Negative Bias Temperature Instability (NBTI) in p-MOSFETs: Characterization, Material/Process Dependence and Predictive Modeling (Part 3 of 3)

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Outline

Introduction, Basic NBTI signatures

Fast / Ultra-fast drain current degradation measurement

Estimation of pre-existing and generated defects

Part - I

Transistor process / material dependence

Role of Nitrogen – Study by Ultrafast measurement

Part - II

Predictive modeling

Conclusions / outlook

Part - III

Outline

Introduction, Basic NBTI signatures

Fast / Ultra-fast drain current degradation measurement

Estimation of pre-existing and generated defects

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Role of Nitrogen – Study by Ultrafast measurement

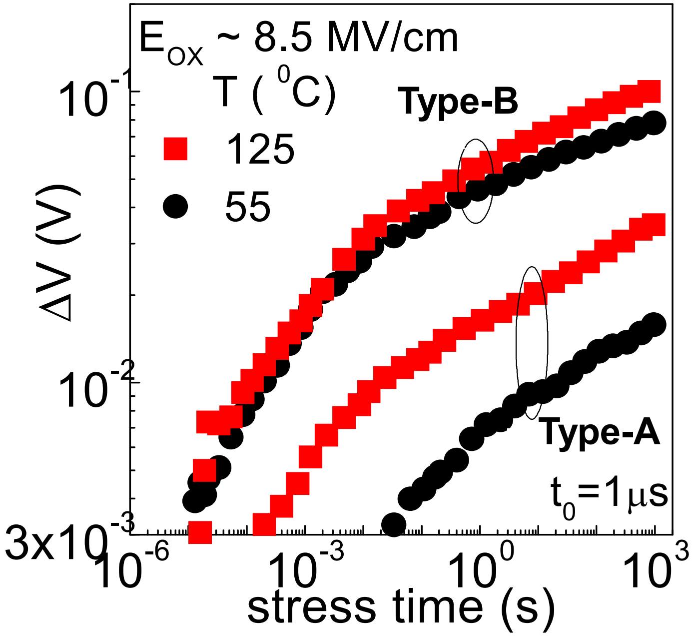
Stress ←

Predictive modeling

Recovery and AC effects

Conclusions / outlook

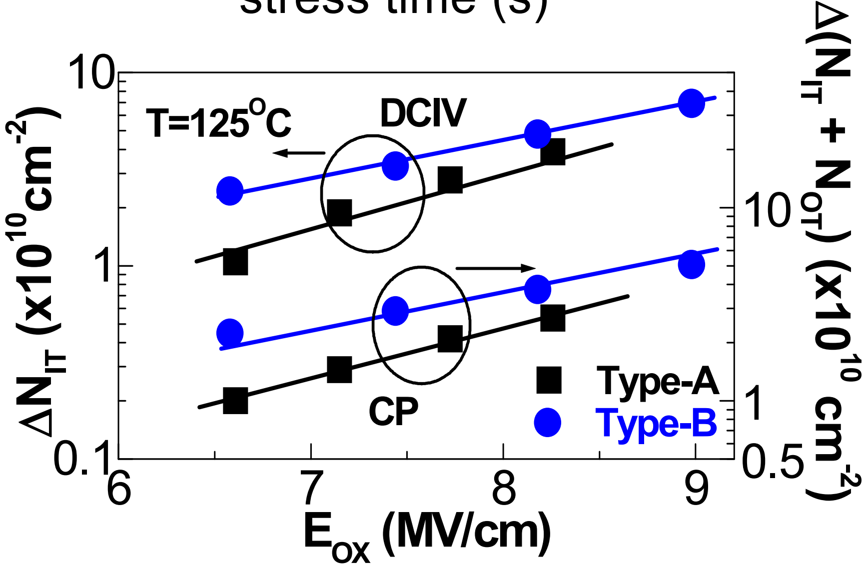
NBTI Experimental Signatures (1)

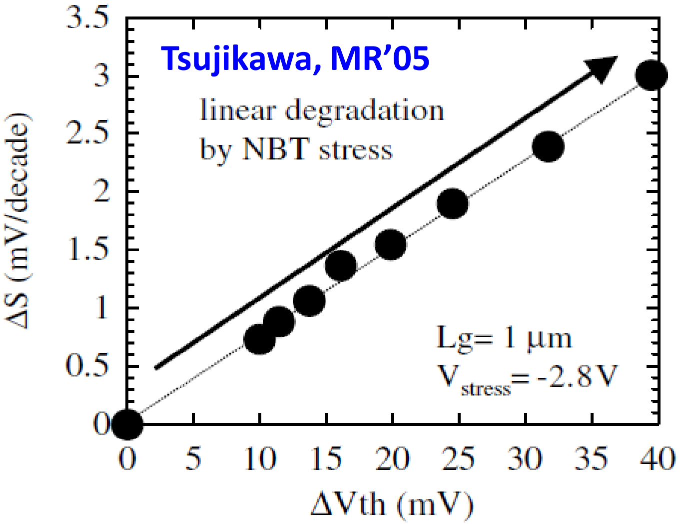


Strong gate insulator process dependence

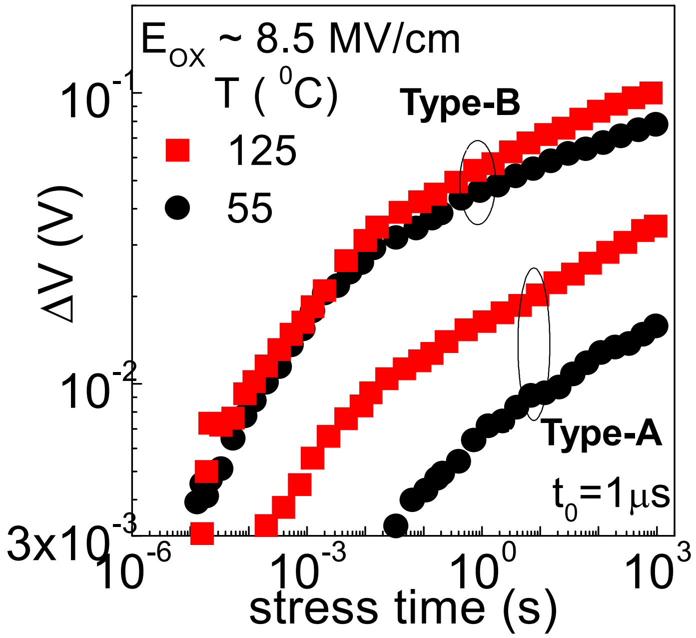
Strong evidence of trap (interface and bulk) generation

Strong evidence of interface trap generation





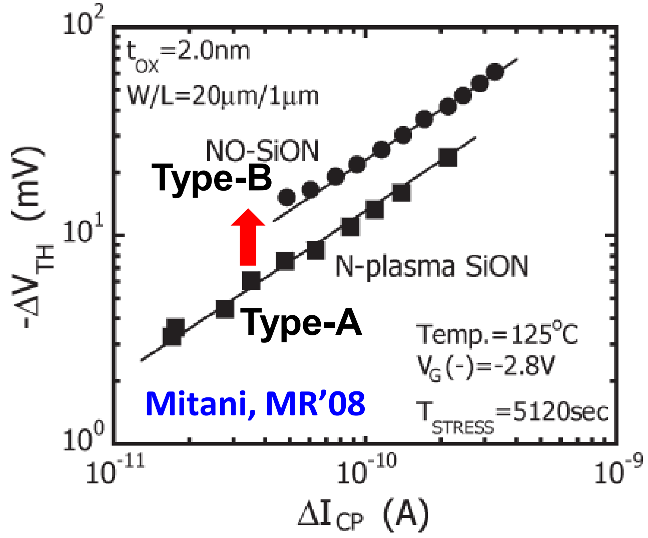
NBTI Experimental Signatures (2)

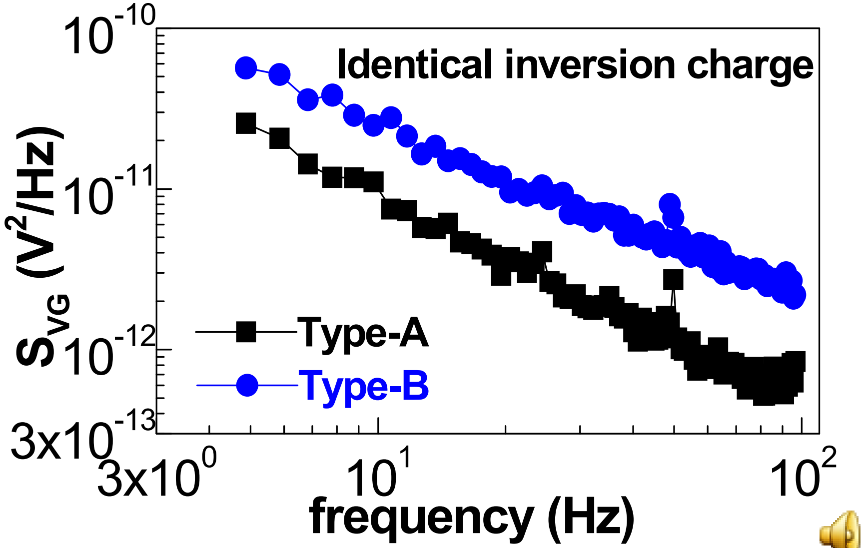


Higher V_T shift compared to trap generation for poor gate insulators

Higher as-processed bulk trap density in poor gate insulators

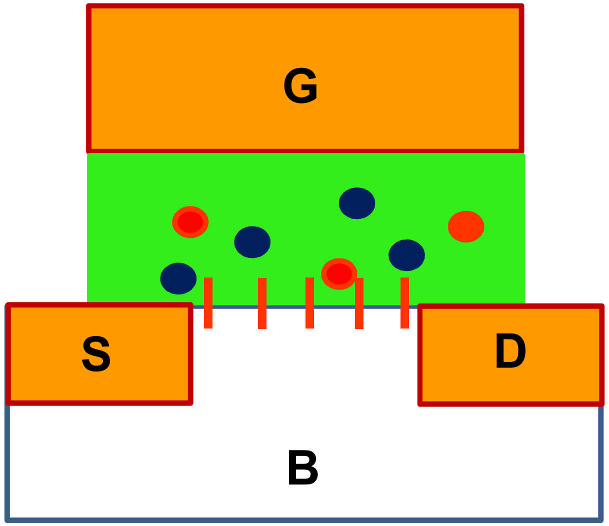
Strong evidence of trapping in as-processed bulk trap density

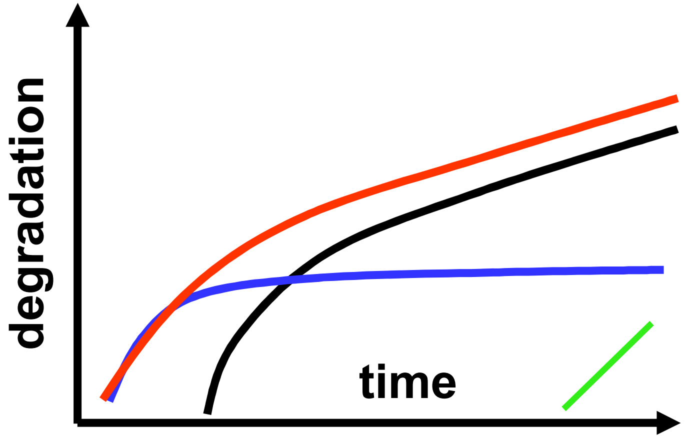




NBTI Degradation Model

Interface trap generation – inversion hole induced breaking of Si-H bonds at Si/SiON interface and subsequent diffusion of Hydrogen (Reaction-Diffusion model) → ΔV_{IT}





Charging of pre-existing bulk oxide traps – analytical expression to account for multiple trapping time constants; saturation at longer time

$\Delta V_{HT} \sim (1 - \exp(-(t/\tau)\text{^}\beta))$

Generation of bulk oxide traps (those cause TDDB failure) – analytical expression for power law time dependence: $\Delta V_{OT} \sim t^n$

Total degradation = sum of all three components

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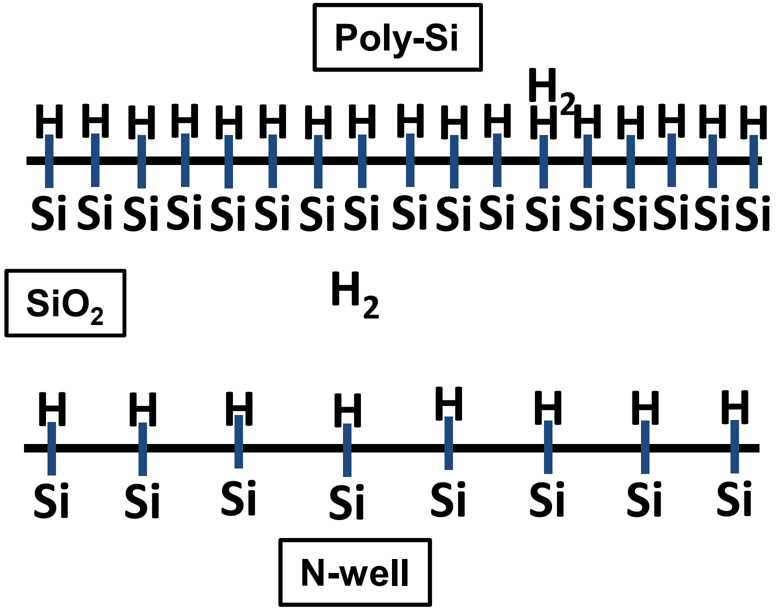
H-H_2 Reaction Diffusion (R-D) Model



Breaking of Si-H bonds at Si/SiO_2 interface by holes (Reaction)

H → H_2 transformation: Broken H reacts with another H and forms H_2

Eventual diffusion of molecular H_2

Broken H reacts with Si-H at poly-Si/ SiO_2 interface and forms H_2

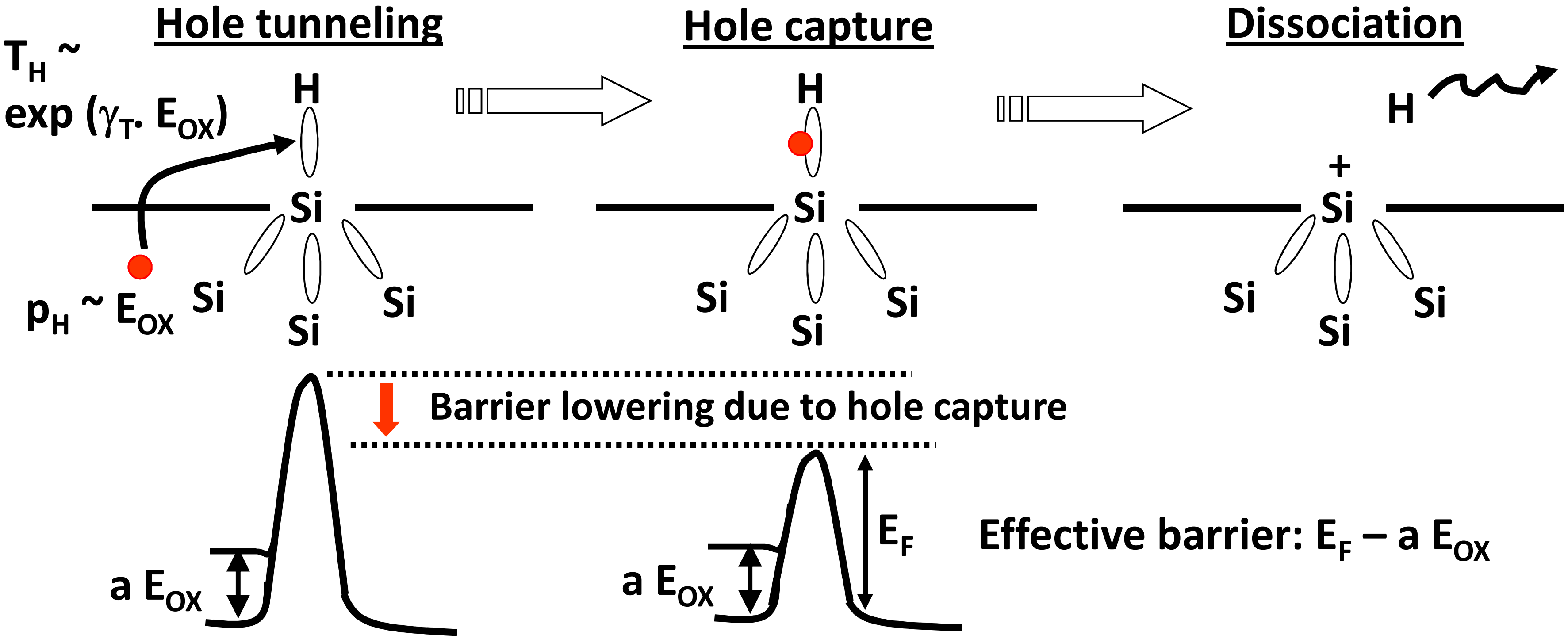
Short time dynamics controlled by Si-H bond breaking reaction

