5 \cdot L_{drawn}} \qquad Inv\_sb = \frac{1}{SB + 0.5 \cdot L_{drawn}}$$

$$Kstress\_u0 = \left(1 + \frac{LKU0}{(L_{drawn} + XL)^{LLODKU0}} + \frac{WKU0}{(W_{drawn} + XW + WLOD)^{WLODKU0}} + \frac{PKU0}{(L_{drawn} + XL)^{LLODKU0} \cdot (W_{drawn} + XW + WLOD)^{WLODKU0}}\right) \times \left(1 + TKU0 \cdot \left(\frac{Temperature}{TNOM} - 1\right)\right)$$



- All data can be fitted well with only one set of parameters (ie. Global model for LOD effect) and do not need extra binning parameters if binning is desired.



- For multi-finger device:

$$Inv\_sa = \frac{1}{NF} \sum_{i=0}^{NF-1} \frac{1}{SA + 0.5 \cdot L_{drawn} + i \cdot (SD + L_{drawn})} \qquad Inv\_sa = \frac{1}{NF} \sum_{i=0}^{NF-1} \frac{1}{SB + 0.5 \cdot L_{drawn} + i \cdot (SD + L_{drawn})}$$

- For irregular LOD device:

$$\frac{1}{SA_{eff} + 0.5 \cdot L_{drawn}} = \sum_{i=1}^{n} \frac{sw_i}{W_{drawn}} \cdot \frac{1}{sa_i + 0.5 \cdot L_{drawn}} \qquad \frac{1}{SB_{eff} + 0.5 \cdot L_{drawn}} = \sum_{i=1}^{n} \frac{sw_i}{W_{drawn}} \cdot \frac{1}{sb_i + 0.5 \cdot L_{drawn}}$$

Stress Effect m_{eff}, u_{sat} Model

$$m_{eff} = \frac{1 + r_{meff}(SA, SB)}{1 + r_{meff}(SA_{ref}, SB_{ref})} m_{effo}$$

$$u_{sat} = \frac{1 + K \cdot r_{meff}(SA, SB)}{1 + K \cdot r_{meff}(SA_{ref}, SB_{ref})} u_{sato}$$

Where m_{effo} , u_{sato} are low field mobility, saturation velocity at SA_{ref}, SB_{ref}

Stress Effect Model to VTH0, K2, ETA0

$$Kstress\_vth0 = 1 + \frac{LKVTH0}{(L_{drawn} + XL)^{LLODKVTH}} + \frac{WKVTH0}{(W_{drawn} + XW + WLOD)^{WLODKVTH}} + \frac{PKVTH0}{(L_{drawn} + XL)^{LLODKVTH} \cdot (W_{drawn} + XW + WLOD)^{WLODKVTH}}$$

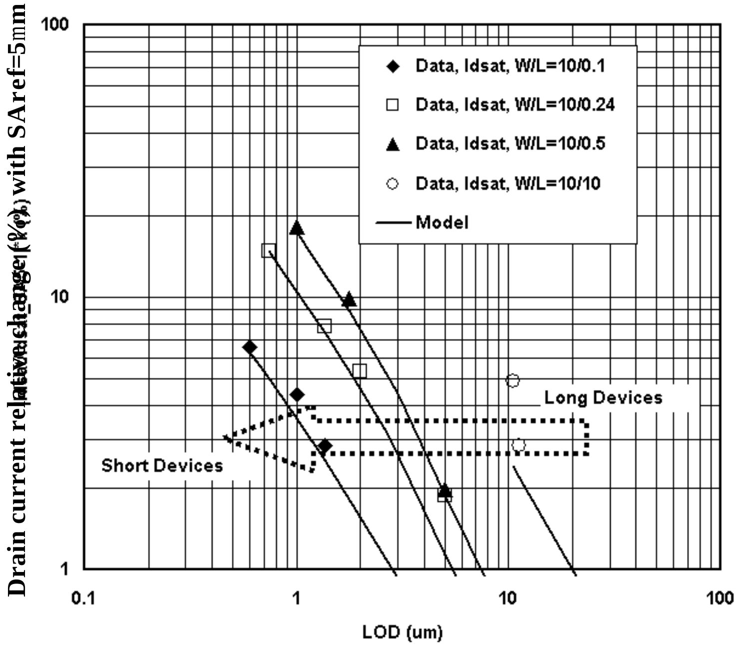
$$VTH0 = VTH0_{original} + \frac{KVTH0}{Kstress\_vth0} \cdot \left(Inv\_sa + Inv\_sb - Inv\_sa_{ref} - Inv\_sb_{ref}\right)$$

$$K2 = K2_{original} + \frac{STK2}{Kstress\_vth0^{LODK2}} \cdot \left(Inv\_sa + Inv\_sb - Inv\_sa_{ref} - Inv\_sb_{ref}\right)$$

