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

Transistor process / material dependence

Role of Nitrogen – Study by Ultrafast measurement

Predictive modeling

Conclusions / outlook
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

Predictive modeling

Stress

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) \( \Delta V_{IT} \)

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

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

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

Mahapatra, IRPS’11
**H-H$_2$ Reaction Diffusion (R-D) Model**

Breaking of Si-H bonds at Si/SiO$_2$ interface by holes (Reaction)

H $\rightarrow$ 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)

Hole tunneling

\[ T_H \sim \exp (\gamma_T \cdot E_{OX}) \]

\[ p_H \sim E_{OX} \]

Barrier lowering due to hole capture

Dissociation

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

Simplification by power law voltage dependence

Details: Islam, IEDM'06
H – H₂ RD Model: Mathematical Formulation

Reaction

\[
\frac{dN_{IT}}{dt} = k_f (N_0 - N_{IT}) - k_r N_{IT} N_H^{(0)}
\]

H ⇔ H₂ transformation

\[
\frac{\delta}{2} \frac{dN_H^{(0)}}{dt} = D_H \frac{dN_H^{(0)}}{dx} + \frac{dN_{IT}}{dt} - \delta k_H \left[ N_H^{(0)} \right]^2 + \delta k_{H_2} N_{H_2}^{(0)}
\]

\[
\frac{\delta}{2} \frac{dN_{H_2}^{(0)}}{dt} = D_{H_2} \frac{dN_{H_2}^{(0)}}{dx} + \frac{dN_{IT}}{dt} - \frac{\delta}{2} k_H \left[ N_H^{(0)} \right]^2 - \delta k_{H_2} N_{H_2}^{(0)}
\]

Diffusion

\[
\frac{dN_H}{dt} = D_H \frac{d^2 N_H}{dx^2} - k_H N_H^2 + k_{H_2} N_{H_2}
\]

\[
\frac{dN_{H_2}}{dt} = D_{H_2} \frac{d^2 N_{H_2}}{dx^2} + \frac{1}{2} k_H N_H^2 - \frac{1}{2} k_{H_2} N_{H_2}
\]

\[
k_f = k_{f0} (V_G - V_T)^3 \Gamma_{IT} e^{-\frac{E_{Akf}}{kT}}
\]

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

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

\[
D_{H_2} = D_{H_20} e^{-\frac{E_{ADH_2}}{kT}}
\]

\[
k_H = k_{H0} e^{-\frac{E_{AKH}}{kT}}
\]

\[
k_{H_2} = k_{H_20} e^{-\frac{E_{AKH_2}}{kT}}
\]

Details: Islam, TED’07
**H – H₂ RD Model Parameters**

**Constant parameters across all** (type, EOT & N%) **devices studied in this work**

\[
k_f = k_{f0} \left( V_G - V_T \right)^3 \Gamma_{IT} \ e^{\frac{E_{Akf}}{kT}} \\
k_r = k_{r0} e^{\frac{E_{Akr}}{kT}} \\
D_H = D_{H0} e^{\frac{E_{ADH}}{kT}} \\
D_{H2} = D_{H20} e^{\frac{E_{ADH2}}{kT}} \\
k_H = k_{H0} e^{\frac{E_{AkH}}{kT}} \\
k_{H2} = k_{H20} e^{\frac{E_{AkH2}}{kT}}
\]

**Only 2 device dependent parameters –** \( k_{f0} \) **and** \( \Gamma_{IT} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{Akf} )</td>
<td>0.175 eV</td>
</tr>
<tr>
<td>( k_{r0} )</td>
<td>9.9 x 10^{-7}</td>
</tr>
<tr>
<td>( E_{Akr} )</td>
<td>0.2 eV</td>
</tr>
<tr>
<td>( D_{H0} )</td>
<td>9.56 x 10^{-11} cm²/s</td>
</tr>
<tr>
<td>( E_{ADH} )</td>
<td>0.2 eV</td>
</tr>
<tr>
<td>( D_{H20} )</td>
<td>3.5 x 10^{-5} cm²/s</td>
</tr>
<tr>
<td>( E_{ADH2} )</td>
<td>0.58 eV</td>
</tr>
<tr>
<td>( k_{H0} )</td>
<td>8.56 cm³/s</td>
</tr>
<tr>
<td>( E_{AkH} )</td>
<td>0.3 eV</td>
</tr>
<tr>
<td>( k_{H20} )</td>
<td>5.7 x 195 s⁻¹</td>
</tr>
<tr>
<td>( E_{AkH2} )</td>
<td>0.3 eV</td>
</tr>
</tbody>
</table>