Mid time dynamics controlled by H to H_2 formation and diffusion of both species

Long time dynamics (time to failure) controlled by H_2 diffusion

Details: Islam, TED'07

Physics of Reaction (Breaking of Si-H Bonds)



$$\text{Si-H} + h^+ \xrightarrow{p_H . T_H . \sigma} \text{Si-H}^+ \xrightarrow{\exp[-(E_F - a\,E_{OX})/kT]} \text{Si}^+ + \text{H}$$

Si-H dissociation reaction: $k_f \sim E_{OX} \exp(\gamma E_{OX}) \exp(-E_F/kT)$; $\gamma = \gamma_T + a/kT$

Simplification by power law voltage dependence

Details: Islam, IEDM’06

H – H$_2$ RD Model: Mathematical Formulation

Reaction

$$\frac{dN_{IT}}{dt} = k_f \left(N_0 - N_{IT}\right) - k_r N_{IT} N_H^{(0)}$$

$$k_f = k_{f0}\left(V_G - V_T\right)^{\frac{3}{2}\Gamma_{IT}} e^{-\frac{E_{Akf}}{kT}}$$

$$k_r = k_{r0} e^{-\frac{E_{Akr}}{kT}}$$

H ←→ H$_2$ transformation

$$\frac{\delta}{2}\frac{dN_H^{(0)}}{dt} = D_H \frac{dN_H^{(0)}}{dx} + \frac{dN_{IT}}{dt} - \delta k_H \left[N_H^{(0)}\right]^2 + \delta k_{H2} N_{H2}^{(0)}$$

$$\frac{\delta}{2}\frac{dN_{H2}^{(0)}}{dt} = D_{H2} \frac{dN_{H2}^{(0)}}{dx} + \frac{dN_{IT}}{dt} - \frac{\delta}{2} k_H \left[N_H^{(0)}\right]^2 - \delta k_{H2} N_{H2}^{(0)}$$

$$D_H = D_{H0} e^{-\frac{E_{ADH}}{kT}}$$

$$D_{H2} = D_{H20} e^{-\frac{E_{ADH2}}{kT}}$$

Diffusion

$$\frac{dN_H}{dt} = D_H \frac{d^2 N_H}{dx^2} - k_H N_H^2 + k_{H2} N_{H2}$$

$$\frac{dN_{H2}}{dt} = D_{H2} \frac{d^2 N_{H2}}{dx^2} + \frac{1}{2} k_H N_H^2 - \frac{1}{2} k_{H2} N_{H2}$$

$$k_H = k_{H0} e^{-\frac{E_{AkH}}{kT}}$$

$$k_{H2} = k_{H20} e^{-\frac{E_{AkH2}}{kT}}$$

Details: Islam, TED’07

H – H_2 RD Model Parameters

Constant parameters across <u>all</u> (type, EOT & N%) devices studied in this work

$$k_f = \overset{\downarrow}{k_{f0}}\left(V_G - V_T\right)^{\frac{3}{2}\overset{\downarrow}{\Gamma_{IT}}} e^{-\frac{E_{Akf}}{kT}}$$

$$k_r = k_{r0} e^{-\frac{E_{Akr}}{kT}}$$

$$D_H = D_{H0} e^{-\frac{E_{ADH}}{kT}}$$

$$D_{H2} = D_{H20} e^{-\frac{E_{ADH2}}{kT}}$$

$$k_H = k_{H0} e^{-\frac{E_{AkH}}{kT}}$$

$$k_{H2} = k_{H20} e^{-\frac{E_{AkH2}}{kT}}$$

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Only 2 device dependent parameters – k_{f0} and Γ_{IT}

E_{AKf} = 0.175eV
k_{r0} = 9.9x10^{-7}, E_{Akr} = 0.2eV
D_{H0} = 9.56x10^{-11} cm²/s, E_{ADH} = 0.2eV
D_{H20} = 3.5x10^{-5}cm²/s, E_{ADH2} = 0.58eV
k_{H0}=8.56cm³/s , E_{AkH} = 0.3eV
k_{H20} = 5.7x195s^{-1},E_{AkH2} = 0.3eV

δ → Si/SiO_2 interfacial layer thickness (~1.5A°)

NBTI Degradation Components

Generation of interface traps (RD): $\Delta V_{IT} = q/C_{OX} * \Delta N_{IT}$

2 device dependent parameters (k_{f0} & Γ_{IT})

Hole trapping in pre-existing bulk insulator traps:

$$\Delta V_{HT} = \frac{q}{C_{ox}} B \left(V_G - V_{T0} - \Delta V_T \right)^{\Gamma_{HT}} e^{-\frac{E_{AHT}}{kT}} \left(1 - e^{\left(-\left(\frac{t}{\tau}\right)^{\beta_{HT}}\right)}\right)$$

E_{AHT} = 0.03eV & $\Gamma_{HT} = \Gamma_{IT}$ (all devices);
3 device dependent parameters (B, τ & β_{HT})

Generation (and subsequent trapping in) bulk insulator traps:

$$\Delta V_{OT} = \frac{q}{C_{ox}} C \left(1 - e^{\left(-\left(\frac{t}{n}\right)^{\beta_{OT}}\right)}\right) \qquad n = \eta (V_G - V_T - \Delta V_T)^{\frac{-\Gamma_{OT}}{\beta_{OT}}} e^{+\frac{E_{AOT}}{kT\beta_{OT}}}$$

$\eta = 5*10^{12}$, $\beta_{OT} = 0.36$, $\Gamma_{OT} = 9$ & E_{AOT} = 0.15eV (for all devices);
1 device dependent parameter (C)

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Device Details – Prediction of NBTI

Table I SiON Wafer Details

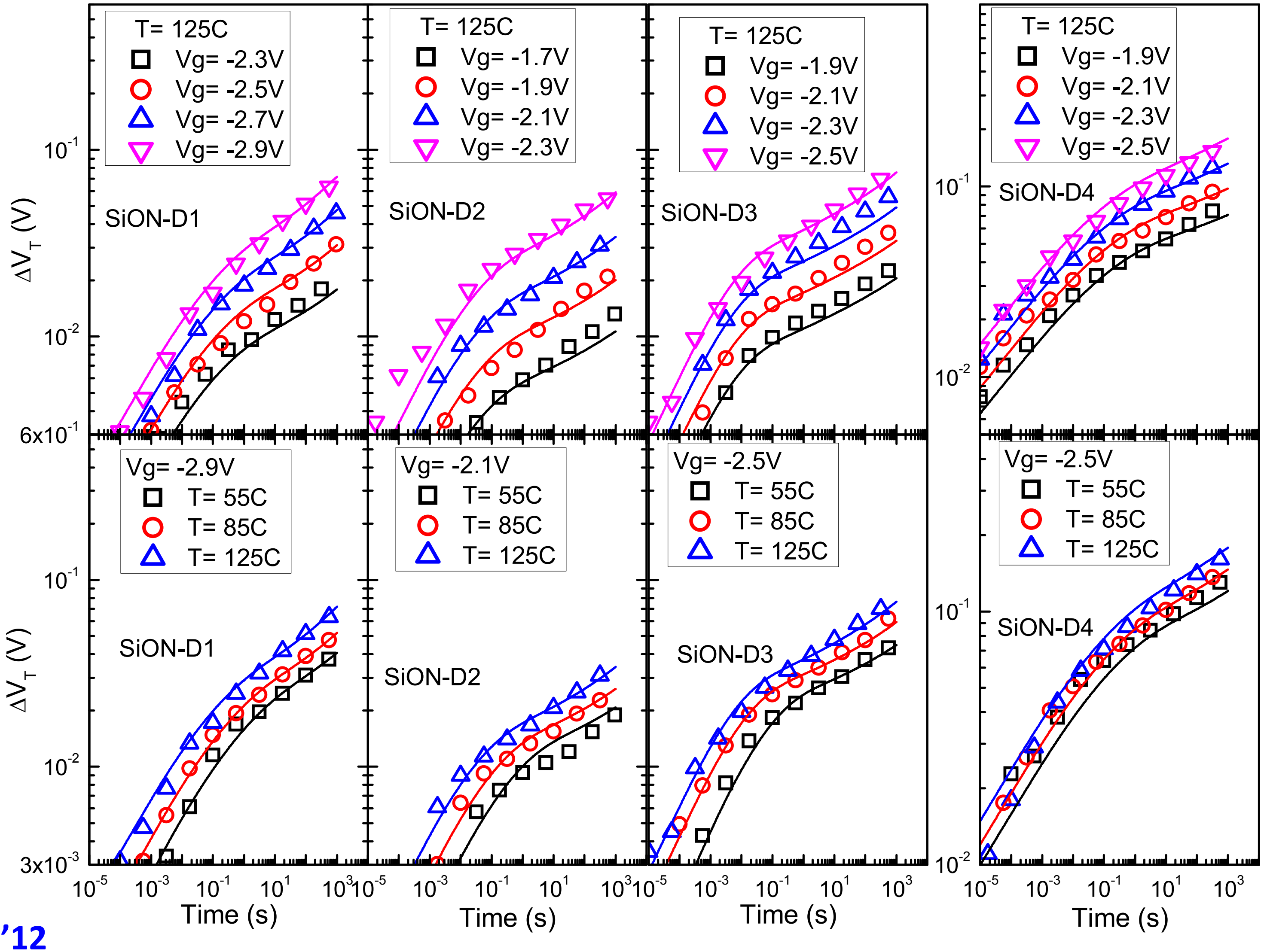
Device	EOT (nm)	%N	
D1	2.35	16.7	Type A
D2	1.4	22.6	Type A
D3	1.56	34.6	Type A/B
D4	1.45	43	Type B

Table II HKMG Wafer Details

Device	HK	IL Thickness (nm)	HK Thickness (nm)
D6	HfSiON	1	2
D7	HfO_2	1	2

Prediction of UF-OTF NBTI Degradation (SiON)

Prediction (lines) of stress V_G/T data for different (EOT, N%) devices



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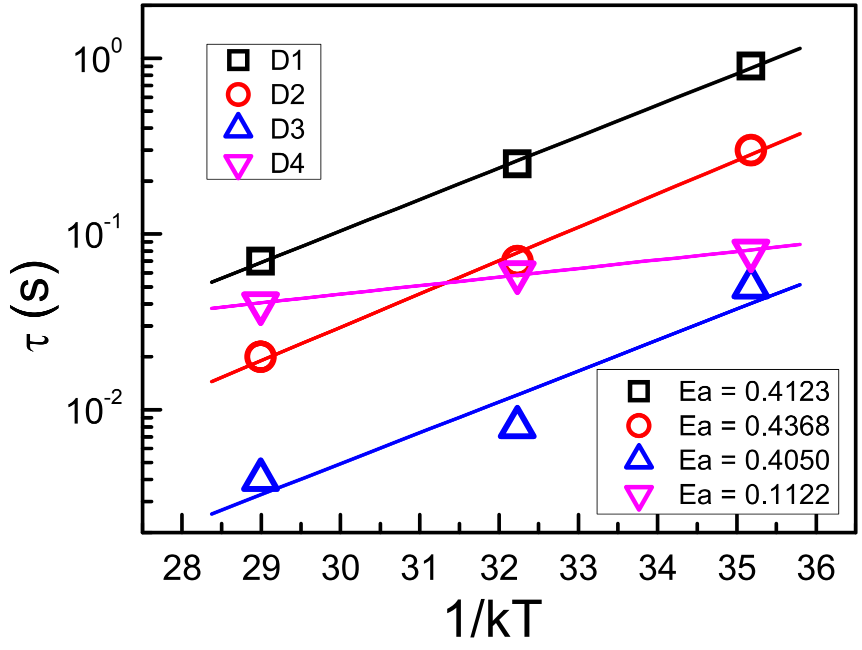
Device Dependent Parameters

Identical parameters for all stress V_G/T

Device	D1	D2	D3	D4
N %	17	23	35	43
EOT (Å)	23.5	14	15.6	14.5
Variable Parameters (not constant across devices)				
k_{f0}	1.1	10	28	350
$\Gamma_{NIT} = \Gamma_{NHT}$	4.3	4.3	3.5	2.2
B (x 10^{10})	1.1	4.2	7.5	85
C (x 10^{13})	2.6	16	13	100
β_{HT}	0.28	0.33	0.37	0.22

Hole trapping time constant (τ) shows T activation

Presence of shallow hole traps for heavily nitrided device (Type-B)



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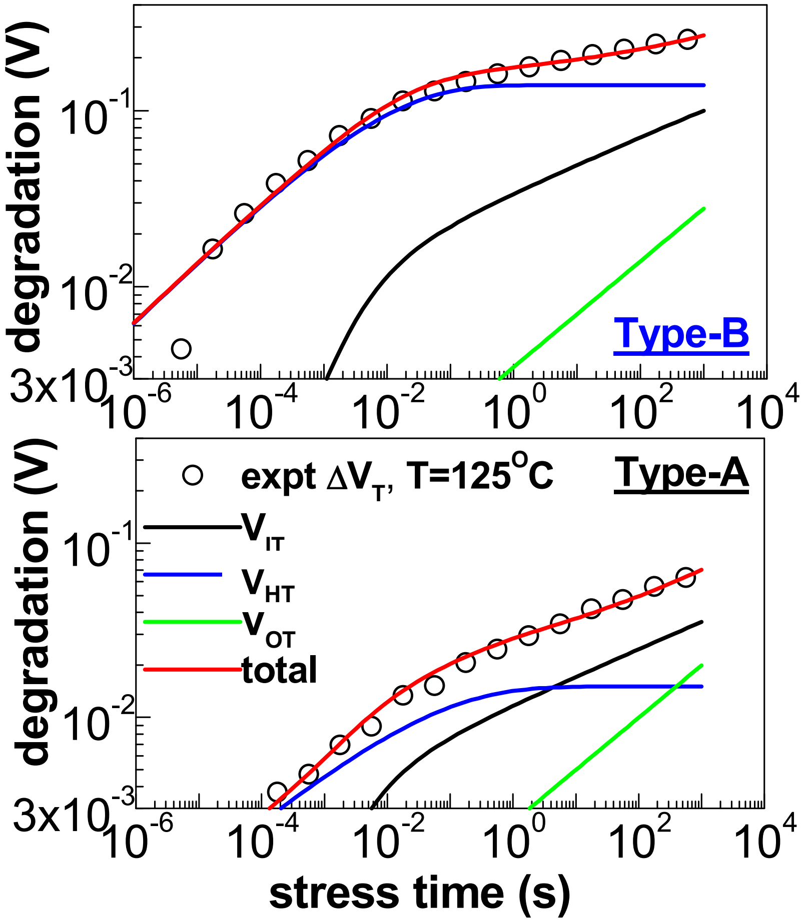
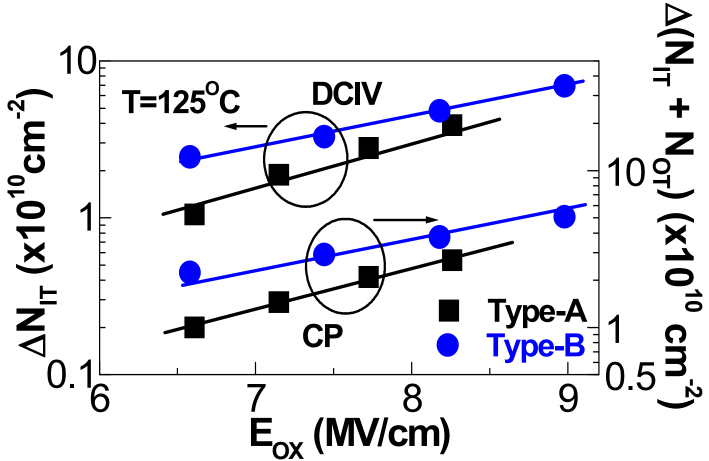
Prediction of NBTI Components (SiON)