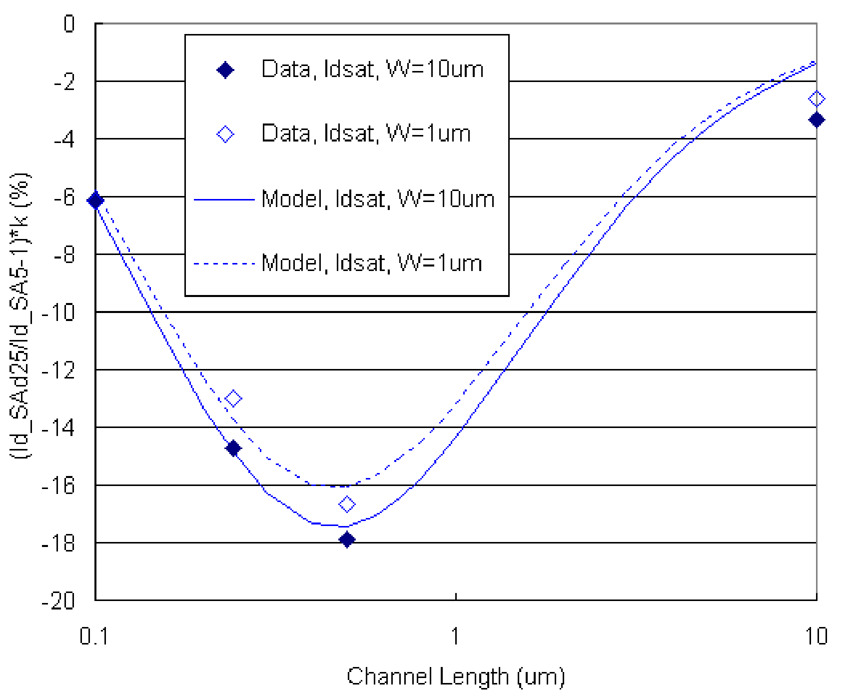
$$ETA0 = ETA0_{original} + \frac{STETA0}{Kstress\_vth0^{LODETA0}} \cdot \left(Inv\_sa + Inv\_sb - Inv\_sa_{ref} - Inv\_sb_{ref}\right)$$

