Macroscopic and Stochastic Aspects of Negative Bias Temperature Instability in CMOS Devices and Circuits

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HKMG MOSFET: Bias Temperature Instability

NBTI: p-MOSFET, $V_G < (V_D, V_B, V_S)$

PBTI: n-MOSFET, $V_G > (V_D, V_B, V_S)$

Transistor parametric drift in time

Circuit performance degradation

Estimation of end of life degradation at use condition
Requirement of NBTI Model Framework

Time evolution during DC / AC stress

Long stress time, prediction of end-of-life degradation

Gate insulator process dependence

Time evolution of recovery after stress

Multiple arbitrary cycles of DC stress and recovery

AC frequency and duty cycle dependence

Time evolution of defect distribution for small area devices

Prediction of circuit degradation, variable BTI
Outline

Mechanism of NBTI degradation

NBTI modeling – macroscopic framework

Stochastic effects

Compact model, SRAM circuit analysis
NBTI Physical Mechanism

Trap generation: Breaking of Si-H (Si/IL interface) and X-H bonds (IL bulk, IL/HK interface and beyond…)

- Si-H (Pb centers)
- X-H
- H passivated Ov defects Si-H, O-H, N-H bonds
- Pre-existing hole traps

Trapping in pre-existing defects

Mahapatra, TED’13
Experimental Details

Gate First HKMG devices, planar Si channel

Measure overall $V_T$ shift by $10\mu$s UF-MSM method

Independently measure trap generation by DCIV, after delay and band gap correction

Independently estimate pre-existing traps by flicker noise (pre-stress)

SiON data (UF-OTF) occasionally used as reference
DCIV: Universality of Trap Generation (TG)

Universal power law time exponent of $n \sim 1/6$ for DC and AC stress

Mahapatra, IRPS’14
Components of NBTI

**Measured:**
- **Black:** MSM $V_T$ (10\(\mu\)s delay)

**Red:** DCIV

**Extracted:**
- **Green:** Trapping

Trap generation dominates NBTI $V_T$ shift – more so for AC stress

Mahapatra, IRPS’14
Significance of Hole Trapping

Correlation of trap generation and overall $V_T$ shift

Gate insulator processes impact pre-stress traps

Poor gate stacks have higher pre-stress defects (flicker noise), higher hole trapping and higher $V_T$ shift for a given $V_{IT}$ shift

Mahapatra, IRPS’14
Hole Trapping: Time Exponent

Universal $n \sim 1/6$ time exponent for trap generation

Hole trapping $\rightarrow$ Saturation $\rightarrow$ Reduction in overall $n$
Hole Trapping: Temperature Activation

Measured $\Delta V_T$ (UF-MSM) and $\Delta V_{IT}$ (DCIV after correction), extracted $\Delta V_{HT}$ (subtraction)

Lower pre-stress defects in process-I w.r.t process-II, lower hole trapping contribution

Higher T activation for trap generation

Lower T activation for hole trapping
Hole Trapping: Field Dependence

Measured $\Delta V_T$ (UF-MSM) and $\Delta V_{IT}$ (DCIV after correction), extracted $\Delta V_{HT}$ (subtraction)

Lower pre-stress defects in process-I w.r.t process-II, lower hole trapping contribution

Similar field acceleration for trap generation and trapping
Universality: Duty Cycle Dependence

Universality of BTI duty cycle data when normalized to 50% AC, appearance of kink near DC

Universal part matches with DCIV data

Trap generation dominates AC BTI up to large duty cycle

Kink near DC duty to trapping / trap occupancy effects

Mahapatra, IRPS’14
Universality: Frequency (In) Dependence

Universal frequency independence of BTI, up to ~GHz

Frequency independence matches with DCIV data

Trap generation dominates AC BTI at different frequencies

Spread near DC duty to trapping / trap occupancy effects

Mahapatra, IRPS’14
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Degradation and Recovery Mechanism

stress: high $|V_G|$  recovery: medium $|V_G|$  recovery: low $|V_G|$
Modeling of NBTI (DC, AC, Stress, Recovery)