\( \delta \rightarrow \) Si/SiO₂ **interfacial layer thickness (~1.5Å)**

*Joshi, IRPS’12*
NBTI Degradation Components

Generation of interface traps (RD): \( \Delta V_{IT} = \frac{q}{C_{OX}} \times \Delta N_{IT} \)

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

Hole trapping in pre-existing bulk insulator traps:

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

\( E_{AHT} = 0.03eV \) & \( \Gamma_{HT} = \Gamma_{IT} \) (all devices);

3 device dependent parameters (\( B, \tau \) & \( \beta_{HT} \))

Generation (and subsequent trapping in) bulk insulator traps:

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

\( n = \eta(V_G - V_T - \Delta V_T) \) e^{-\frac{-\Gamma_{OT}}{kT}}

\( \eta = 5 \times 10^{12}, \ \beta_{OT} = 0.36, \ \Gamma_{OT} = 9 \) & \( E_{AOT} = 0.15eV \) (for all devices);

1 device dependent parameter (\( C \))

Joshi, IRPS’12
### Device Details – Prediction of NBTI

<table>
<thead>
<tr>
<th>Device</th>
<th>EOT (nm)</th>
<th>%N</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Type A</td>
</tr>
<tr>
<td>D1</td>
<td>2.35</td>
<td>16.7</td>
<td>A</td>
</tr>
<tr>
<td>D2</td>
<td>1.4</td>
<td>22.6</td>
<td>A</td>
</tr>
<tr>
<td>D3</td>
<td>1.56</td>
<td>34.6</td>
<td>A/B</td>
</tr>
<tr>
<td>D4</td>
<td>1.45</td>
<td>43</td>
<td>B</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Device</th>
<th>HK</th>
<th>IL Thickness (nm)</th>
<th>HK Thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D6</td>
<td>HfSiON</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>D7</td>
<td>HfO$_2$</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
Prediction of UF-OTF NBTI Degradation (SiON)

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

Joshi, IRPS’12
Device Dependent Parameters

Identical parameters for all stress $V_G/T$

<table>
<thead>
<tr>
<th>Device</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
</tr>
</thead>
<tbody>
<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>
</tbody>
</table>

Variable Parameters (not constant across devices)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{f_0}$</td>
<td>1.1</td>
<td>10</td>
<td>28</td>
<td>350</td>
</tr>
<tr>
<td>$\Gamma_{NIT} = \Gamma_{NHT}$</td>
<td>4.3</td>
<td>4.3</td>
<td>3.5</td>
<td>2.2</td>
</tr>
<tr>
<td>$B \times 10^{10}$</td>
<td>1.1</td>
<td>4.2</td>
<td>7.5</td>
<td>85</td>
</tr>
<tr>
<td>$C \times 10^{13}$</td>
<td>2.6</td>
<td>16</td>
<td>13</td>
<td>100</td>
</tr>
<tr>
<td>$\beta_{HT}$</td>
<td>0.28</td>
<td>0.33</td>
<td>0.37</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Hole trapping time constant ($\tau$) shows T activation

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

Joshi, IRPS’12
Prediction of NBTI Components (SiON)

Total $\Delta V_T$ (mobility corrected) = \( \frac{q}{C_{Ox}} \) * 
($\Delta N_{IT} + \Delta N_{HT} + \Delta N_{OT}$)

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

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

Mahapatra, IRPS’11
Prediction of NBTI Components (HKMG)