Stress Effect Model Verification

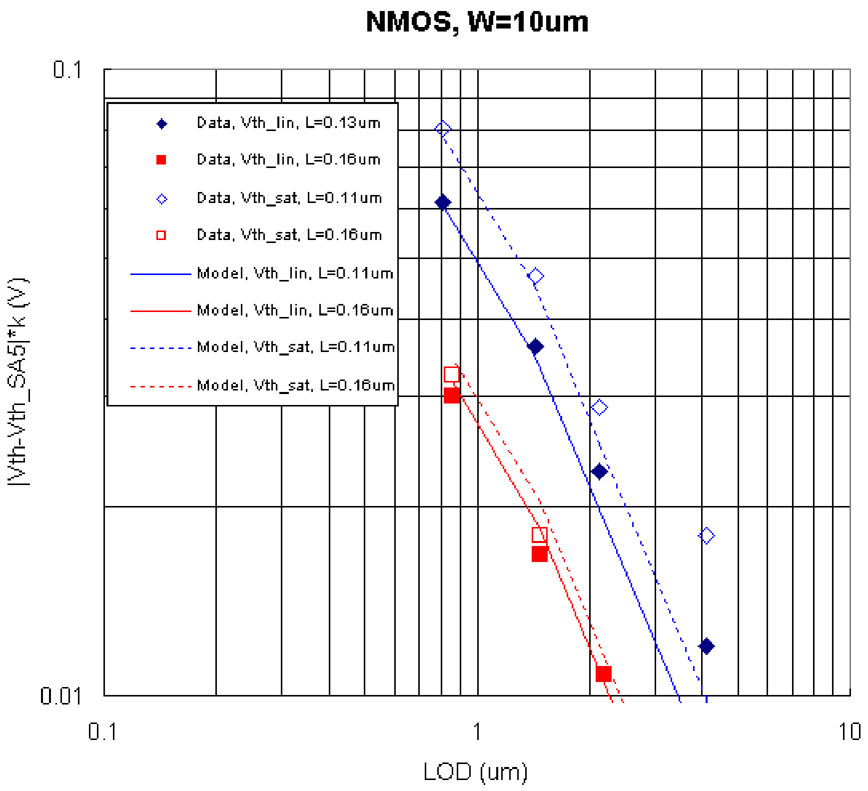
SA=SB

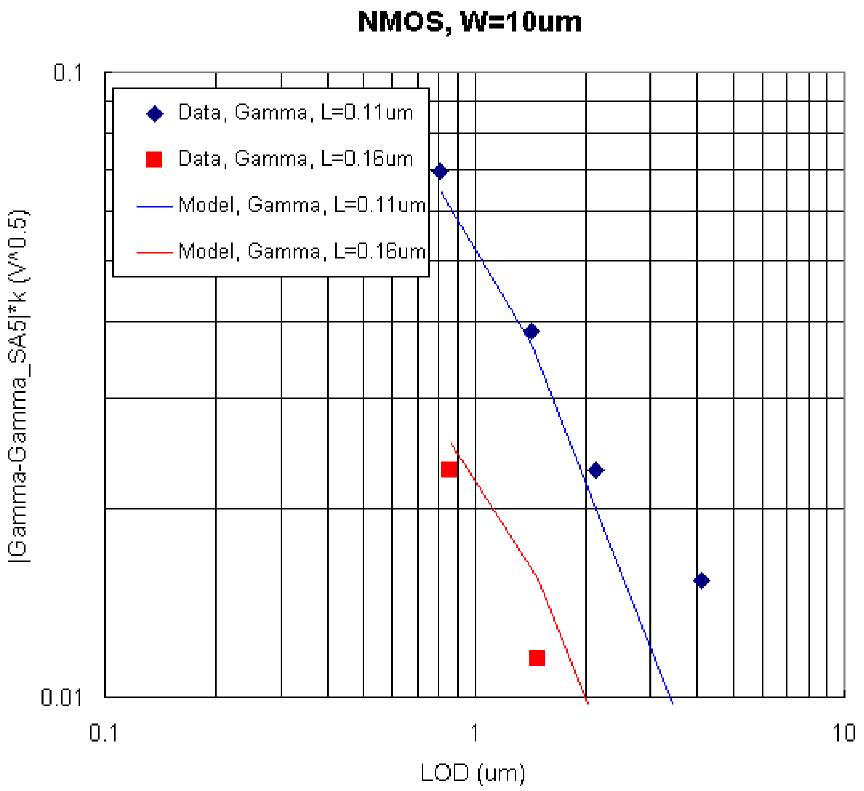


NMOS, W=10um vs W=1.0um

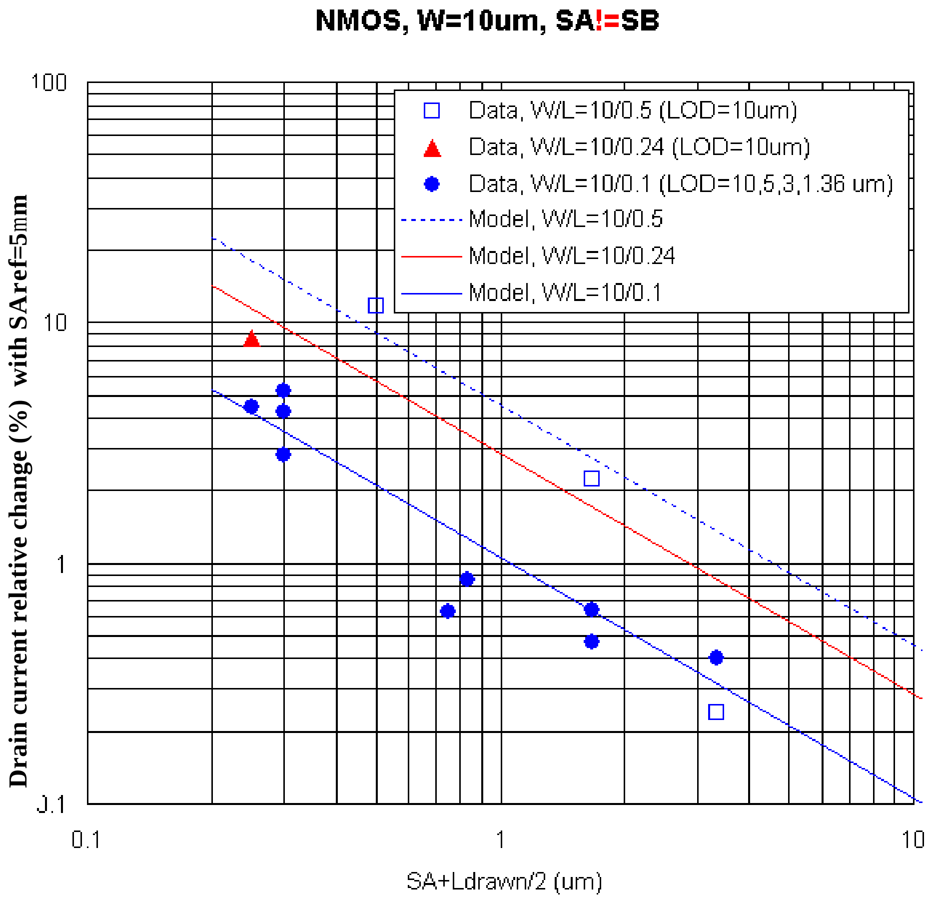


Stress Effect Model Verification





Stress Effect Model Verification



Temperature Model Enhancement

Temperature mode TEMPMOD created:

- **TEMPMOD = 0: current model with VFB enhancement**
- **TEMPMOD = 1: New format for vsat, prt, ua, ub, uc:**

$$PARAM(T) = PARAM(TNOM)\cdot\left[1 + TEMP\_COEFF\cdot(T - TNOM)\right]$$

Holistic Thermal Noise Model Enhancement

Refer to Chapter 9 of BSIM4 manual

$$q_{tnoi} = \boldsymbol{RNOIB} \cdot \left[1 + \boldsymbol{TNOIB} \cdot \boldsymbol{L}_{eff} \cdot \left(\frac{\boldsymbol{V}_{gsteff}}{\boldsymbol{E}_{sat} \boldsymbol{L}_{eff}} \right)^2 \right] \quad (9.2.5)$$

$$b_{tnoi} = \boldsymbol{RNOIA} \cdot \left[1 + \boldsymbol{TNOIA} \cdot \boldsymbol{L}_{eff} \cdot \left(\frac{\boldsymbol{V}_{gsteff}}{\boldsymbol{E}_{sat} \boldsymbol{L}_{eff}} \right)^2 \right] \quad (9.2.6)$$

Default RNOIA=0.577; RNOIB=0.37