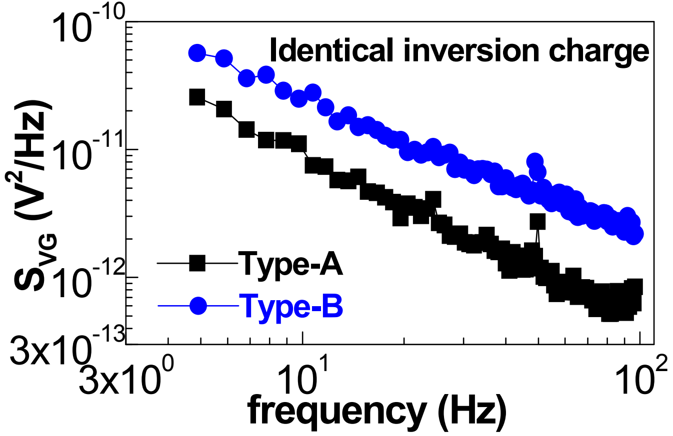
Total ΔV_T (mobility corrected) = q/C_{OX} * $(\Delta N_{IT} + \Delta N_{HT} + \Delta N_{OT})$

Large Type-A vs. Type-B difference <u>primarily</u> due to trapping in pre-existing traps



Small difference in generated traps, larger difference in pre-existing traps





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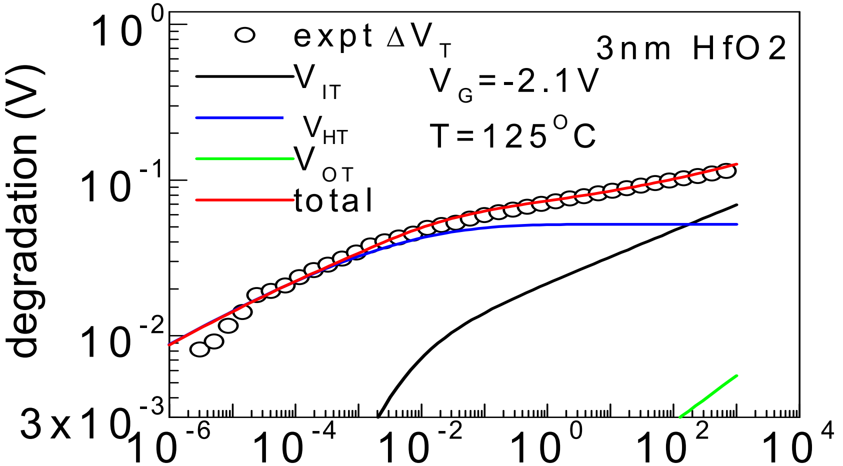
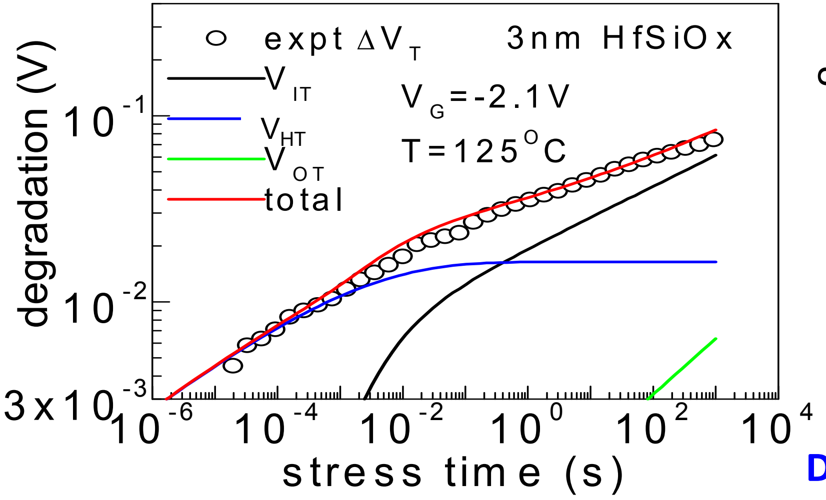
Prediction of NBTI Components (HKMG)

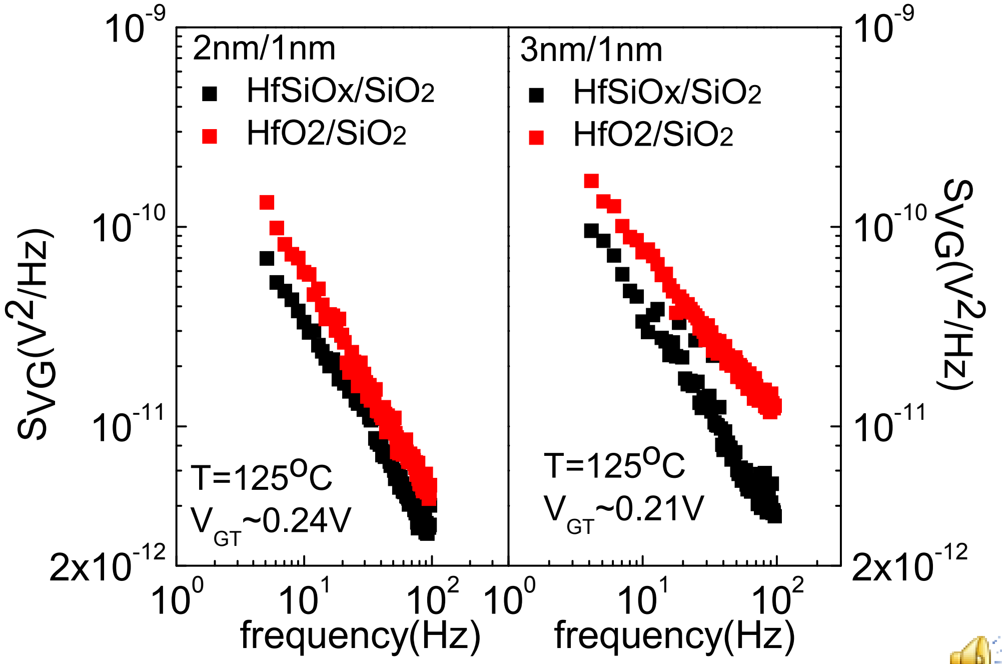
Total ΔV_T (mobility corrected) = q/C_{OX} * ($\Delta N_{IT} + \Delta N_{HT} + \Delta N_{OT}$)





Large Hi-K Type-A (HfSiON) vs. Type-B (HfO_2, un-optimized) difference primarily due to trapping in pre-existing traps

Recap: Higher flicker noise for HfO_2 compared to HfSiON



Deora, PhD thesis (IITB)

$H - H_2$ RD Model: Analytical Solution (Long time)

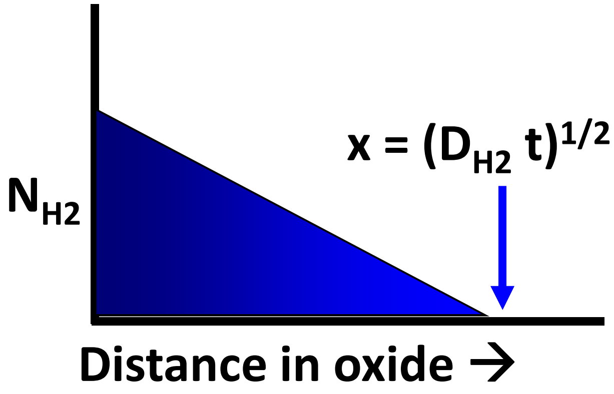
$dN_{IT}/dt = k_F (N_0 - N_{IT}) - k_R . N_H(x=0) N_{IT}$

$N_{IT} << N_0$, dN_{IT}/dt small → $N_H(x=0) N_{IT} = k_F N_0 / k_R$

$N_H^2(x=0) / N_{H2}(x=0) = \text{const.}\ (2H = H_2)$

$N_{IT}^2 = (k_F N_0/k_R)^2 / N_{H2}(x=0)$

$dN_{H2}/dt = D_{H2}\, d^2N_H/dx^2 \rightarrow x = (D_{H2}\, t)^{1/2}$



Generated N_{IT} = 2 * Total no. of released H molecules

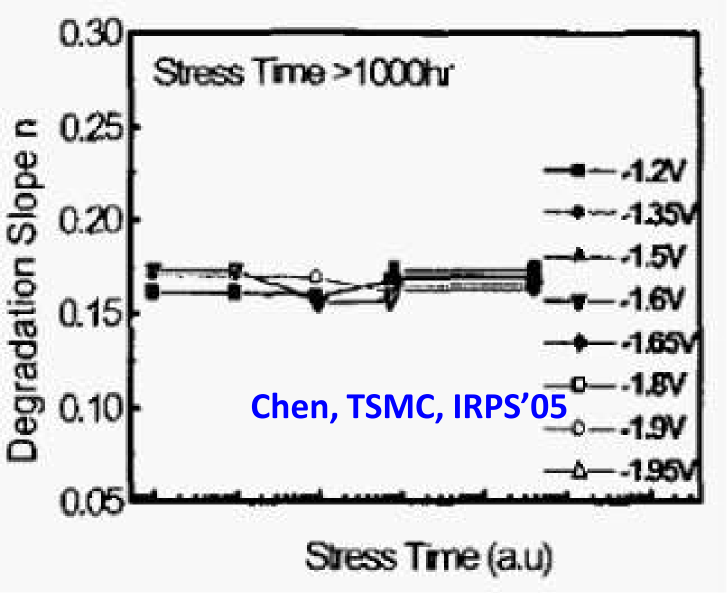
$N_{IT} = 2 * ½\, N_{H2}(x=0)\, (D_{H2}\, t)^{1/2}$

$N_{IT} = (k_F N_0/k_R)^{2/3} (D_{H2}\, t)^{1/6}$

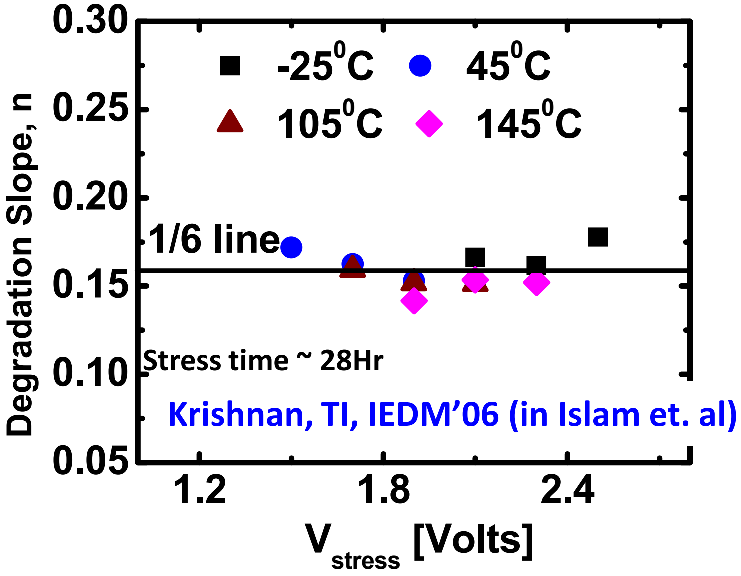
Prediction of 1/6 power law time exponent

Details: Alam, IRPS'05 (Tutorial)

Very Long Time Degradation

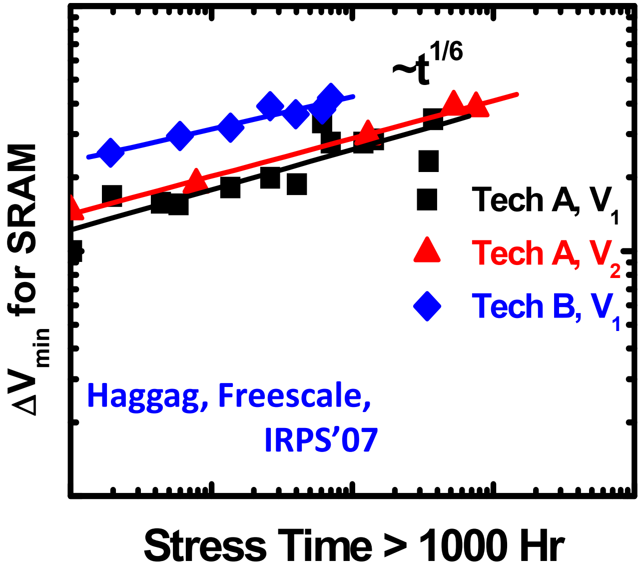


Chen, TSMC, IRPS'05



Krishnan, TI, IEDM'06 (in Islam et. al)

Universally observed long-time power-law time exponent of n = 1/6 in "production quality" devices & circuits



Haggag, Freescale, IRPS'07

Important feature for prediction of degradation at end-of-life

Accurate prediction by RD model

Simplified NBTI Degradation Model (Long Time)

Power law (n = 1/6) time dependence of interface traps

$$\Delta V_{IT} = \frac{q}{C_{ox}} A(V_G - V_{T0} - \Delta V_T)^{\Gamma_{IT}} e^{-\frac{E_{AIT}}{kT}} t^{\frac{1}{6}}$$

$$E_{AIT} = (\frac{2}{3}(E_{Akf} - E_{Akr}) + \frac{E_{ADH2}}{6})$$

Saturation of hole trapping

$$\Delta V_{HT} = \frac{q}{C_{OX}} B(V_G - V_T - \Delta V_T)^{\Gamma_{HT}} e^{-\frac{E_{AHT}}{kT}}$$

Bulk trap generation and subsequent hole trapping

$$\Delta V_{OT} = \frac{q}{C_{ox}} C(1 - e^{(-(\frac{t}{n})^{\beta_{OT}})})$$

$$n = \eta(V_G - V_T - \Delta V_T)^{\frac{-\Gamma_{OT}}{\beta_{OT}}} e^{+\frac{E_{AOT}}{kT\beta_{OT}}}$$

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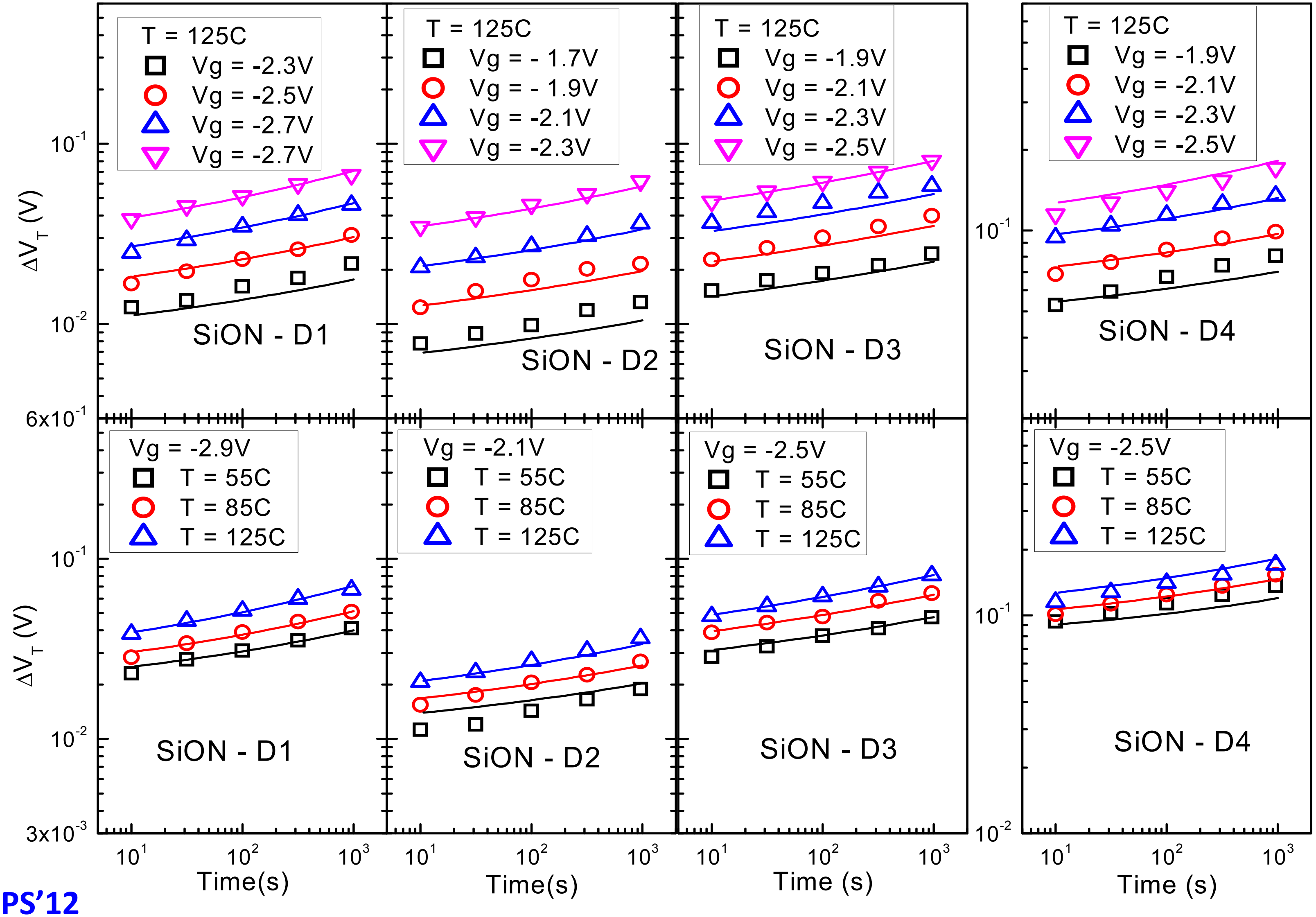
Prediction of UF-OTF NBTI Degradation (SiON)

