Different impact of HCS and BTI on the variability of MOSFET parameters

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Purpose

• Electrical parameter of MOSFET devices show a statistical variation

• Device stress due to NBTI or HCS influences this parameter variability

• Since the degradation mechanisms are different also the impact on the distributions differs

• This work investigates these phenomena based on array-structure measurements and discusses the physical background
Investigation of the stress induced variability

Outline:

• Impact of NBTI stress on the variability
• Smart device array test-structure
• $V_{th}$ distributions before and after NBTI stress
• Influence of active area size on results
• HCS degradation and variability
• Recovery behavior (HCS / NBTI)
• Conclusion
The distribution of the threshold voltage $V_{th}$ after NBTI stress originates from a convolution of the distribution of the virgin devices together with the additional distribution of the NBTI degradation itself.

The variability of e.g. $V_{th}$ of the virgin devices bases on process induced fluctuations of dopant atoms, gox thickness, channel length, etc.

The dependence on the transistor size is proven by several publications [e.g. Pelgrom 1989, Lakshmikumar 1986]
Position of trapped charges determines the impact on the $V_{th}$.
- Water-level to overcome the barriers is the equivalent of $V_{th}$.
- Red / violet dots mark possible positions of trapped charges.
Severe restriction of regular array test structures

- Distinct IR-drops at select devices impact the applied voltages
- Parallel stress and serial characterization aggravates the recovery trouble:
- Strong and in particular non-uniform recovery handicaps BTI investigations

Increasing non-uniform recovery for each device

- The first device is characterized directly after the stress cycle
- The second device could already recovery in the meantime
- Each following device gets a longer recovery time
Solution: Two different voltage rails for each DUT

- Own select devices for drain- and gate-node
- Selection by a control signal
- Linear apposition of those T-cells
- Not pad limited

- For each DUT stress- or characterization-voltages can be applied individually
- With transmission-gates the entire voltage range can be applied

C. Schlünder et al., IEEE IRPS, pp. 56-60, 2011
Stress- / Characterization with our structure

- Parallel stress of all devices under test
- For characterization only one device is switched from the stress voltage
- All other DUTs stay under stress
- Exact stress times of all devices were logged

Each transistor will be characterized directly after stress
All transistors get shortest possible uniform recovery time
Measurement values of all DUTs are comparable
Investigated material

- MOSFETs with different geometries / sizes
- Two different standard logic technologies
- a) 1.8nm / b) 2.2nm SiON gate oxide
- Each test-transistor is surrounded by dummy devices (nested) to ensure product relevance

Investigated DUTs:

<table>
<thead>
<tr>
<th>DUT</th>
<th>w/l</th>
<th>Area</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>70nm/58nm</td>
<td>4060nm²</td>
<td>a)</td>
</tr>
<tr>
<td>B</td>
<td>120nm/55nm</td>
<td>4800nm²</td>
<td>a)</td>
</tr>
<tr>
<td>C</td>
<td>1.45µm/58nm</td>
<td>106640nm²</td>
<td>a)</td>
</tr>
<tr>
<td>D</td>
<td>3.0µm/40nm</td>
<td>151250nm²</td>
<td>a)</td>
</tr>
<tr>
<td>E</td>
<td>600nm/120nm</td>
<td>72000nm²</td>
<td>a) &amp; b)</td>
</tr>
<tr>
<td>F</td>
<td>120nm/600nm</td>
<td>72000nm²</td>
<td>a) &amp; b)</td>
</tr>
<tr>
<td>G</td>
<td>10µm/120nm</td>
<td>72000nm²</td>
<td>b)</td>
</tr>
</tbody>
</table>
$V_{th}$-Distributions after NBTI stress ($V_{G,\text{stress}} = -2.2\,\text{V}$ for 14h)

- **T=125°C**
- **DUT F:** 72000nm²
- **100 devices**

The variability ($\sigma$) increases with longer stress times.

