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NBTI Induced Mobility Degradation - Models for TCAD and SPICE Applications

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Introduction: Negative Bias Temperature Instability (NBTI) is now a well-known p-MOSFET reliability issue that threatens both digital and analog CMOS circuits [1, 2]. Past studies have focused on establishing (i) strong gate insulator process impact on NBTI [3,4]; (ii) new characterization methods for delay-free measurements [5,6]; and (iii) physical mechanisms governing time (t), temperature (T), stress bias (V_G), AC frequency and duty cycle dependence of NBTI [7-10]. Till date, most efforts focused on modeling threshold voltage shift (ΔV_T), while fewer attempts were made to model mobility degradation ($\Delta\mu$) [11-13] and drain current degradation (ΔI_D) [15] due to NBTI. The expressions used in [11-13] to model $\Delta\mu$ are suitable only for large gate overdrive (beyond V_{DD}) and not in the range of interest (V_G up to V_{DD}), and therefore are not suitable for SPICE applications. The physics-based $\Delta\mu$ models [11,14] suitable for TCAD applications needs validation against wide range of experimental data. Note, accurate modeling of $\Delta\mu$ is essential for developing accurate ΔI_D models in both TCAD and SPICE framework respectively for device and circuit analysis. In this work, a compact mobility model suitable for SPICE applications is proposed, which can predict temporal transconductance (g_m) and I_D degradation due to NBTI stress, for a wide range of V_G from sub-threshold to strong inversion. The model is a simple extension to standard BSIM expression and is validated by predicting experimental data for varied stress conditions on devices having wide range of Nitrogen content (N%) and Effective Oxide Thickness (EOT). Further, the physics based μ degradation model suitable for TCAD applications is also verified against such wide range of experimental data. Robustness of extracted model parameters across devices are demonstrated.

Experimental: SiON p-MOSFETs (W/L=15/0.16 μm) used in this study have wide range of N% and EOT (Table I). Impact of stress on degradation of I_D-V_G (and hence g_m-V_G) curves are obtained using the Measure-Stress-Measure (MSM) method. All experiments are done at T=125°C, and I_D-V_G measurements were taken at low drain voltage ($|V_{DS}|$=0.1V) to avoid any velocity saturation effects.

Physical Model: Note, effective channel mobility (μ_{eff}) is determined by three scattering mechanisms; coulomb scattering (μ_C), phonon scattering (μ_{PH}) and surface roughness scattering (μ_{SR}) [11,14], while Mathiessen's rule is employed to calculate μ_{eff} ($1/\mu_{eff} = 1/\mu_C + 1/\mu_{PH} + 1/\mu_{SR}$) (Table-II). As shown, the impact of NBTI is accounted for by the term N_T (=$C_{OX}/q.\Delta V_T$, net generated charges at the interface) in μ_C. Fig.1 shows measured and predicted μ_{eff} - E_{eff} data before and after stress on devices having very different N% and EOT. Effective vertical field is estimated as $E_{eff} = 1/\varepsilon_{si}\ (Q_{dep}+Q_{inv}/3)$; Q_{dep} and Q_{inv} are respectively the depletion and inversion charge densities [11,14], and μ_{eff} is extracted from measured I_D data using standard BSIM expression [16,17]. N_T at a given stress time is computed using measured ΔV_T. Note, appreciable μ_{eff} degradation ($\Delta\mu_{eff}$) is observed, and larger $\Delta\mu_{eff}$ is seen for device having larger N%. The physics-based model can predict mobility degradation for different stress time, stress biases, and on devices having different N% and EOT values (not explicitly shown) with parameters listed in Table-III. Only 2 parameters (α_1, β) show EOT dependence as shown (Fig.2). This calibrated physical model (with extracted parameters) is readily implementable in TCAD.

Empirical Model: Although the above analysis is good to obtain physical insight into μ_{eff} degradation due to NBTI, a closed form mobility expression is necessary for SPICE simulations. Fig.3 shows measured g_m-V_G data and model prediction using first order mobility model $\mu_{eff}=\mu_0/(1+\theta(V_{gs}-V_{th})^{\eta})$ [11]. A match is observed only at high V_G overdrive and hence this popular expression cannot be used for device operating regime. In this work, BSIM3v3 model [16,17] is used (without loss of generality) for predicting I_D before and after stress (Table-IV), ***where the mobility model is suitably modified by including "DR3" term to incorporate the effect of stress generated N_T***. Figs.4(a and b) show measured g_m-V_G data and prediction using the proposed model for devices having wide range of N% and EOT. Unlike standard expression, the proposed model can predict g_m before and after stress for the entire range of V_G. Measured time evolution of Δg_m at 2 different sense V_G's for both these devices and model prediction are shown in Fig.5. Although g_m degrades at $|V_G|$=0.5V, an improvement in g_m is observed at $|V_G|$=1.2V, in spite of μ_{eff} degradation for the entire E_{eff} range (Fig.1). The g_m degradation at $|V_G|$=0.5V is ascribed to dominant columbic scattering from N_T. The g_m improvement at $|V_G|$=1.2V can be attributed to decrease in $|V_G-V_T|$ with time and hence decrease in vertical field [18]. The corresponding measured and predicted I_D-V_G data before and after stress are shown in Figs.6 (a and b). The capability of the proposed model to predict I_D before and after stress in linear and subthreshold regimes can be readily seen. Measured time evolution of ΔI_D at 2 different sense V_G's for both these devices and model prediction are shown in Fig.7. The empirical model can predict g_m and I_D degradation for different stress time, stress biases, and on devices having different N% and EOT values (not explicitly shown) with parameters listed in Table-V. Only 1 parameter (β_1) show N% dependence as shown (Fig.8). This calibrated empirical model (with extracted parameters) is readily implementable in SPICE.