UF-OTF measurement with t_0 delay of 1μs at different stress V_G/T



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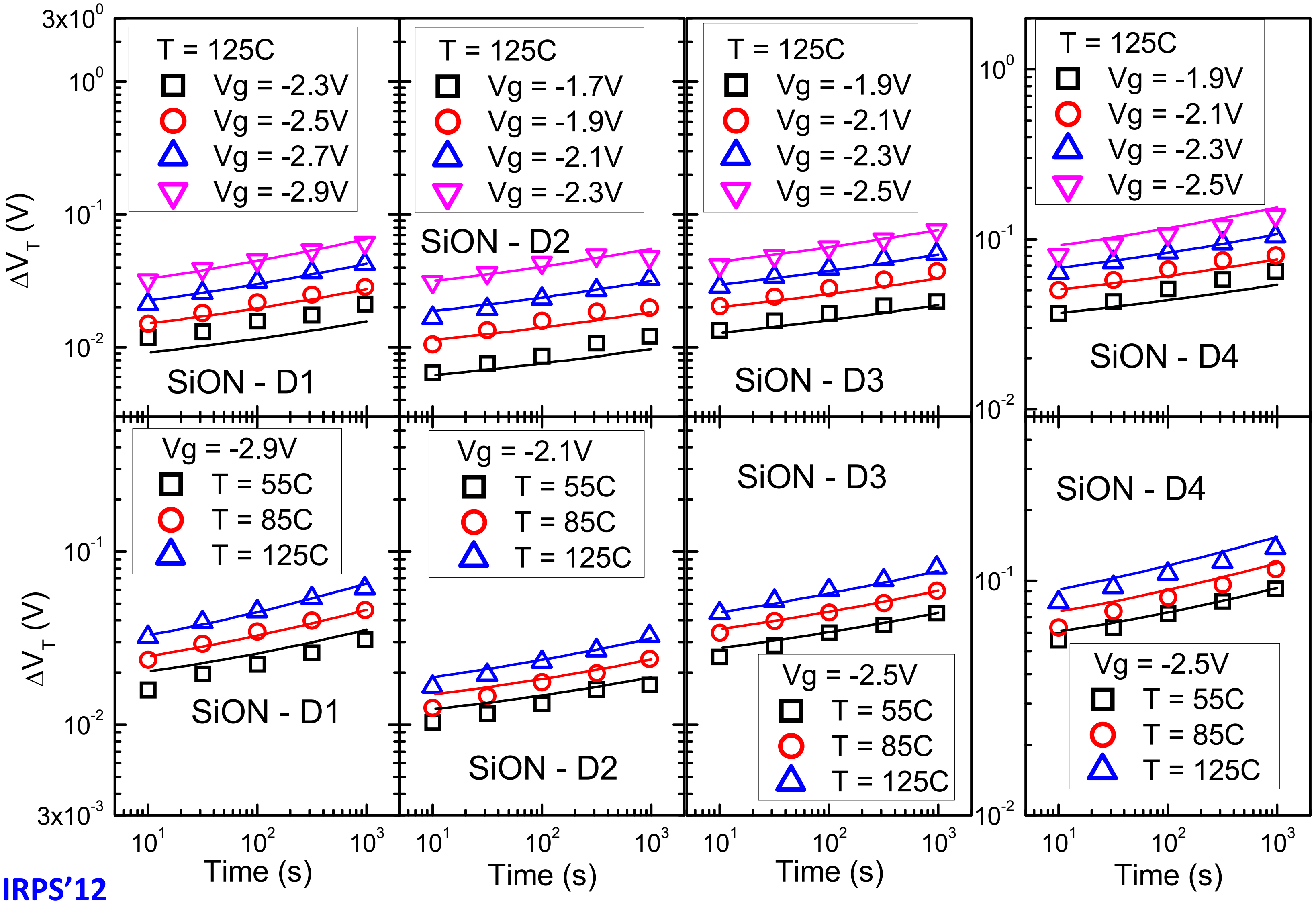
Prediction of OTF NBTI Degradation (SiON)

OTF measurement with t_0 delay of 1ms at different stress V_G/T



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Device Dependent Parameters (SiON, Simple Model)

Prediction of V_G/T dependence by only 4 adjustable parameters

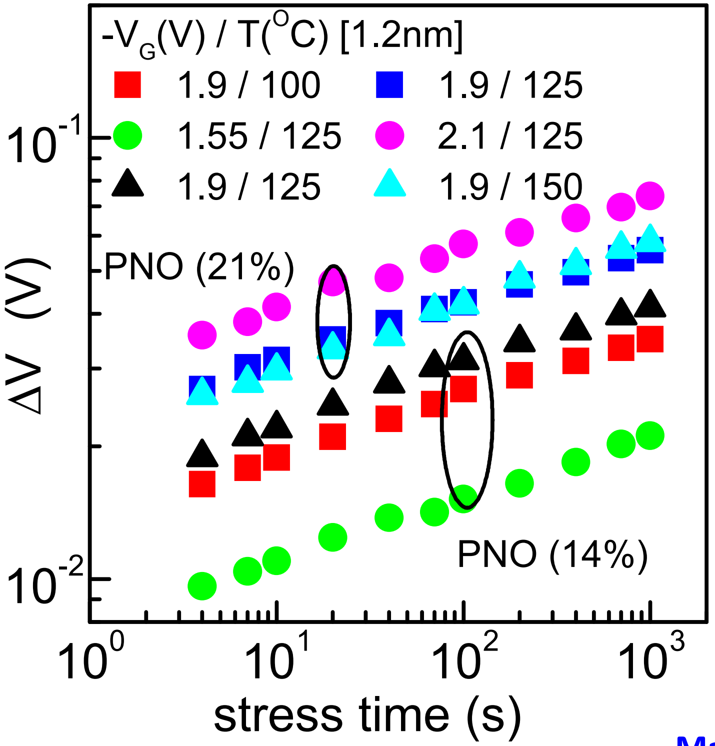
<table>
<tr><th>Device</th><th>D1</th><th>D2</th><th>D3</th><th>D4</th></tr>
<tr><td>N %</td><td>17</td><td>23</td><td>35</td><td>43</td></tr>
<tr><td>EOT (Å)</td><td>23.5</td><td>14</td><td>15.6</td><td>14.5</td></tr>
<tr><td colspan="5">Variable Parameters (not constant across devices)</td></tr>
<tr><td>A (x 10^{10})</td><td>2</td><td>8.5</td><td>20</td><td>90</td></tr>
<tr><td>B (x 10^{10}) (UF-OTF, t_0 = 1us)</td><td>1.1</td><td>4.2</td><td>7.5</td><td>85</td></tr>
<tr><td>B (x 10^{10}) (OTF, t_0 = 1ms)</td><td>0.75</td><td>3.4</td><td>6</td><td>45</td></tr>
<tr><td>C (x 10^{13})</td><td>2.6</td><td>16</td><td>13</td><td>100</td></tr>
<tr><td>$\Gamma_{IT} = \Gamma_{HT}$</td><td>4.3</td><td>4.3</td><td>3.5</td><td>2.2</td></tr>
<tr><td colspan="5">Fixed Parameters (constant across all devices)</td></tr>
<tr><td>E_{Akf} = 0.175eV</td><td colspan="2">E_{Akr} = 0.2eV</td><td>E_{ADH2} = 0.58eV</td><td>E_{AHT}= 0.03eV</td></tr>
<tr><td>Γ_{OT} = 9</td><td colspan="2">E_{AOT} = 0.15 eV</td><td>β_{OT} = 0.36</td><td>$\eta = 5 \times 10^{12}$</td></tr>
</table>

Conventional OTF Measurement Results

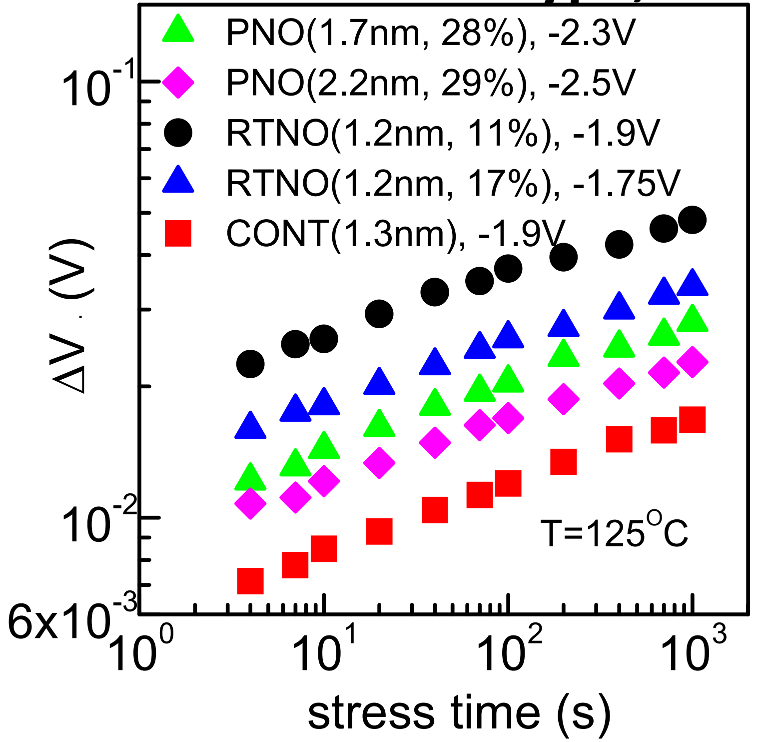
Power law time dependence of longer time data, with time exponent n ~ 0.14-0.15 for all stress bias and temperature

Relatively smaller hole trapping, NBTI dominated by generation of interface traps

Stress V_G and T



Film type, EOT



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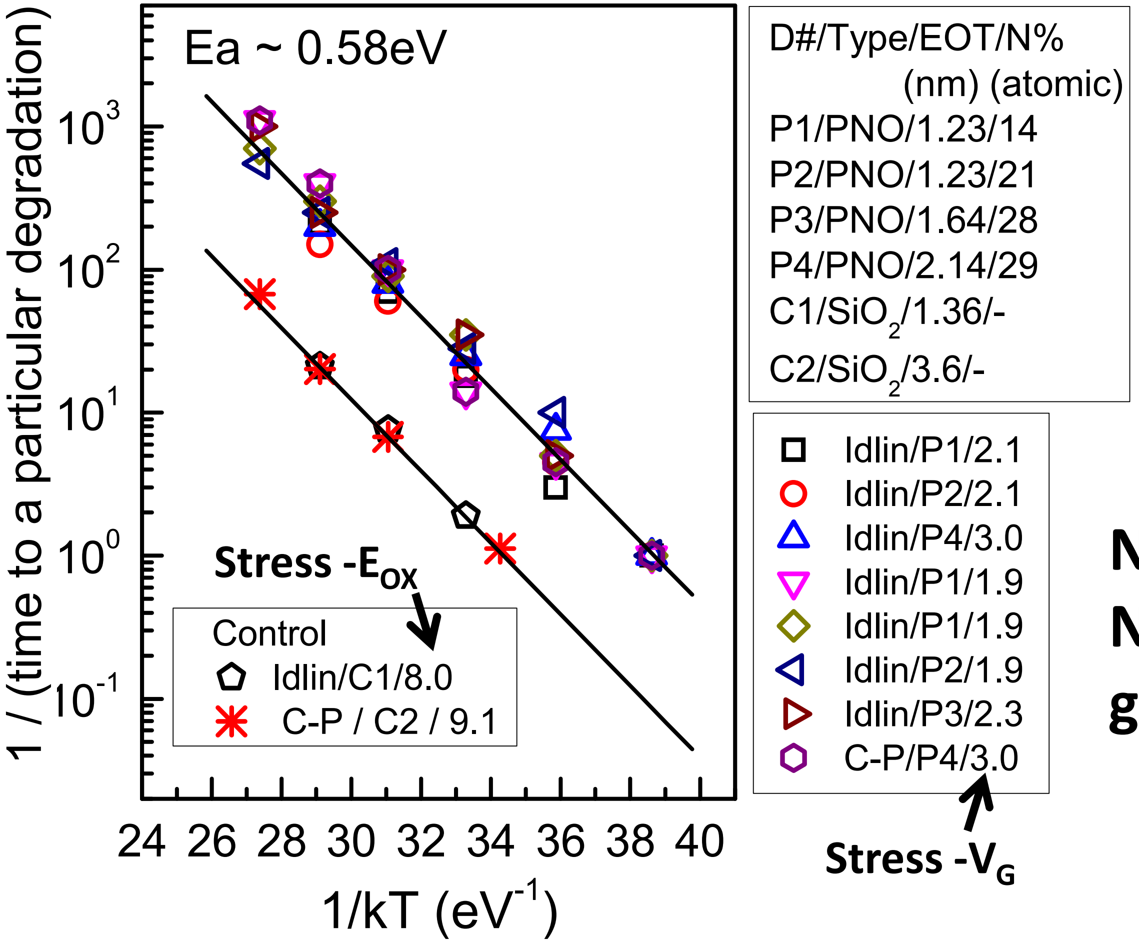
NBTI Temperature Activation

Time to reach a particular degradation from OTF (1ms) I_{DLIN} and Charge Pumping



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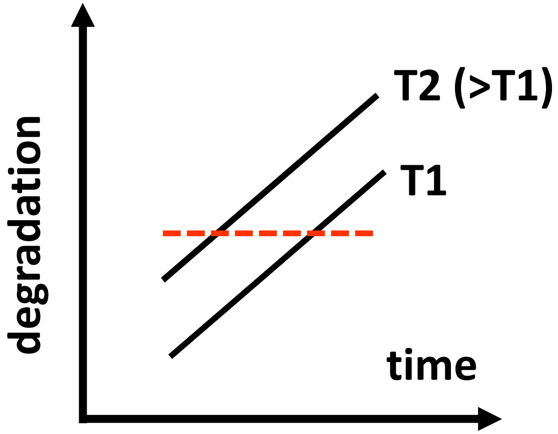


Identical T activation across devices and measurement methods

Negligible hole trapping, NBTI dominated by generation of interface traps

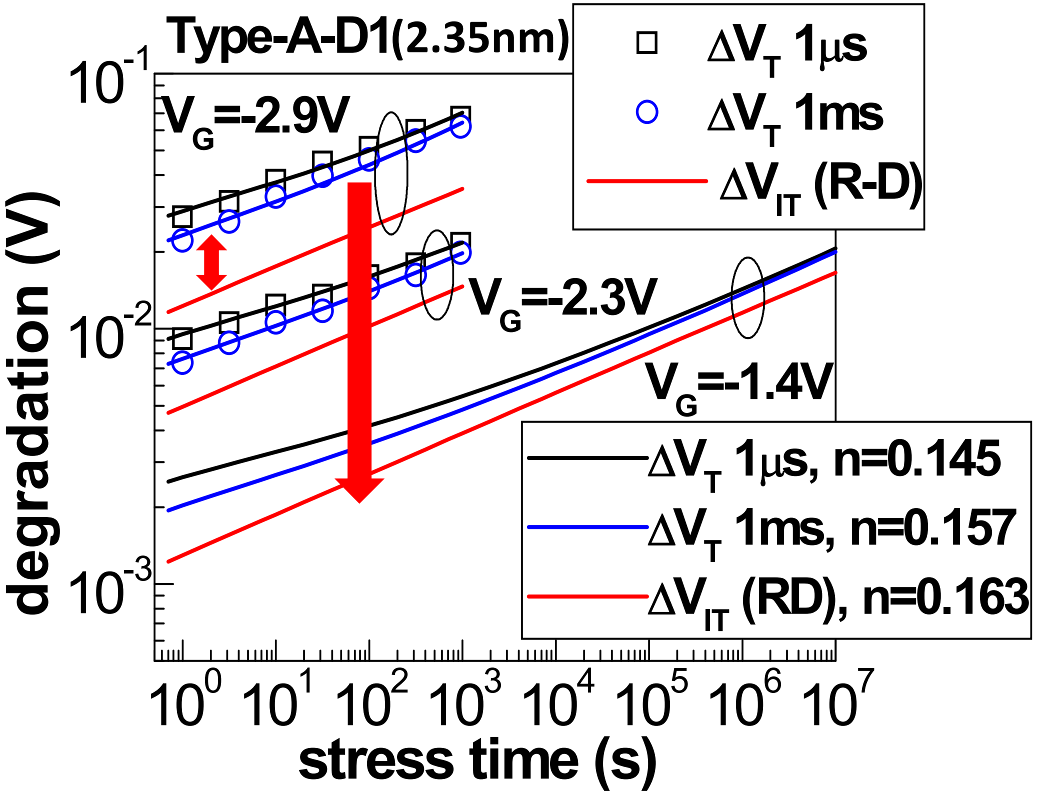
E_A refers to activation of molecular H_2 diffusion