**Total $\Delta V_T$ (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 – H₂ RD Model: Analytical Solution (Long time)

\[ \frac{dN_{IT}}{dt} = k_F (N_0 - N_{IT}) - k_R \cdot N_H(x=0) \cdot N_{IT} \]

\[ N_{IT} \ll N_0, \text{ } \frac{dN_{IT}}{dt} \text{ small } \rightarrow N_H(x=0) \cdot N_{IT} = k_F N_0 / k_R \]

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

\[ N_{IT}^2 = \left( k_F N_0 / k_R \right)^2 / N_{H2}(x=0) \]

\[ \frac{dN_{H2}}{dt} = D_{H2} \frac{d^2N_H}{dx^2} \rightarrow x = (D_{H2} \cdot t)^{1/2} \]

Generated \( N_{IT} = 2 \times \text{Total no. of released H molecules} \)

\[ N_{IT} = 2 \times \frac{1}{2} N_{H2}(x=0) \left( D_{H2} \cdot t \right)^{1/2} \]

\[ N_{IT} = \left( k_F N_0 / k_R \right)^{2/3} \left( D_{H2} \cdot t \right)^{1/6} \]

Prediction of 1/6 power law time exponent

Details: Alam, IRPS’05 (Tutorial)
Very Long Time Degradation

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

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

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

\[ E_{AIT} = \left( \frac{2}{3} (E_{Akf} - E_{Akr}) + \frac{E_{ADH2}}{6} \right) \]

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

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

\[ n = \eta(V_G - V_T - \Delta V_T)^{\beta_{OT}} e^{\frac{-\Gamma_{OT}}{kT\beta_{OT}}} \]

Joshi, IRPS’12
Prediction of UF-OTF NBTI Degradation (SiON)

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

Joshi, IRPS’12
Prediction of OTF NBTI Degradation (SiON)

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

Joshi, IRPS’12
Device Dependent Parameters (SiON, Simple Model)

Prediction of $V_G/T$ dependence by only 4 adjustable parameters

<table>
<thead>
<tr>
<th>Device</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
</tr>
</thead>
<tbody>
<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>
</tbody>
</table>

Variable Parameters (not constant across devices)

<table>
<thead>
<tr>
<th>Variable</th>
<th>A ($\times 10^{10}$)</th>
<th>B ($\times 10^{10}$) (UF-OTF, $t_0 = 1\mu$s)</th>
<th>B ($\times 10^{10}$) (OTF, $t_0 = 1\text{ms}$)</th>
<th>C ($\times 10^{13}$)</th>
<th>$\Gamma_{IT} = \Gamma_{HT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>1.1</td>
<td>0.75</td>
<td>2.6</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>8.5</td>
<td>4.2</td>
<td>3.4</td>
<td>16</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>7.5</td>
<td>6</td>
<td>13</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>85</td>
<td>45</td>
<td>100</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Fixed Parameters (constant across all devices)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{Akf}$</td>
<td>0.175 eV</td>
</tr>
<tr>
<td>$E_{Akr}$</td>
<td>0.2 eV</td>
</tr>
<tr>
<td>$E_{ADH2}$</td>
<td>0.58 eV</td>
</tr>
<tr>
<td>$E_{AHT}$</td>
<td>0.03 eV</td>
</tr>
<tr>
<td>$\Gamma_{OT}$</td>
<td>9</td>
</tr>
<tr>
<td>$E_{AOT}$</td>
<td>0.15 eV</td>
</tr>
<tr>
<td>$\beta_{OT}$</td>
<td>0.36</td>
</tr>
<tr>
<td>$\eta$</td>
<td>$5 \times 10^{12}$</td>
</tr>
</tbody>
</table>
Conventional OTF Measurement Results

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

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

**Stress $V_G$ and $T$**

- $-V_G(V) / T(°C)$ [1.2nm]
  - PNO (21%)
  - PNO (14%)

**Film type, EOT**

- PNO (1.7nm, 28%), -2.3V
- PNO (2.2nm, 29%), -2.5V
- RTNO (1.2nm, 17%), -1.75V
- RTNO (1.2nm, 11%), -1.9V
- CONT (1.3nm), -1.9V