Unified Current Saturation

-Velocity Overshoot Model

Price’s approximation to HD model:

$$J = qnmE_y\left(1+\frac{l}{mE_y}\frac{\partial E_y}{\partial x}\right)+qD\frac{\partial n}{\partial x}$$

Approximate solution of Price’s equation yields unified current expression that includes velocity saturation and velocity overshoot:

$$I_{DS,HD} = \frac{I_{DS0}}{1+\dfrac{V_{dseff}}{L_{eff}\,E_{sat}^{OV}}}$$

where $E_{sat}^{OV} = E_{sat}\left[1+\dfrac{LAMBDA}{L_{eff}\cdot m_{eff}}\cdot\dfrac{\left(1+\dfrac{V_{ds}-V_{dseff}}{Esat\cdot litl}\right)^2-1}{\left(1+\dfrac{V_{ds}-V_{dseff}}{Esat\cdot litl}\right)^2+1}\right]$ $\quad I_{DS0} = I_{DS}(BSIM4.2.1)\cdot\left(1+\dfrac{V_{dseff}}{L_{eff}E_{sat}}\right)$

Unified Current Saturation:

-Source–end Velocity Limit and Quasi-Ballistic Transport

HD transport source carrier velocity: $v_{sHD} = I_{DS,HD} \big/ Wq_s$

Ballistic transport source carrier velocity: $v_{sBT} = \dfrac{1-r}{1+r} VTL$

where VTL: thermal velocity, $r = \dfrac{L_{eff}}{XN \cdot L_{eff} + LC} \quad XN \geq 3.0$

