Negative Bias Temperature Instability (NBTI) in p-MOSFETs: Characterization, Material/Process Dependence and Predictive Modeling (Part 2 of 3)

Souvik Mahapatra
Department of Electrical Engineering
Indian Institute of Technology Bombay, Mumbai, India
Email: souvik@ee.iitb.ac.in; mahapatra.souvik@gmail.com


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

Part - I

Part - II

Part - III
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
Impact of Oxide Type and PMA

Lower NBTI for dry oxide due to lower water content

Lower NBTI for oxides with D₂ PMA

Lower interface trap generation for oxides with D₂ PMA

Impact of interface trap generation and role of hydrogen
Impact of Backend Processes

Higher NBTI for P-SiN w.r.t P-SiC cap
Higher NBTI for P-SiO IMD w.r.t SiLK IMD for P-SiN cap layer
Similar NBTI for P-SiO IMD w.r.t SiLK IMD for P-SiC cap layer

Higher water content in P-SiO compared to SiLK IMD (from TDS)
Water cannot escape to upper layers for P-SiN cap, goes down to SiON gate stack causing higher NBTI for P-SiO IMD
Escape of water to upper layers for P-SiC cap, lower NBTI

Suzuki, VLSI’02
Impact of Backend Processes

Different barrier metals, P-SiN cap and SiLK IMD (small water content)

Large NBTI for TaN barrier metal

H$_2$ diffusion during P-SiN deposition via Cu to barrier

H$_2$ desorption during PMA and subsequent diffusion to SiON

Largest H$_2$ content for TaN barrier (SIMS) – highest NBTI

Enhanced NBTI for larger PMA temperature

Suzuki, VLSI’02
Role of Hydrogen (NBTI Degradation & Recovery)

Degradation: Increase in $V_T$ shift (slow MSM) and CP current

Recovery after stoppage of stress

Recovery after high T anneal in $N_2$

Complete recovery after high T anneal in $H_2$

Identical re-degradation rate for $\Delta V_T$ and $\Delta I_{CP}$ after full recovery

Mitani, MR’08
Impact of Nitrogen

Higher NBTI for nitrided gate oxides \( \Rightarrow \) Increases with N\(_2\) content

\[ \Delta V_{th} = A \cdot t^n \]

Depends on method of Nitrogen incorporation:

- NISS > N\(_2\)O > RT-N\(_2\)O > RPN
Si/SiON Interfacial N Driven NBTI

Higher Si/SiON N density for NO last process $\rightarrow$ Higher NBTI

Variation in N density at Si/SiON interface by different Electron Cyclotron Resonance (ECR) plasma N process

Lower lifetime (higher NBTI) for higher Si/SiON N density (ECR-C)
Role of Nitrogen

**NO SiON (Type-B)** shows larger $V_T$ shift and trap generation (CP)

Higher trap generation in Type-B SiON – consistency in CP & DCIV data

Larger $V_T$ shift for a given trap generation for NO SiON

Larger process related traps for NO-SiON

---

**Mitani, MR’08**

**Mahapatra, IRPS’11**

**Identical inversion charge**
Impact of Fluorine

Lower $V_T$ shift and for Fluorine incorporated samples

F incorporation causes reduction in interface trap generation

Higher reduction in NBTI for larger F dose
Summary

Increased NBTI for larger water content in gate dielectric (type of oxidation / incorporation from backend films)

Reduced NBTI for D\textsubscript{2} (w.r.t H\textsubscript{2}) PMA samples – lower generation of interface traps

Increased NBTI due to N\textsubscript{2} incorporation in gate stack
  Increase in trap generation
  Increase in trapping in process related traps

Reduced NBTI due to F incorporation in gate stack
  Reduction in interface trap generation
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
Measured UF-OTF $I_{DLIN}$ Degradation

Measured degradation (magnitude, time & T dependence) strongly impacted by SiON gate insulator process

Maheta, PhD thesis (IITB)
PNO: Impact of Post Nitridation Anneal

Improper PNA: Large sub-ms degradation, weak T activation

Correct PNA (A) – lower magnitude, stronger T activation

PNA: NBTI reduction, increase in n

Similar process optimization of NBTI from other group

Sakuma IRPS’06

Maheta, PhD thesis (IITB)
PNO: Impact of Nitridation Dose

Increased PNO N content – higher magnitude, weaker T activation

Large sub-ms degradation, negligible T activation at short time

Reduction in time exponent ($n$) with higher PNO dose

Increased PNO N content – higher magnitude, weaker T activation

Large sub-ms degradation, negligible T activation at short time

Reduction in time exponent ($n$) with higher PNO dose

Maheta, PhD thesis (IITB)
Time Exponent: Process / Material Dependence

Long-time power law time exponent \((n)\) depends on gate insulator process (PNO, PNA, RTNO) \& \(N\%\).