Mahapatra, IRPS’07
NBTI Temperature Activation

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

$E_a \sim 0.58\text{eV}$

$1 / (\text{time to a particular degradation})$

$1 / kT (\text{eV}^{-1})$

$E_a$ refers to activation of molecular $H_2$ diffusion

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

Mahapatra, IRPS’07

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

High stress $V_G$: Significant contribution from bulk trap generation – large difference between data and RD model

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

Mahapatra, IRPS’11
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

![Graph showing long-time degradation projections and data points.](image)
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
### Device Dependent Parameters (HKMG, Simple Model)

**Prediction of $V_G/T$ dependence by only 4 parameters**

<table>
<thead>
<tr>
<th>Device</th>
<th>D6 (SiON/HfSiON)</th>
<th>D7 (SiON/HfO$_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variable Parameters (not constant across devices)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A \times 10^{12}$</td>
<td>3.1</td>
<td>5.5</td>
</tr>
<tr>
<td>$B \times 10^{11} \ (t0 = 1\mu s)$</td>
<td>3.5</td>
<td>8</td>
</tr>
<tr>
<td>$C \times 10^{12}$</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>$\Gamma_{IT} = \Gamma_{HT}$</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td><strong>Fixed Parameters (constant across all devices)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{Akf} = 0.195\text{eV}$</td>
<td>$E_{Akr} = 0.2\text{eV}$</td>
<td>$E_{ADH2} = 0.58\text{eV}$</td>
</tr>
<tr>
<td>$\Gamma_{OT} = 9$</td>
<td>$E_{AOT} = 0.15\text{eV}$</td>
<td>$\beta_{OT} = 0.36$</td>
</tr>
</tbody>
</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

Low N%

- $t_{\text{STR}} = 1000$ s
- $V_{\text{STR}} / V_{\text{REC}}$ (V)
- $-1.7 / -1.3$
- $-2.3 / -1.8$
- $-2.3 / -1.3$
- $-2.3 / -1.0$

High N%

- $t_{\text{STR}} = 1000$ s
- $V_{\text{STR}} / V_{\text{REC}}$ (V)
- $-2.3 / -1.3$
- $-2.3 / -1.8$
- $-2.3 / -1.3$
- $-2.3 / -1.0$

Kapila, IEDM’08

Mitani, MR’08

Strong evidence of recovery of interface traps

Kapila, IEDM’08

Mitani, MR’08

Tsujikawa, MR’05
NBTI Experimental Signatures (2)

- Short-time recovery shows weak T dependence
- Short-time recovery rate slope $\sim -1$
- Consistent with flicker noise (trapping-detrapping of holes)

**Graphical Data**

- **Graph 1:**
  - X-axis: Recovery time (s)
  - Y-axis: Recovery (V)
  - Plot showing data points for EOT=1.46nm, N=42% and EOT=1.8nm, N=20%.
  - Data points for T=85°C and 125°C.
  - Consistent with trapping-detrapping of holes.

- **Graph 2:**
  - X-axis: Recovery time (s)
  - Y-axis: $\Delta V_{th}$ (mV) and $-d\Delta V_{th}/dt$ (V/dec)
  - Linear fit with slope of $-1$.
  - Data for SiON, $t_{stress} = 0.1$ s, $V_{stress} = -2$ V, $T = 125$ °C.

- **Graph 3:**
  - X-axis: $1000/T$ (K$^{-1}$)
  - Y-axis: Recovery rate (V/dec)
  - Data points for $V_G = -0.6$ V.
  - Consistent with Kaczer, IRPS'09.

**References**

- Deora, EDL'09
- 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) → $\Delta V_{IT}$ 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

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

Total recovery = sum of two components

Mahapatra, IRPS’11
Prediction of Recovery Transients

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

RD model cannot explain NBTI recovery!

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 $\text{H}_2$ 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

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

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

AC simulation of RD model for interface trap contribution

Up to \sim80\% 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

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

Fernandez, IEDM'06
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 2\textsuperscript{nd} (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