Unified current expression with **velocity saturation, velocity overshoot and source velocity limit**:

$$I_{DS} = \frac{I_{DS,HD}}{\left[1 + \left(v_{sHD} / v_{sBT}\right)^{2MM}\right]^{1/2MM}}$$

Direct Tunneling through Multiple-Layer Gate Stacks

- Gate Current modeled as $J_G = Q_{INV} \cdot f_{IMP} \cdot T$
- For a single layer $T \propto \exp(-\alpha t_{oxe})$
- For two layer case $T \propto \exp(-\alpha_{new} t_{oxe})$ where

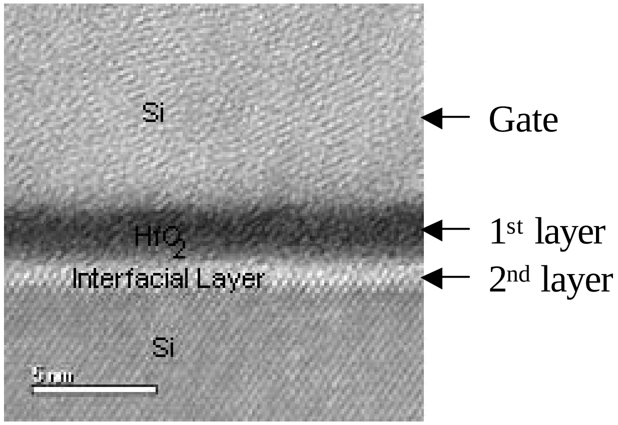
$$\alpha_{double} = \alpha_1 \cdot f + \alpha_2 \cdot (1 - f) + f \cdot (1 - f) \cdot \frac{V_{ox}}{3\hbar} \left(K_1 \cdot \sqrt{\frac{qm_1}{2 f_{B1}}} - K_2 \cdot \sqrt{\frac{qm_2}{2 f_{B2}}} \right)$$

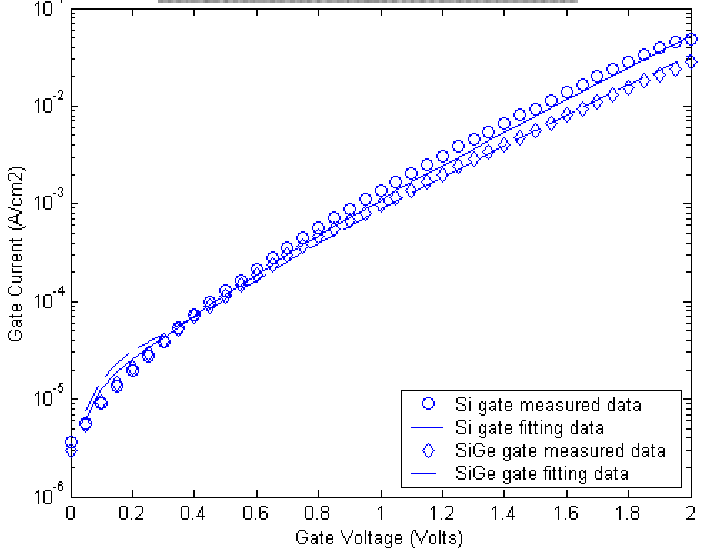
α is the tunneling attenuation coefficient already modeled in BSIM4, $f = Toxe1 / Toxe$

- Stands for multiple layers(N≥2) as well.
- Using new tunneling attenuation coefficient and interpreted with tunneling equations in BSIM4, BSIM4 is now capable of modeling multi-layer gate tunneling.

Verification

- ❖ Verified with data of existing gate stack of HfO_2 and silicon oxynitride.
- ❖ Very good fit observed using BSIM model.
- ❖ BSIM4 direct tunneling equation thus models the multi-layer case.