Reed, JAP'88

Voltage Acceleration & Projection

Black and blue lines: NBTI model, sum of N_{IT}, N_{HT} and N_{OT}

Type-A: Reduced hole trapping in pre-existing bulk traps



<u>High stress V_G:</u> Significant contribution from bulk trap generation – large difference between data and RD model

<u>Lower stress V_G:</u> Much reduced bulk trap generation (stronger V_G acceleration) – extrapolated measured data close to RD prediction

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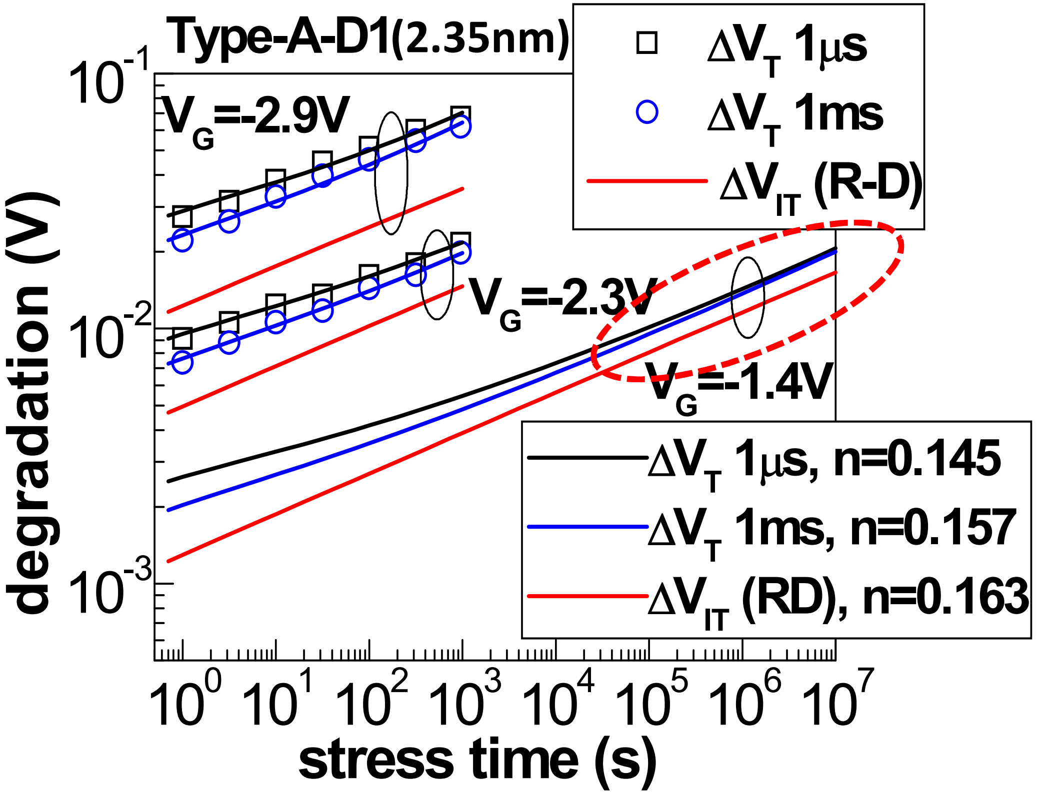
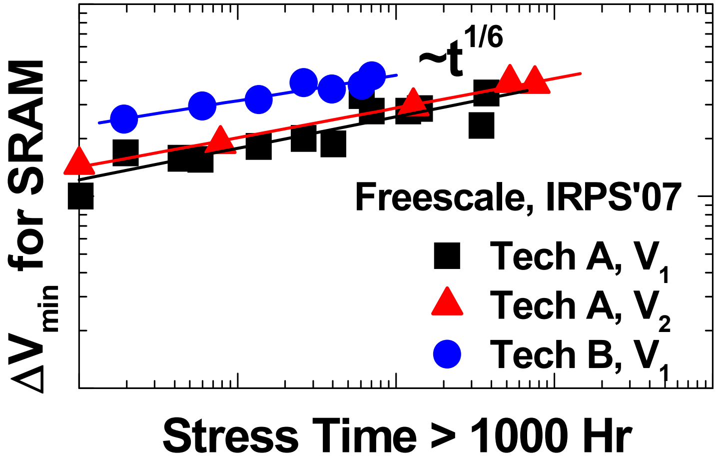
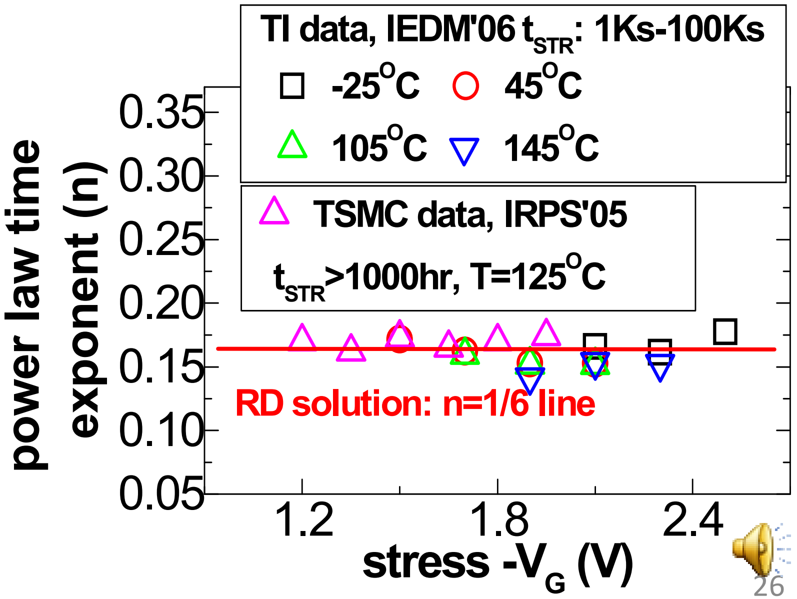
Projection: Long Time Degradation

Predicted very long-time power-law exponent at use V_G consistent with measured data

N_{IT} governed long-time NBTI at use condition



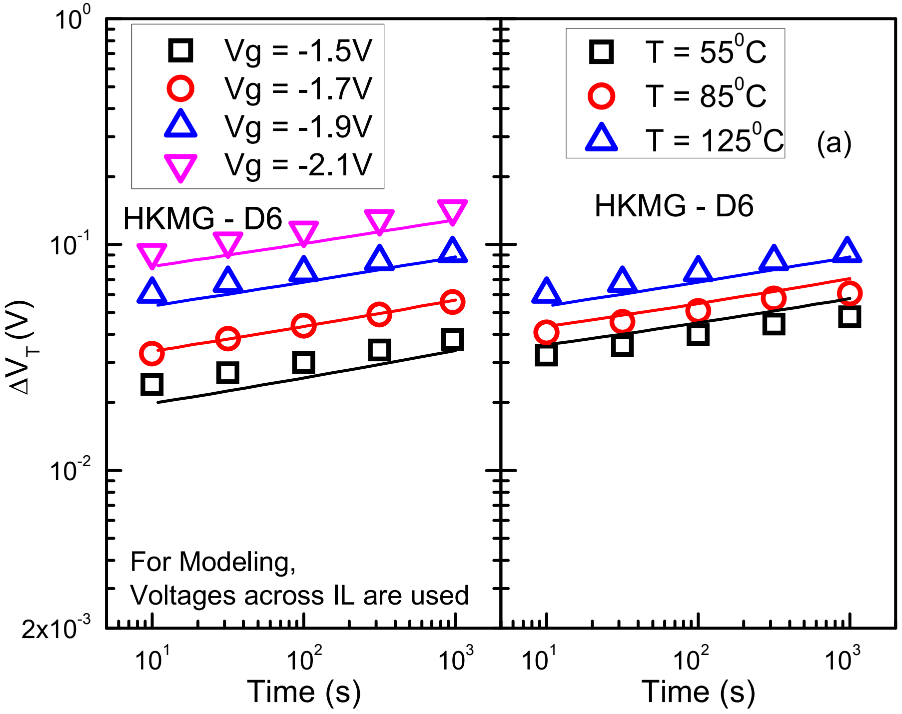


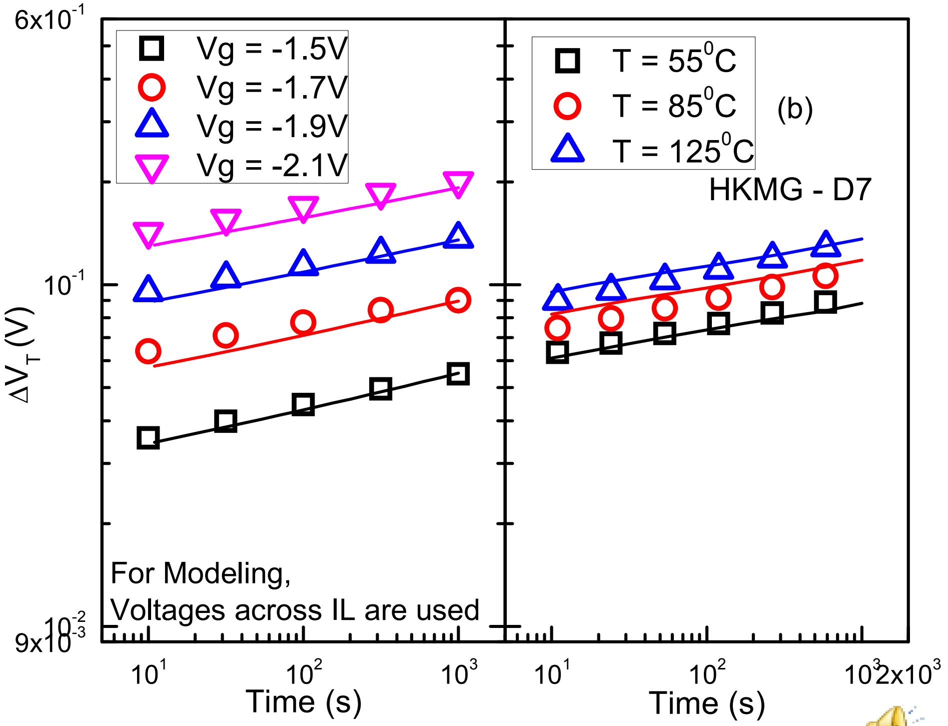


Prediction of UF-OTF NBTI Degradation (HKMG)

Prediction of long time NBTI degradation for different V_G/T in different HKMG stacks: SiON/HfSiON and SiON/HfO_2

Device D7 has higher N% in IL and show larger NBTI





Joshi, IRPS'12

Device Dependent Parameters (HKMG, Simple Model)

Prediction of V_G/T dependence by only 4 parameters

<table>
<tr><th>Device</th><th>D6 (SiON/HfSiON)</th><th colspan="2">D7 (SiON/HfO_2)</th></tr>
<tr><td colspan="4">Variable Parameters (not constant across devices)</td></tr>
<tr><td>A (x 10^{12})</td><td>3.1</td><td colspan="2">5.5</td></tr>
<tr><td>B (x 10^{11}) (t0 = 1us)</td><td>3.5</td><td colspan="2">8</td></tr>
<tr><td>C (x 10^{12})</td><td>3.1</td><td colspan="2">3.1</td></tr>
<tr><td>$\Gamma_{IT} = \Gamma_{HT}$</td><td>4.5</td><td colspan="2">4.5</td></tr>
<tr><td colspan="4">Fixed Parameters (constant across all devices)</td></tr>
<tr><td>$E_{Akf} = 0.195eV$</td><td>$E_{Akr} = 0.2eV$</td><td>$E_{ADH2} = 0.58eV$</td><td>$E_{AHT} = 0.03eV$</td></tr>
<tr><td>$\Gamma_{OT} = 9$</td><td>$E_{AOT} = 0.15$ eV</td><td>$\beta_{OT} = 0.36$</td><td>$\eta = 5 \times 10^{12}$</td></tr>
</table>

Summary – Model for NBTI DC Stress

NBTI stress transients at different stress V_G/T and different devices can be successfully explained using a RD model based framework with minimal adjustable parameters

Interface trap generation plays an important role, together with hole trapping in pre-existing and generated traps

The proposed physical mechanism is consistent with experimental results obtained from multiple methods

A simplified model can be developed to explain long time NBTI degradation with only 4 adjustable parameters

NBTI in HKMG devices is governed by SiON IL, and can be predicted using the model developed for SiON devices, with similar model parameters

Outline

Introduction, Basic NBTI signatures

Fast / Ultra-fast drain current degradation measurement

Estimation of pre-existing and generated defects

Transistor process / material dependence

Role of Nitrogen – Study by Ultrafast measurement

Predictive modeling

Stress

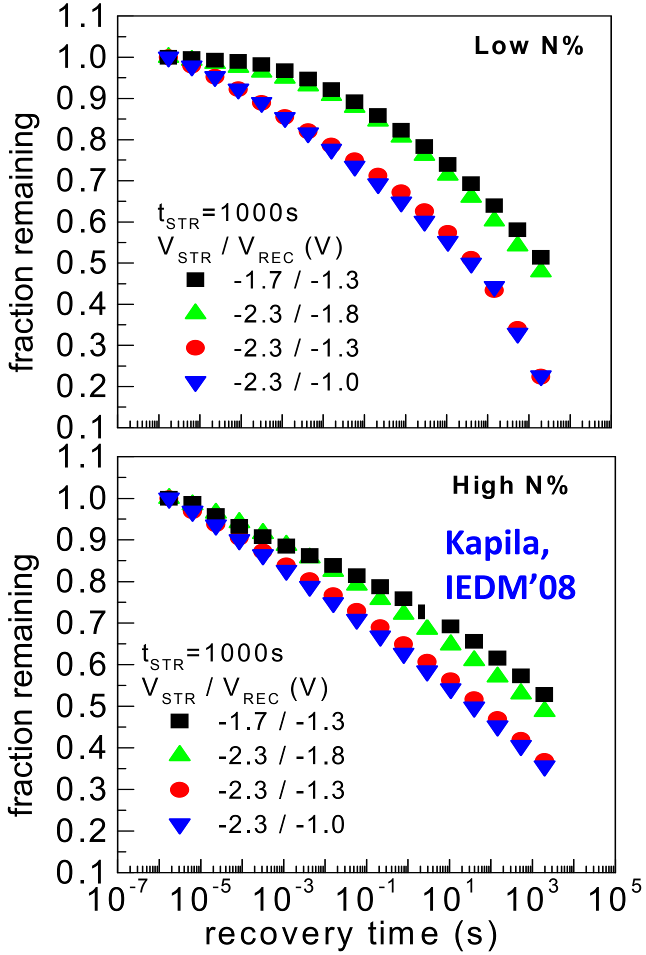
Recovery and AC effects ⬅

Conclusions / outlook

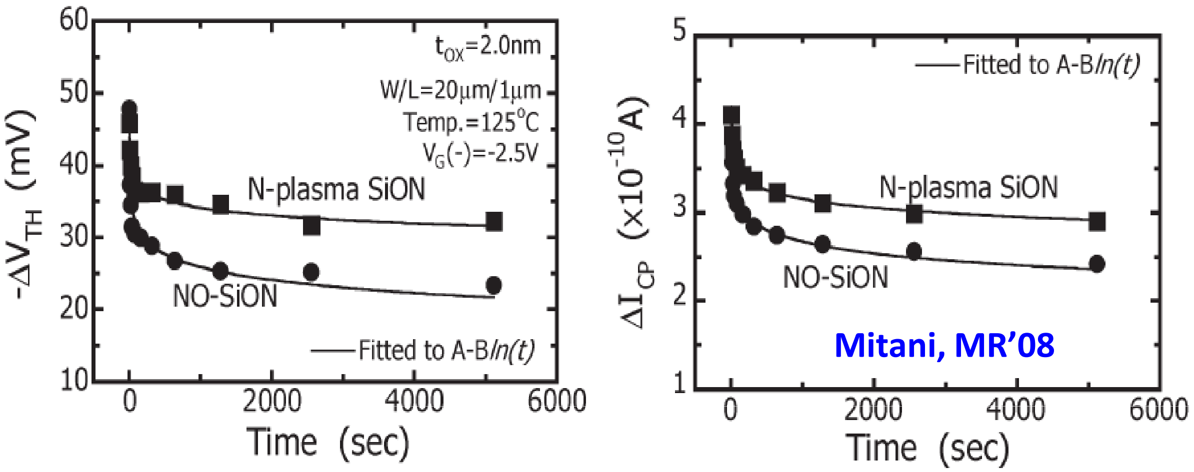
NBTI Experimental Signatures (1)