[Schlünder et al., IIRW 15]
Standard deviations of the $V_{th,lin}$ distribution as a function of stress time for all investigated geometries

\[ \text{NBTI: } V_{G,\text{stress}} = -2.2\text{V} \quad T=125^\circ\text{C} \]

Virgin values are set to $x=0.4\text{s}$ to make them visible.
Distributions of the NBTI induced $V_{th}$-shift

Delta Vth_lin
$V_{G,\text{stress}} = -2.2\, \text{V}$ $T=125^\circ\text{C}$
100 devices each

All values are scaled to 0 by subtracting the median of each distribution

The variability of the NBTI degradation shows also clear area dependence
Standard deviation of $V_{\text{th,lin}}$ of the different areas before and after stress

The additional NBTI induced variability is much smaller than the variability already present at 0h.
Also the NBTI stress induced additional variability follows the Pelgrom law: $\infty 1/\sqrt{w/l}$
HCS degradation and variability

- HCS shows a stronger dependence of degradation on the statistically distributed virgin parameters.
- Especially the drain current and channel length influences the degradation.
- Devices at the edge of the distribution “move” into the center.
- The distribution is more narrow after HCS.
Idsf distributions after HCS stress steps

All values were converted to use condition at Vdd = 1.6V

- HCS shows only a small impact on the variability
- The standard deviation even improves due to HCS

<table>
<thead>
<tr>
<th>Quantile</th>
<th>Idsf [μA/μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>620</td>
</tr>
<tr>
<td>0.25</td>
<td>640</td>
</tr>
<tr>
<td>0.50</td>
<td>660</td>
</tr>
<tr>
<td>0.75</td>
<td>680</td>
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<tr>
<td>1.0</td>
<td>700</td>
</tr>
<tr>
<td>1.25</td>
<td>720</td>
</tr>
<tr>
<td>1.50</td>
<td>740</td>
</tr>
</tbody>
</table>

Standard deviation: 6.47       6.82       7.27       7.82       8.43
Idsf distributions after HCS stress steps

Values are scaled to 0 by subtracting the median

- Quantile
- Delta Idsf [μA]
- 120 devices

Symbols:
- Idsf current values 0h
- step 1 = 8y use conditions
- step 2 = 10y use conditions
- step 3 = 12y use conditions
- step 4 = 20y use conditions
Recovery

- NBTI shows a strong recovery behavior back to (almost) zero hour values (permanent component under discussion)
- HCS at standard CMOS devices has no recovery effect (annealing processes at high temperatures can be obtained)
- What’s up with the impact on the variability?
$V_{th}$-Distributions after NBTI recovery (up to 10 weeks)

VG = 0V
T = 125°C
Degradation / Recovery of $V_{th}$ and $\sigma$

- 15h NBTI stress for two different stress conditions
- Recovery at $V_G=0V$ up to 10 weeks

[Schlünder et al., ESREF 16]
Summary

- Transistor degradation has a clear impact on parameter variability
- The influence on the statistical distribution depends on the mechanism (HCS/BTI)
- BTI increases the variability but the stress induced additional variability is much smaller than the variability already present at 0h
- Active transistor area shows a clear impact not only on zero variability but also on the stress induced additional variability
- Distribution of the BTI induced $V_{th}$-shift follows $\sim 1/\sqrt{WxL}$ plus deviations
- HCS shows a different behavior, the distributions are more narrow after stress
- Devices at the edge of the distribution “move” into the center
- Besides the parameter degradation itself also the variability ‘recovers’ after NBTI
Backup
Distributions before and after stress

\[ V_{G,\text{stress}} = -2.2V \quad T=125^\circ\text{C} \]

100 devices each

To compare the variabilities the median virgin Vth -values are normalized to -390mV, stressed values are normalized to -419mV.
Verification of the Smart Array test-structure

- $\Delta V_{th}$ of all DUTs of a test-array
- Values of the 100 identically drawn transistors are randomly distributed
- there is no influence of DUT position

- $\Delta V_{th}$ as function of virgin $V_{th}$ values
- Degradation shows no dependency on the initial values
- Slightly higher electrical field of low $V_{th}$-devices is negligible
Results NBTI stress: Scattering of small area devices

Symbols of large DUT D are based on the left y-axis, small DUT A on the right. For small area devices many DUTs necessary for meaningful statements.

\[ y = 5.0631x^{0.1833} \]

\begin{align*}
\Delta V_{\text{th sat}} \text{ DUT D (mV)} &\geq 10^4 \\
\Delta V_{\text{th sat}} \text{ DUT A (mV)} &\leq 10^2
\end{align*}
NBTI:

\[ V_{G,\text{stress}} = -2.3V \text{ / } -2.5V \]

\[ T_{\text{stress}} = 125^\circ C/150^\circ C \]