Forward Body Bias

To ensure a good model behavior of body effect, body bias is usually bounded between (Vbsc, and f_{s0} where f_{s0} = 0.95 f_s). BSIM4.2.1 already has the smooth function for Vbs low bound. Following is the upper bound smooth function:

$$\boldsymbol{V_{bseff}} = 0.95\Phi_s - 0.5\left(0.95\Phi_s - \boldsymbol{V'_{bseff}} - d_1 + \sqrt{\left(0.95\Phi_s - \boldsymbol{V'_{bseff}} - d_1\right)^2 + 4d_1 . 0.95\Phi_s}\right)$$

Where:

$$V_{bseff} = V_{bc} + 0.5 \cdot \left[\left(V_{bs} - V_{bc} - d_1\right) + \sqrt{\left(V_{bs} - V_{bc} - d_1\right)^2 - 4d_1 \cdot V_{bc}}\right]$$

Is the low bound smooth function. d_1 = 0.001V, and V_{bc} is the maximum allowable V_{bs} and found from dV_{th}/dV_{bs}= 0 to be

$$V_{bc} = 0.9\left(\Phi_s - \frac{K1^2}{4K2^2}\right)$$

Gate Current Partition Bugfix

From Original:

$$Igcs = Igc \cdot \frac{PIGCD \cdot V_{ds} + exp\left(-PIGCD \cdot V_{ds}\right) - 1 + 1.0e-4}{PIGCD^2 \cdot V_{ds}{}^2 + 2.0e-4}$$

and

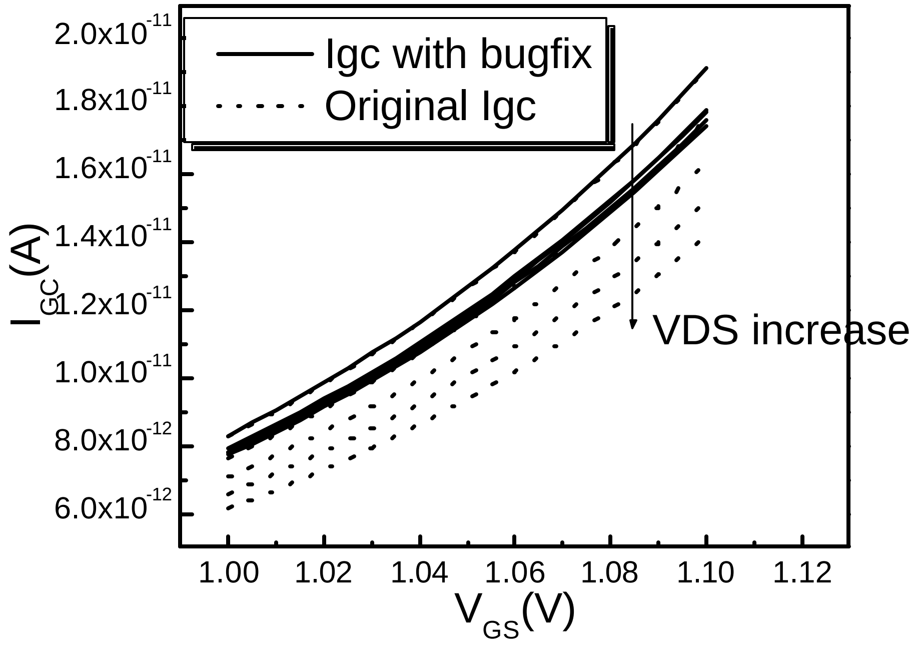
$$Igcd = Igc \cdot \frac{1 - \left(PIGCD \cdot V_{ds} + 1\right) \cdot exp\left(-PIGCD \cdot V_{ds}\right) + 1.0e-4}{PIGCD^2 \cdot V_{ds}{}^2 + 2.0e-4}$$

To:

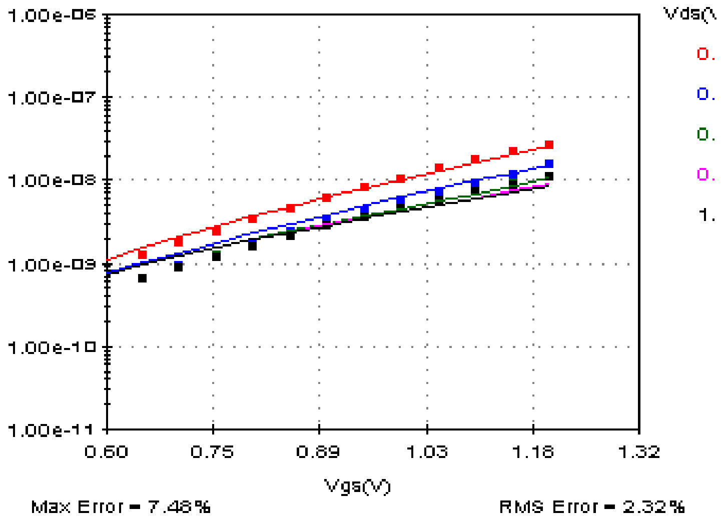
$$Igcs = Igc \cdot \frac{PIGCD \cdot V_{dseff} + exp\left(-PIGCD \cdot V_{dseff}\right) - 1 + 1.0e-4}{PIGCD^2 \cdot V_{dseff}{}^2 + 2.0e-4}$$