Strong gate insulator process dependence

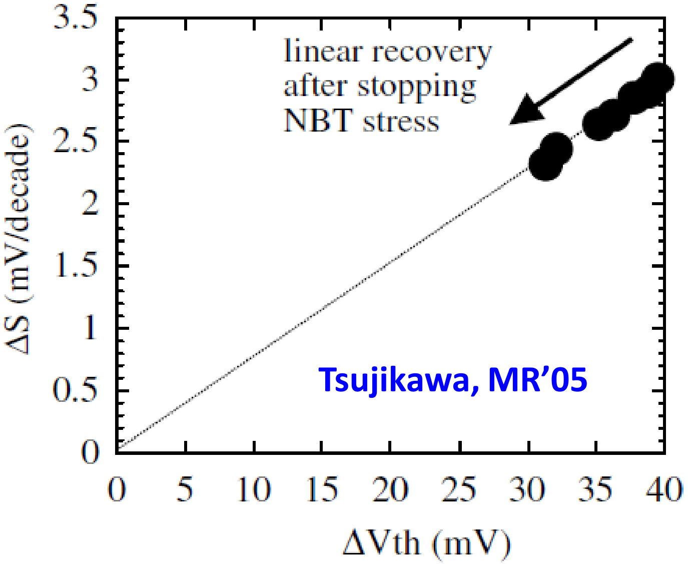
Strong evidence of recovery of generated traps



Kapila, IEDM'08



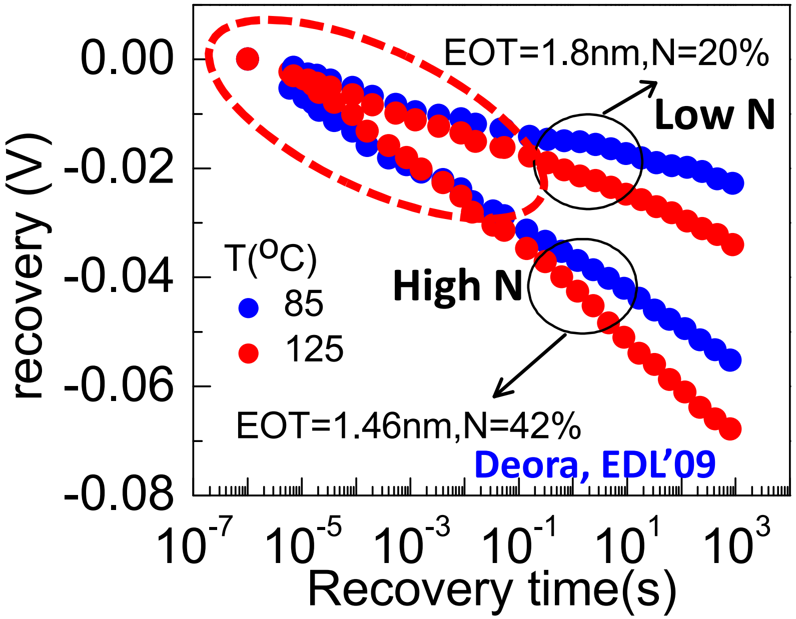
Mitani, MR'08



Tsujikawa, MR'05

Strong evidence of recovery of interface traps

NBTI Experimental Signatures (2)

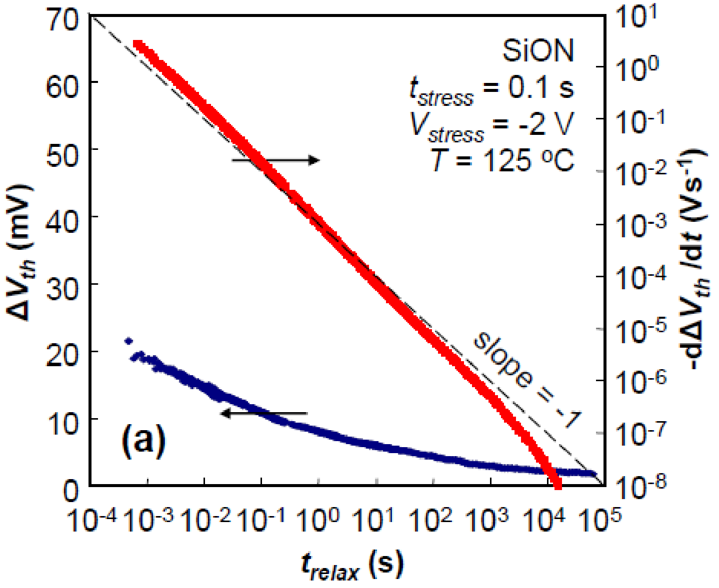


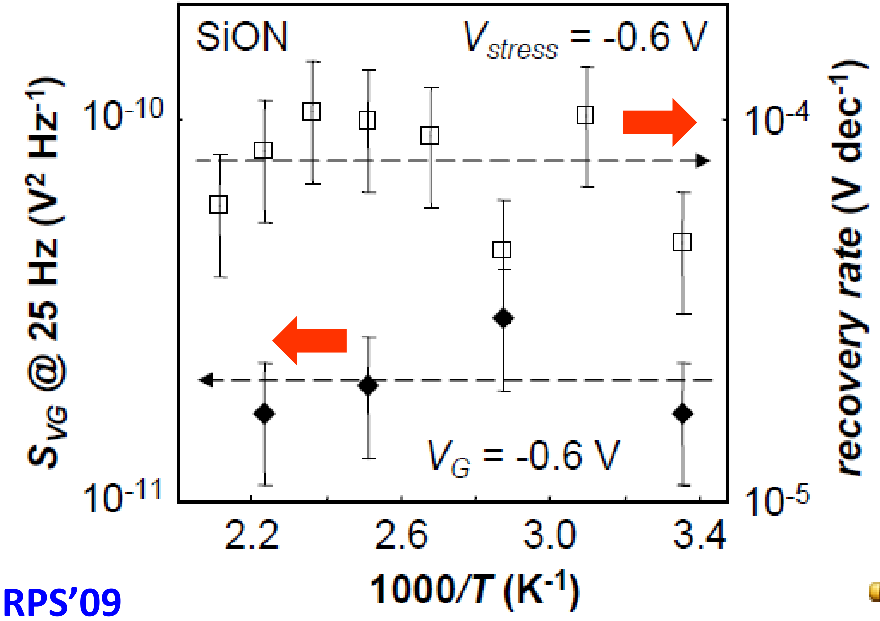
Deora, EDL'09

Short-time recovery shows weak T dependence

Short-time recovery rate slope ~ -1

Consistent with flicker noise (trapping-detrapping of holes)

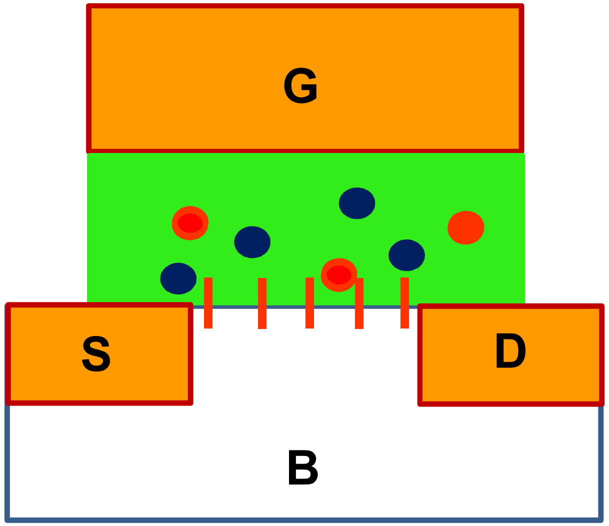




Kaczer, IRPS'09

NBTI Recovery Model

Interface trap passivation – re-formation of Si-H bonds at Si/SiON interface by back diffusion of Hydrogen (RD model) → ΔV_{IT} reduction

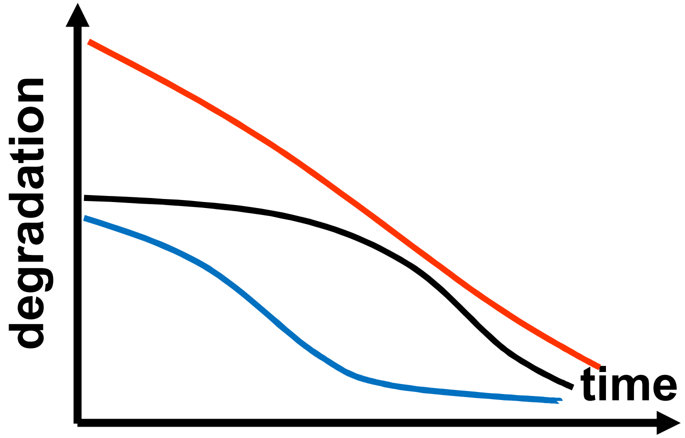


Discharging of pre-existing bulk oxide traps

Detrapping of trapped holes in generated bulk oxide traps (traps do not recover)

Both hole detrapping terms merged into one (fast detrapping) – analytical expression to account for multiple detrapping time constants

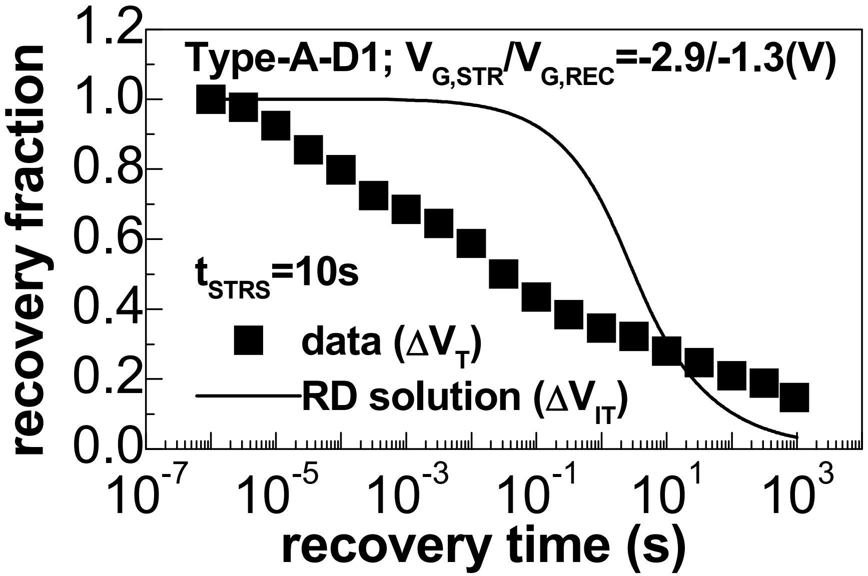
$\Delta V_{HT} \sim \exp(-(t/\tau)^\beta)$

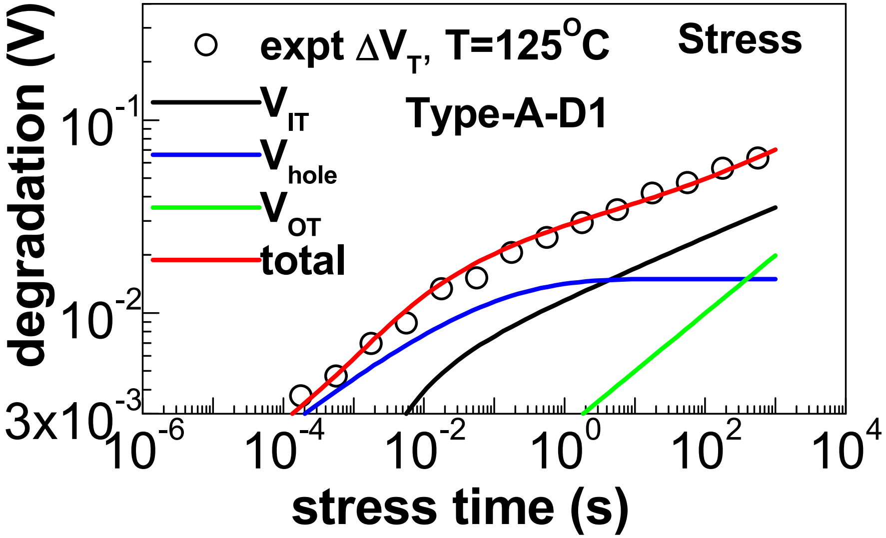


Total recovery = sum of two components

Mahapatra, IRPS'11

Prediction of Recovery Transients





RD model cannot explain NBTI recovery!

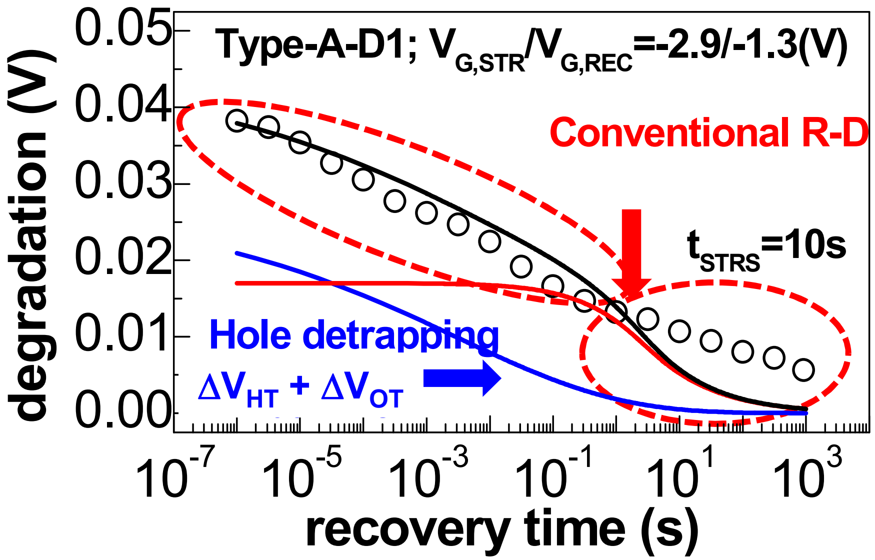
Recap: NBTI is interface trap generation (R-D) plus hole trapping in pre-existing and stress generated traps

Erroneous criticism when NBTI recovery is compared to recovery of interface traps (R-D solution)

Need to account for hole detrapping

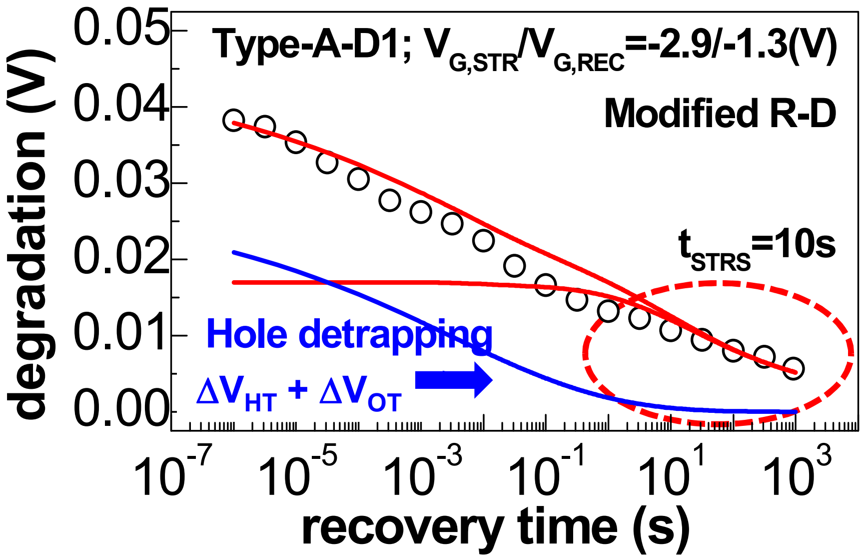
Mahapatra, IRPS’11

Prediction of Recovery Transients



Early part of NBTI recovery due to fast hole detrapping from pre-existing and generated traps

Accurate prediction of start time of NBTI recovery as controlled by interface trap re-passivation (R-D solution)