Maheta, PhD thesis (IITB)
Temperature Activation of Degradation

RTNO shows higher degradation and lower $E_A$ compared to PNO

$T$ activation energy depends on gate insulator process (PNO, PNA, RTNO) & $N\%$

Maheta, PhD thesis (IITB)
Oxide Field Dependence of Degradation

<table>
<thead>
<tr>
<th>D#</th>
<th>$N_{DOS}(\times 10^{15}\text{cm}^{-2})$</th>
<th>N%</th>
<th>EOT(Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.0+2.9</td>
<td>19</td>
<td>17.7</td>
</tr>
<tr>
<td>B</td>
<td>0.0+5.3</td>
<td>35</td>
<td>15.6</td>
</tr>
<tr>
<td>C</td>
<td>0.0+6.8</td>
<td>42</td>
<td>14.6</td>
</tr>
<tr>
<td>D</td>
<td>0.8+5.1</td>
<td>39</td>
<td>13.1</td>
</tr>
<tr>
<td>E</td>
<td>0.8+0.0</td>
<td>6</td>
<td>18.5</td>
</tr>
</tbody>
</table>

PNO: Increased degradation & lower field dependent slope for higher N%

RTNO, RTNO+PN: Very high degradation and low slope

Si/SiON interface density governs overall degradation magnitude & oxide field-dependent slope

Maheta, PhD thesis (IITB)
Field Acceleration Factor: Process Dependence

Magnitude and field acceleration govern by SiON process; more importantly by N density at Si/SiON interface

Maheta, PhD thesis (IITB)
**Correlation: Process Dependence of n, E_A, \( \Gamma \)**

Strong parametric correlation across gate insulator processes.
Hi-K/MG vs. SiON: Role of Nitrogen

SiON: N density at Si/SiON interface governs NBTI magnitude, time exponent, T activation, field acceleration

Hi-K/MG: IL (1nm) / HfSiO (2nm, 3nm) and IL (1nm) / HfO$_2$ (2nm, 3nm) stacks, NH$_3$ anneal following Hi-K deposition

Presence of Si in HfSiO reduces N from entering IL (formation of Si-N bonds in Hi-K)

IL N density: 3nm HfSiO stack < 2nm HfSiO stack < HfO$_2$ stack (Note: Hi-K processes are *not* optimized)
Hi-K/MG vs. SiON: T Dependent Transients

HfSiON behaves like Type-A SiON (low Si/SiO₂ N)

HfO₂ behaves like Type-B SiON (high Si/SiO₂ N)

HfSiON: Clear T dependence from short to long stress time

HfO₂: Negligible T dependence at short time, weak T dependence at long time
Flicker Noise Measurement (Hi-K/MG)

Larger noise magnitude in HfO<sub>2</sub> compared to HfSiON

Higher N (pre-existing hole traps) in IL of HfO<sub>2</sub> stack compared to HfSiON stack

Similar N related pre-existing trap increase reported by others

IL N density: 3nm HfSiO stack < 2nm HfSiO stack < HfO<sub>2</sub> stack
Hi-K/MG vs. SiON: Time Exponent (n)

Hi-K: HfSiON shows higher n compared to HfO$_2$, n independent of T

SiON: PNO shows higher n (reduces with increase in N) compared to RTNO

Deora, PhD thesis (IITB)
Hi-K/MG vs. SiON: Temperature Activation ($E_A$)

**Hi-K:** HfSiON shows lower magnitude and higher $E_A$ compared to HfO$_2$

**SiON:** PNO (magnitude increases, $E_A$ reduces with increase in N) shows lower magnitude and higher $E_A$ compared to RTNO

Deora, PhD thesis (IITB)
Hi-K/MG vs. SiON: Field Acceleration ($\Gamma$)

Hi-K: HfSiON shows lower magnitude and higher $\Gamma$ compared to HfO$_2$

SiON: PNO (magnitude increases, $\Gamma$ reduces with increase in N) shows lower magnitude and higher $\Gamma$ compared to RTNO

Deora, PhD thesis (IITB)
Role of Nitrogen

Process impact on NBTI: Higher degradation for Type-B (more N close to Si/SiON interface)

Traps are generated, small difference in generated traps (DCIV, CP)

Large difference in pre-existing traps linked to N in GOX (Flicker noise)
Short Time Degradation: Different Devices

RTNO shows large sub-ms degradation that has negligible T activation

Similar observation for PNO devices with improper PNA

Short-time negligible T dependence - artifact due to time-zero subtraction?

Maheta, TED July’08
Short Time Degradation: $V_G$ and $T$ Dependence

$T$ dependent data show negligible $T$ activation especially at sub-ms time

Bias dependent data show strong acceleration for entire stress duration

OTF (1ms) $T$ dependent data also shows strong acceleration

Sub 1ms negligible $T$ dependence – real physical phenomenon
Short Time Degradation: Other Measurements

Negligible short time T dependence

Strong short time bias dependence – no time zero subtraction issue

Similar behavior of short time T independence for PBTI in Hi-K/MG
Summary

Enhanced NBTI for Type-B (poorly optimized) devices having higher N density close to Si/SiON interface

Slightly larger trap generation, significantly higher trapping in N related pre-existing traps responsible for enhanced NBTI

Only Type B devices show significant sub-ms degradation, which has negligible T activation, feature only captured by UF-OTF $I_{DLIN}$

Strong correlation of NBTI features and parameters across different GOX processes

More N $\rightarrow$ Larger magnitude $\rightarrow$ lower long time n, $E_A$ and $\Gamma$

NBTI in HKMG devices governed by IL, follow similar (to SiON) N dependent signature of time, T and bias dependence
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

Go to Part - III