$$Igcd = Igc \cdot \frac{1 - \left(PIGCD \cdot V_{dseff} + 1\right) \cdot exp\left(-PIGCD \cdot V_{dseff}\right) + 1.0e-4}{PIGCD^2 \cdot V_{dseff}{}^2 + 2.0e-4}$$

Gate Current Partition Bugfix



Effect of gate current
bug fix



Comparison with experimental data

New Parameters in BSIM4.3.0

-Stress Effect

Parameter Name	Description	Default Value	Binnable?	Note
SA	**INSTANCE** parameter: Distance between OD edge to Poly from one side	0.0		If not given or (≤0.0), stress effect will be turned off
SB	**INSTANCE** parameter: Distance between OD edge to Poly from the other side	0.0		If not given or (≤0.0), stress effect will be turned off
SD	**INSTANCE** parameter: Distance between neighbour fingers	0.0		for NF >1: if not given or (≤0.0), stress effect will be turned off
saref	Reference distance between OD edge to poly of one side	1.E-06[m]	no	>0.0
sbref	Reference distance between OD edge to poly of the other side	1.E-06[m]	no	>0.0
wlod	Width parameter for stress effect	0.0 [m]	no	
ku0	Mobility degradation/enhancement coefficient for stress effect	0.0 [m]	no	
kvsat	Saturation velocity degradation/enhancement parameter for stress effect	0.0[m]	no	-1 ≤ kvsat ≤ 1
tku0	Temperature coefficient of ku0	0.0	no	
lku0	Length dependence of ku0	0.0 $[m^{llodku0}]$	no	

New Parameters in BSIM4.3.0

-Stress Effect

Parameter Name	Description	Default Value	Binnable ?	Note
wku0	Width dependence of ku0	0.0 [m^{wlodku0}]	no	
pku0	Cross-term dependence of ku0	0.0[m$^{llodku0+wlodku0}$]	no	
llodku0	Length parameter for u0 stress effect	0.0	no	>0
wlodkuo	Width parameter for u0 stress effect	0.0	no	>0
kvth0	Threshold shift parameter for stress effect	0.0[V*m]	no	
lkvth0	Length dependence of kvth0	0.0[V*m^{llodku0}]	no	
wkvth0	Width dependence of kvth0	0.0[V*m^{wlodku0}]	no	
pkvth0	Cross-term dependence of kvth0	0.0[V*m$^{llodku0+wlodku0}$]	no	
llodvth	Length parameter for Vth stress effect	0.0	no	>0
wlodvth	Width parameter for Vth stress effect	0.0	no	>0
stk2	K2 shift factor related to Vth0 change	0.0[m]	no	
lodk2	K2 shift modification factor for stress effect	1.0	no	>0
steta0	eta0 shift factor related to Vth0 change	0.0[m]	no	
lodeta0	eta0 shift modification factor for stress effect	1.0	no	>0

New Model Parameters in BSIM4.3.0

-Unified Current Saturation

Parameter Name	Description	Default Value	Binnable ?	Note
LAMBDA	Velocity overshoot coefficient	0.0	yes	If not given or (≤0.0), velocity overshoot will be turned off
VTL	Thermal velocity	2.0e5 [m/s]	yes	If not given or (≤0.0), source end thermal velocity limit will be turned off
LC	Velocity back scattering coefficient	0.0[m]	no	~5e-9(m) at room temperature
XN	Velocity back scattering coefficient	3.0	yes	

Temperature Model

TEMPMOD	Temperature mode selector	0	no	If=0, original model will be used If=1, new format will be used

Holistic Thermal Noise

RNOIA	Thermal noise coefficient	0.577	no	
RNOIB	Thermal noise coefficient	0.37	no	