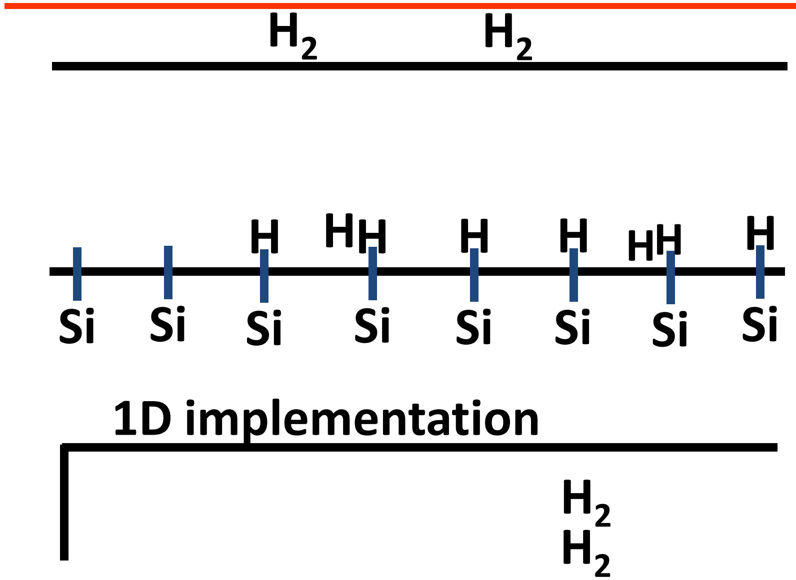


Rate of recovery cannot be matched by conventional R-D solution

Rate of N_{IT} recovery accurately predicted by modified RD approach

Mahapatra, IRPS'11

Modification of R-D Framework

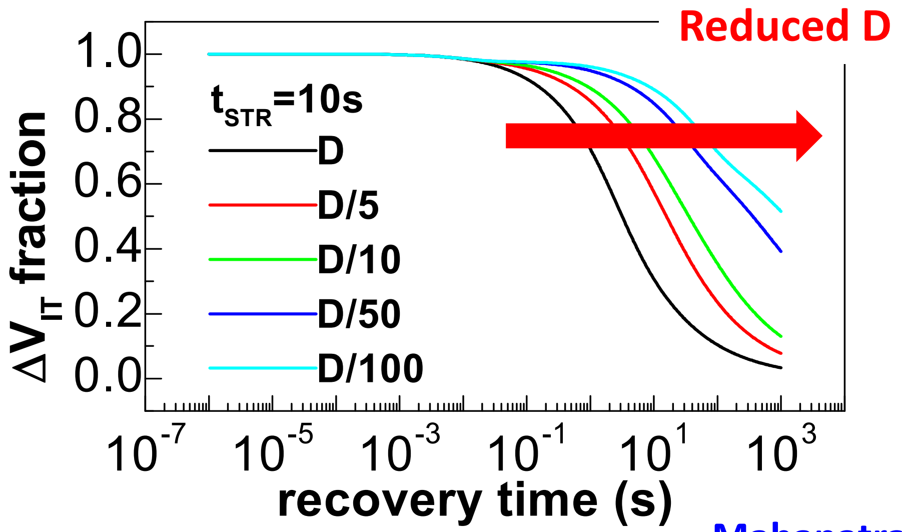


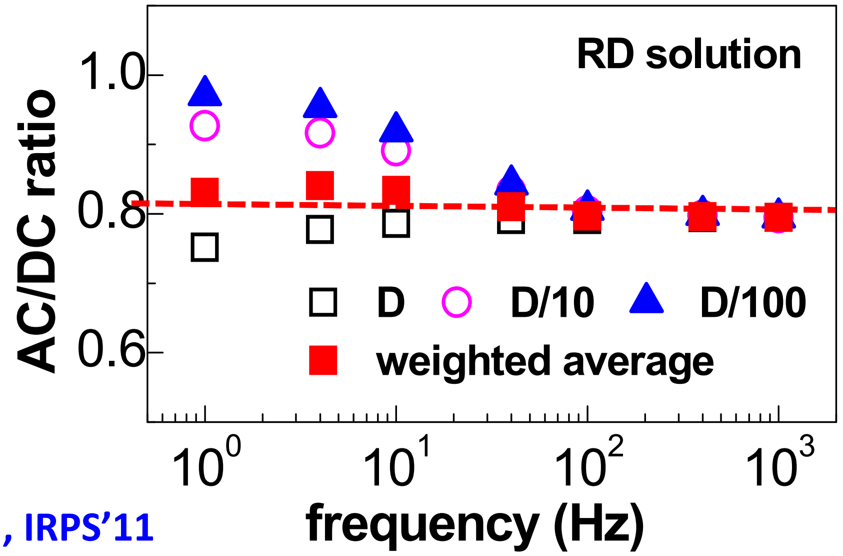
Multiple 3D H_2 back-diffusion pathways

Simple 1D implementation by reduction of diffusivity during recovery

A weighted average predicts rate of long-time recovery

Consistent with NBTI frequency independence

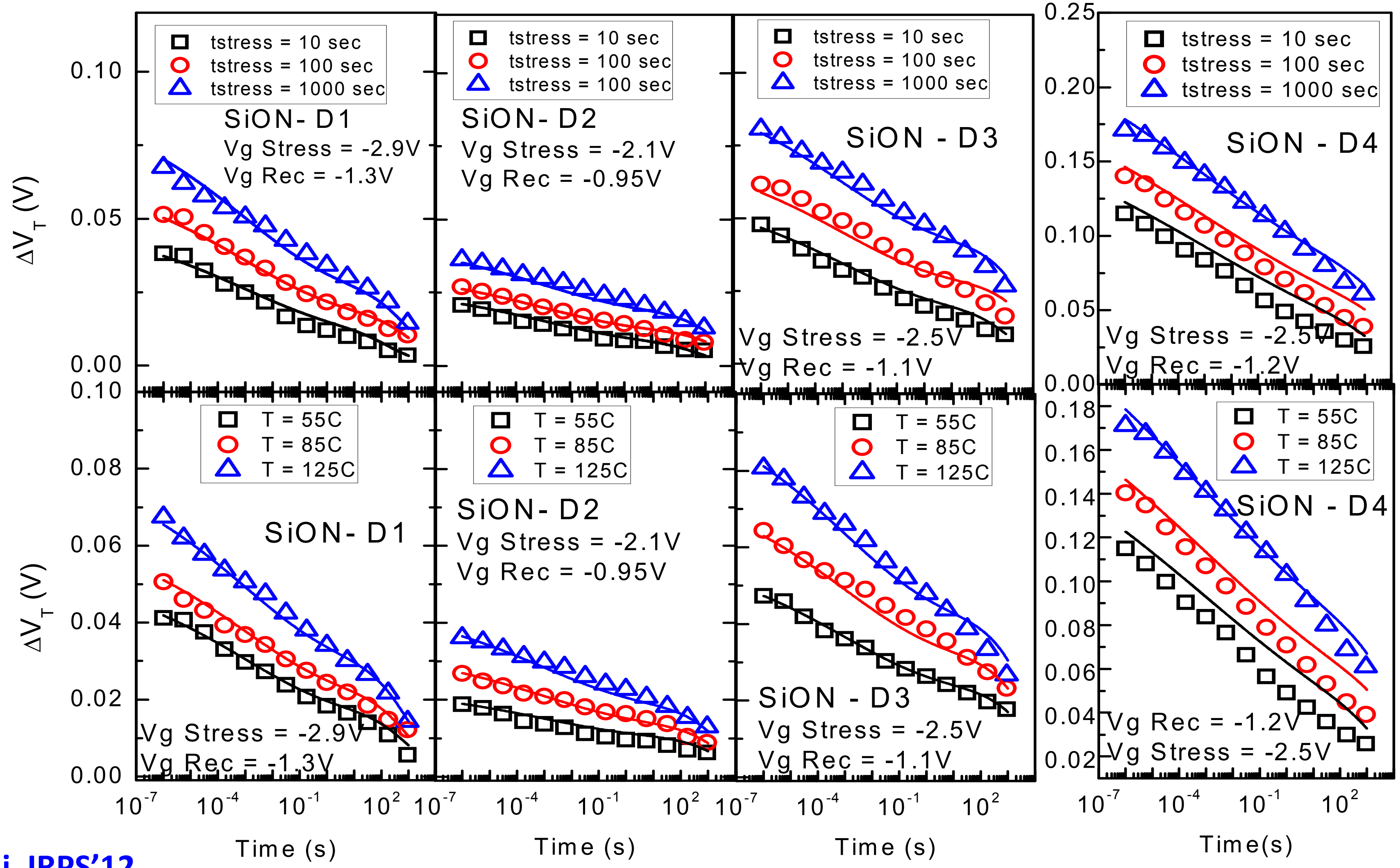




Mahapatra, IRPS'11

Prediction of NBTI Recovery – Material Dependence

Modified RD framework can successfully predict recovery transients following different stress time & T

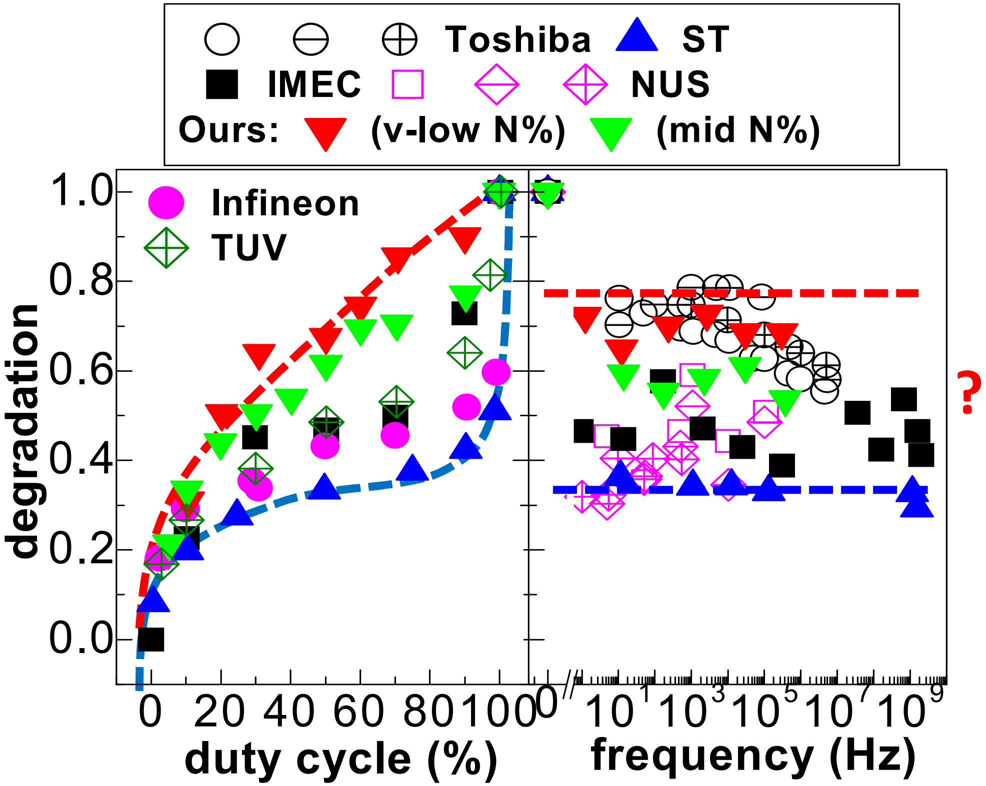


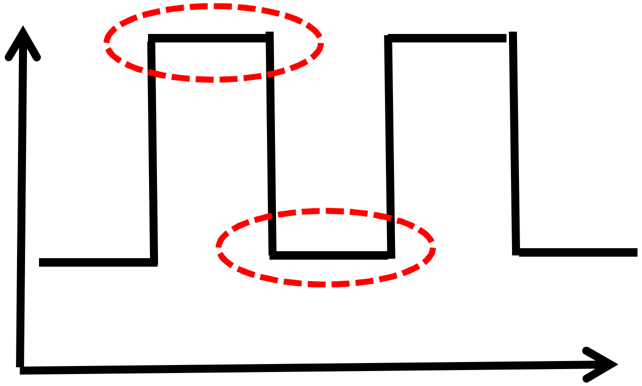
Joshi, IRPS'12

AC Degradation – Duty Cycle and Frequency

Recap: Measured data from different industry/academia

Normalized to DC → Large difference in "shape" of duty cycle dependence and AC/DC ratio → Modeling a challenge!



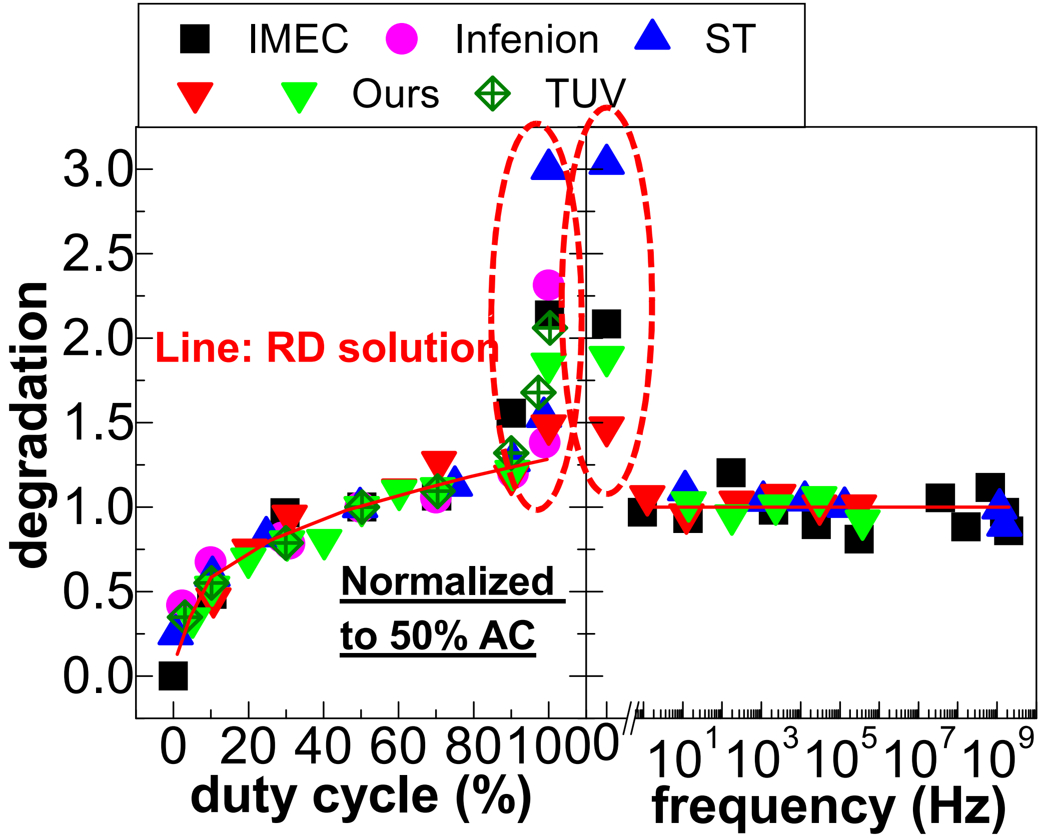


Hole trapping and interface trap generation

Hole detrapping and recovery of interface traps

Renormalization of AC Degradation

Measured data from different industry/academia



Re-normalized to 50% AC data

Universal relation versus duty cycle up to ~80%

Successful prediction by R-D model

Spread close to DC due to differences in AC-DC measurement methods and hole trapping

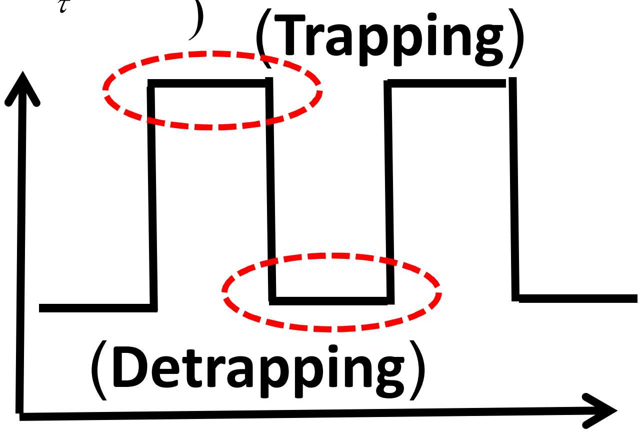
Mahapatra, IRPS'11

Prediction of Duty Cycle Dependence

Solution of analytical models for hole trapping detrapping

$$\Delta V_{HT} = \frac{q}{C_{ox}} B \left(V_G - V_{T0} - \Delta V_T\right)^{\Gamma_{HT}} e^{-\frac{E_{AHT}}{kT}} \left(1 - e^{\left(-\left(\frac{t}{\tau}\right)^{\beta_{HT}}\right)}\right)$$