Conclusions: It is shown that NBTI exhibits significant mobility degradation that has to be modeled for accurate device and circuit simulations. The physics-based mobility model involving multiple scattering mechanisms is validated against experimental data from a wide range of devices and stress conditions. The robustness of extracted parameters is demonstrated, which makes the proposed model readily implementable in TCAD. An empirical mobility degradation model is proposed based on BSIM implementation for SPICE simulations, and is also validated against experimental data from a wide range of devices and stress conditions. The model has only 1 device dependent parameter and can predict temporal g_m and I_D degradation for below and above threshold regimes. The model predictability and robustness of extracted parameters makes the proposed model readily implementable in SPICE.

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Refs: [1] Reddy, p.248, IRPS 2002, [2] Jha, p.2609, TED 2005, [3] Mahapatra, p.1, IRPS 2007, [4] Maheta, p.1630, TED 2008, [5] Shen, p.1, IEDM 2006, [6] Kumar, p.809, IEDM 2007, [7] Grasser, p.33, IRPS 2009 [8] Mahapatra, p.614, IRPS 2011, [9] Reisinger, p.597, IRPS 2011, [10] Joshi, IRPS 2012, [11] Islam, p.87, IRPS 2008, [12] Denais, p.109, IEDM 2004 [13]Hu, p.743, IRPS 2008 [14] Cheng, p.343, TED 1997, [15] Varghese, p.51, IRPS 2011, [16] Cheng, MOSFET Modeling & BSIM3User's Guide, 2002 [17] BSIM 4v4.7 Manual, 2011 [18] Islam, p.173504-1, APL 2008.

Table I: Device Details

Device#	N2 Dose[%]	Txps [Å]	EOT [Å]
1	16.67	28.13	23.50
2	19.46	22.34	17.70
3	22.64	18.48	13.98
4	34.58	23.16	15.55
5	35.92	28.85	19.90
6	41.27	21.12	12.25
7	42.48	24.37	14.60
8	49.19	23.89	11.88

Table II: Physical Model Expressions

1. Coulombic Scattering Term

$$\mu_C=\frac{\mu_1 Q_{inv}^{\alpha 1}}{Q_{dep}+\beta Q_{inv} N_T}\ ; \quad \mu_1=\mu_{1a}-\mu_{1b}.T$$

2. Phonon Scattering Term

$$\mu_{PH}=\mu_2\left(\frac{E_{eff}}{1e6}\right)^{\alpha 2}\ ; \quad \mu_2=a.T^{-\gamma}$$

3. Surface Roughness Term

$$\mu_{SR}=\mu_3\left(\frac{E_{eff}}{1e6}\right)^{\alpha 3}$$

Table III: Physical Model Parameters

a	$(2.81\pm0.365)\times10^5$
μ_{1a}	264.9
μ_{1b}	0.4
μ_3	126.16±10.71
$\alpha 2$	-0.35
$\alpha 3$	-1.5
γ	1.5

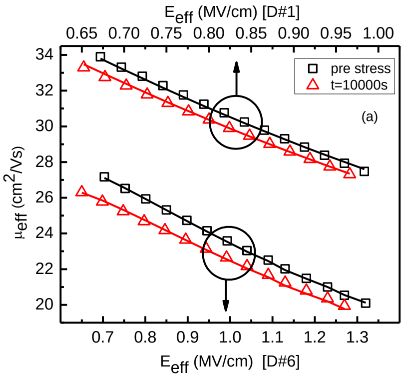

Fig1 . μ_{eff} degradation for devices with very different N% and EOT.

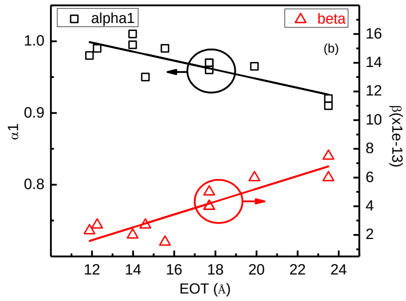

Fig2. α1 and β dependence on EOT.