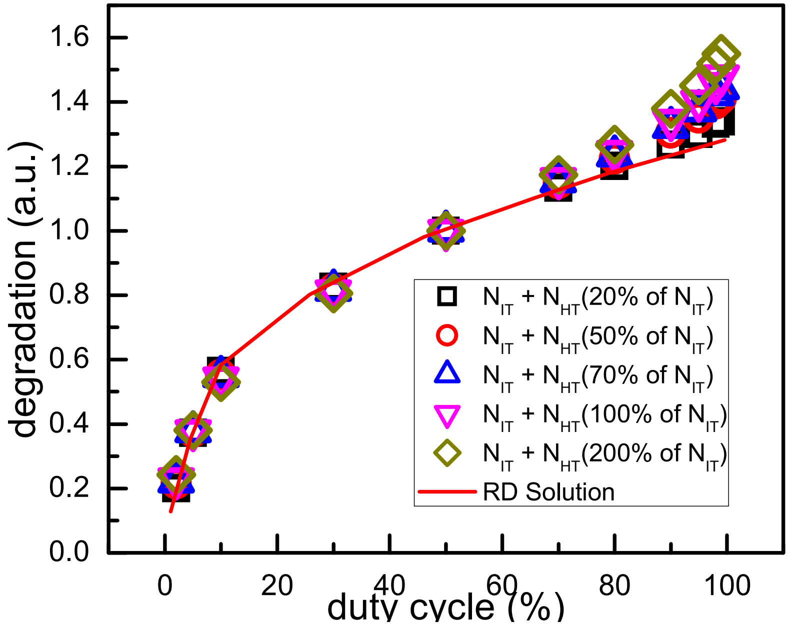
$$\Delta V_{HT} = B' e^{-\left(\frac{t}{\tau_r}\right)^{\beta_r}} \quad (B' \text{obtained from end of stress})$$



AC simulation of RD model for interface trap contribution

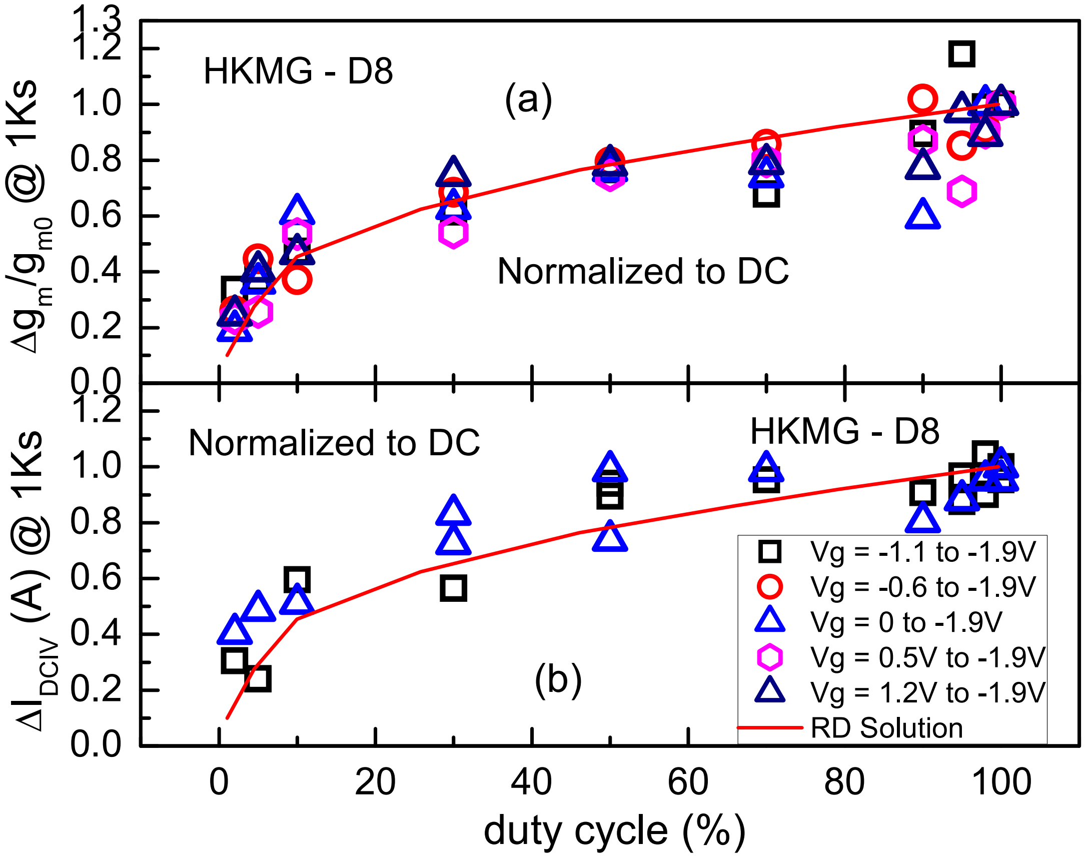
Up to ~80% duty cycle dominated by interface traps (fast hole trapping - detrapping)

Large spread close to DC due to hole trapping contribution



Joshi, IRPS'12

Trap Generation – Duty Cycle Dependence



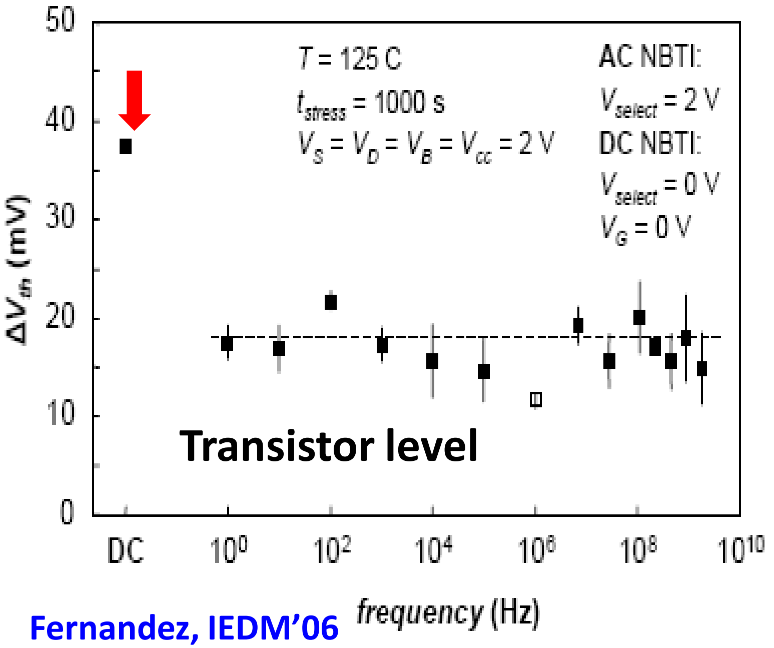
Normalized to DC, independent of pulse low bias

Identical AC/DC versus duty cycle for both measurements

Prediction by RD model solution of interface traps

Joshi, IRPS'12

NBTI Frequency (In)dependence



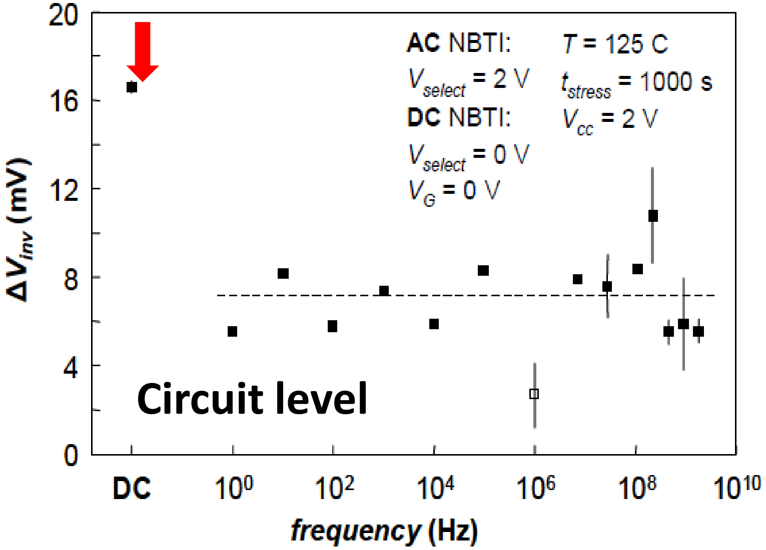
Fernandez, IEDM'06

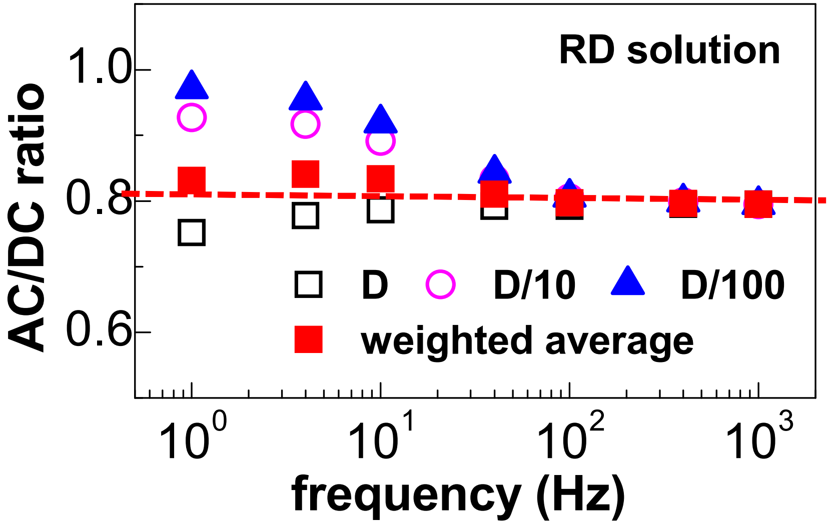
Careful experiments (on-chip circuitry to minimize high frequency reflection) shows frequency independent AC NBTI

Similar observation in circuits (inverter max gain point shift)

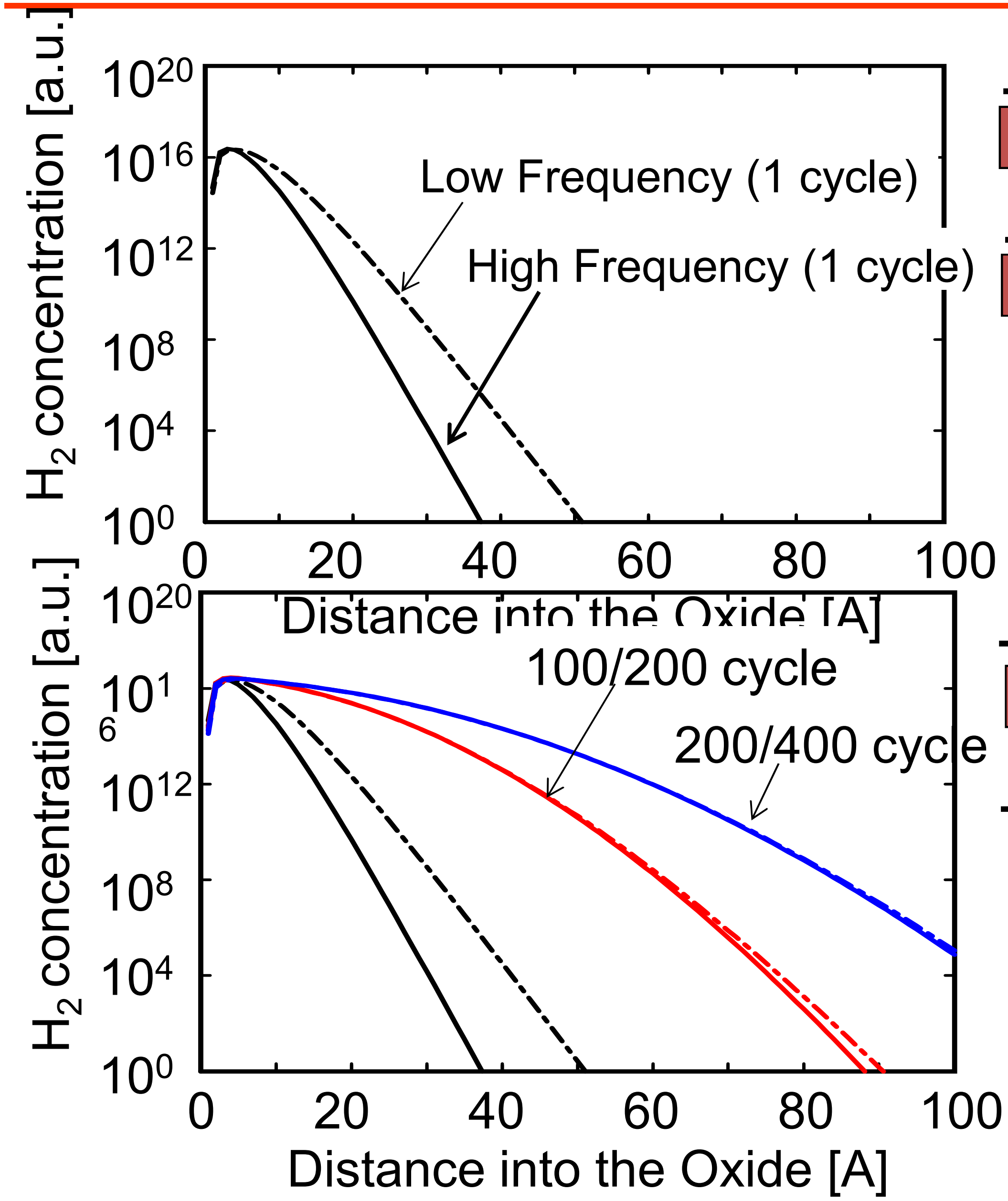
Prediction by RD, but higher AC/DC ratio

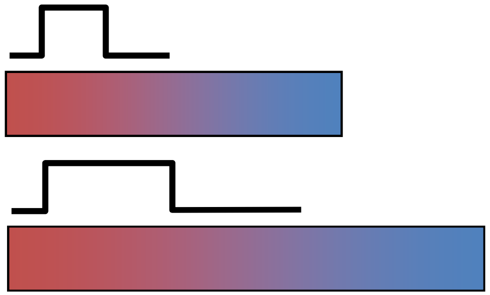
Additional hole trapping at DC stress



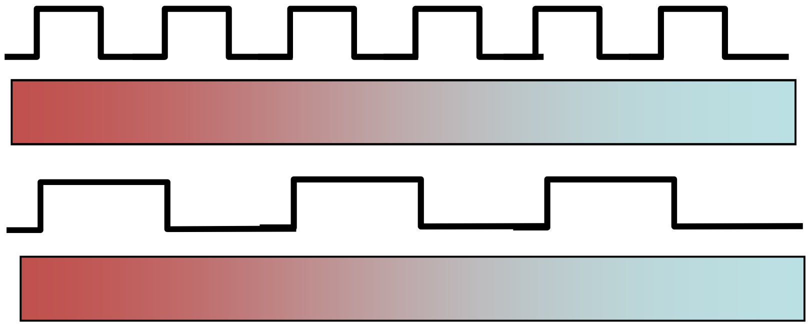


RD solution: NBTI Frequency Independence





Low f – greater distance of H_2 diffusion in oxide bulk



Multiple cycles – equal distance of H_2 diffusion in oxide bulk

Alam, IEDM'03

Summary – Model for NBTI Recovery & AC Stress

NBTI recovery transients at different stress time & T and different devices can be successfully explained using a RD model based framework with similar parameters as stress

Early part of recovery dominated by hole detrapping, long time part by recovery of interface traps

The proposed physical mechanism is consistent with experimental results obtained from multiple methods

AC duty cycle dependence of degradation shows universality when properly normalized and can be successfully explained

Observed frequency independence of AC (~50% duty) degradation is an inherent outcome of RD model

Outline

Introduction, Basic NBTI signatures

Fast / Ultra-fast drain current degradation measurement

Estimation of pre-existing and generated defects

Transistor process / material dependence

Role of Nitrogen – Study by Ultrafast measurement

Predictive modeling

Conclusions / outlook ⬅

Conclusions

NBTI in both SiON and Hi-K/MG devices results in generation of interface traps plus hole trapping in pre-existing and generated bulk traps (mutually uncoupled components)

Pre-existing traps primarily responsible for NBTI material dependence; reduction by suitable processes

Bulk trap generation reduction at lower stress bias

Interface trap generation shows universality in long-time degradation, AC duty and frequency dependence, responsible for long-time NBTI failure

Reaction-Diffusion (R-D) model can fully explain NBTI stress, recovery and AC degradation once hole trapping contribution is identified and isolated

Outlook

NBTI in scaled IL HKMG stacks → Possible role of 2nd (IL/HK) interface

Develop physics based trapping model for large area device and correlation to flicker noise → Completion of macroscopic model

Extension of macroscopic trap generation model to small area device

Extension of macroscopic trapping model to small area device and correlation to RTN

Suitable addition of microscopic trap generation and trapping models to predict long time NBTI variability for small area devices