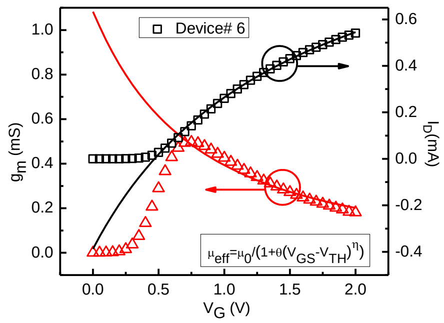

Fig3 . Simple first order mobility model can predict I_D and g_m accurately only at high V_G.

Table IV: Empirical Model Expressions

$$\mu_{eff}=\frac{\mu_0}{1+DR1+\frac{DR2}{1+DR3}}\ ; \quad DR1=(UA+UC.Vbseff)\frac{(Vgsteff+2Vth)}{Tox}$$

$$DR2=UB\left(\frac{V_{gsteff}+2V_{th}}{Tox}\right)^2\ ; \quad DR3=\beta_1.N_T(C_{ox}.V_{gsteff})^{\alpha}$$

$$I_D=\frac{W_{eff}C_{ox}\mu_{eff}V_{gsteff}V_{dseff}\left(1-\frac{V_{dseff}}{2V_b}\right)}{L_{eff}}$$

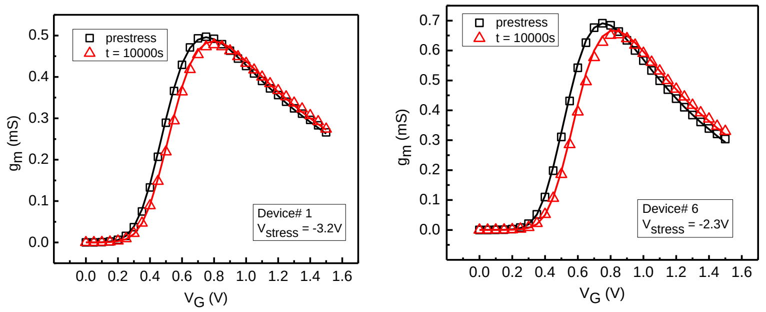

Fig4 .(a) and (b) g_m-V_G for two devices with different EOT and N% accurately predicted by the proposed model.

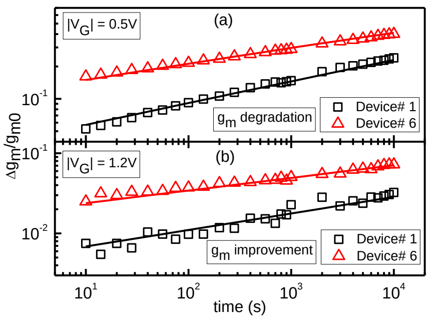

Fig5 . Time evolution of Δg_m for two different sense voltages.

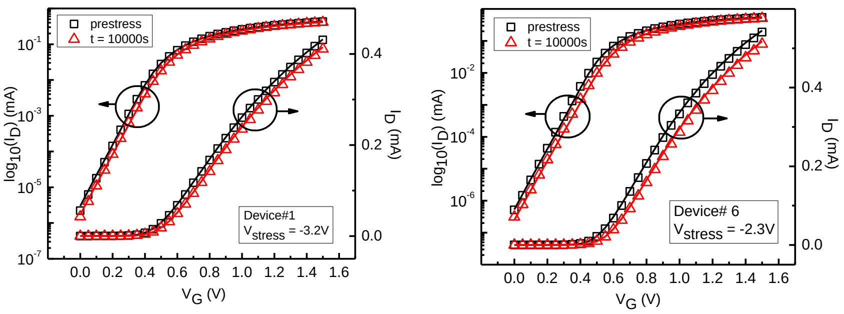

Fig6 . (a) and (b) I_D-V_G for pre and post stress accurately predicted by the proposed model.

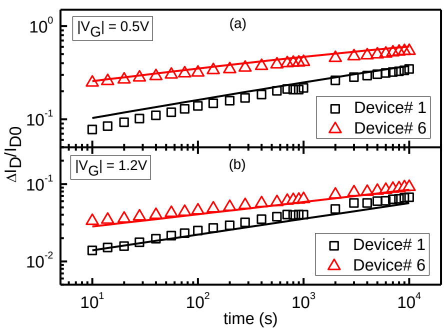

Fig7 . Time evolution of ΔI_D for two different sense voltages..

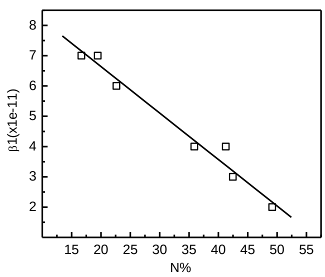

Fig8. β1 dependence on N%

Table V: Empirical Model Parameters

V_{OFF}	-0.132±0.005
μ_0	44.96±2.95
UA	2.2×10^{-8}
UB	$(3.92\pm1.11)\times10^{-15}$
A_{bulk}	0.65
MINV	1.04±0.067
α	0.5