- Reaction-Diffusion (RD) Model*
  - New trap generation and recovery (DCIV)
- Hole trapping / detrapping in pre-existing traps (~Flicker noise)
- Multi-State-Model (MSM)***
- Charge occupancy of generated traps
- Transient Trap Occupancy Model (TTOM)**
- Degradation and recovery of $V_T$ shift

* Mahapatra, TED’13
** Goel, IRPS’15
*** Grasser, IRPS’10
Trap generation: Breaking of Si-H (Si/IL interface) and X-H bonds (IL bulk, IL/HK interface and beyond…)

- Si-H (Pb centers)
- X-H
- H passivated Ov defects Si-H, O-H, N-H bonds
- Pre-existing hole traps
**H-H₂ Reaction Diffusion (R-D) Model**

Breaking of Si-H bonds at Si/SiO₂ 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/SiO₂ 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: Mahapatra, TED’13
R-D Framework: Stochastic Diffusion Effect

Stochastic hopping, multiple 3D $H_2$ back diffusion pathways

Returning $H$ to “look for” open sites – recovery slows down at longer time

Simple 1D implementation by reduction of diffusivity during recovery

Important to consider this effect for accurate prediction of recovery

Mahapatra, TED’13
Trap Generation (DCIV): Time Evolution

Power law time dependence of measured data

Lines: RD Model simulation

RD model:
Universal power law time exponent of \( n \approx 1/6 \) for DC and AC stress

Goel; MR’14 & IRPS’14
Trap Generation (DCIV): Duty and Frequency

Symbols: DCIV data

Lines: RD model simulation

- Unique dependence on duty cycle (absence of kink near DC)
- Normalized (to DC) data independent of pulse high/low bias
- Frequency independence

Goel; MR’14 & IRPS’14
Prediction of Stress: Time Evolution

Add trap generation and trapping

Larger hole trapping for Process-II

Trap generation verified by DCIV data

\[ V_{G,STR} = \triangle -1.7 \text{ V} \quad \circ -1.5 \text{ V} \quad \square -1.3 \text{ V} \]

Goel; MR’14 & IRPS’14
Prediction of Recovery: Time Evolution

Hole detrapping, electron capture and trap passivation

Prediction of wide variety of recovery experiments

Goel; MR’14 & IRPS’14

solid lines: $\Delta V_T$, dashed lines: $\Delta V_{IT}$

$V_{G,REC} = -0.8V$

$V_{G,REC} = 0V$

$V_{G,STR} (V)$

-1.7
-1.5
-1.3

T ($^\circ$C)

155
130
100

$V_{G,STR} (V)$

-1.7
-1.5
-1.3

T ($^\circ$C)

155
130
100

$V_{G,STR} = -1.5V, T = 130^\circ C$
TTOM Enabled RD Model

TTOM = Time evolution of “charged state” of generated traps

DC Multi-cycle and AC stress

Different fraction of traps for electron capture (different pulse low bias)

Goel, IRPS’15
Model prediction of Multi-cycle data

Symmetric cycle with different pulse low bias.

Asymmetric cycles with different ON/OFF ratio.

Goel, IRPS’15
AC NBTI: Prediction using TTOM model

Accurate prediction of time evolution of AC stress

Different duty cycle

Different pulse low bias – accuracy of TTOM model

Goel, IRPS’15
Duty Cycle Dependence: Pulse Low Impact

Mode-A: End of last half cycle; Mode-B: End of last full cycle

Mode-B: RD model with trap occupancy

Mode-A: RD model with trap occupancy and hole trapping / detrapping

Accurate prediction of kink near DC

Goel, IRPS’15
Frequency Dependence: Duty and pulse low

Mode-A: End of last half cycle; Mode-B: End of last full cycle

Mode-B: RD model with trap occupancy

Mode-A: RD model with trap occupancy and hole trapping / detrapping

Frequency independence of trap generation

Trapping diminishes at larger frequency

Goel, IRPS’15
End-of-Life Projection

Model parameter extraction using prediction of short time, higher $V_G$, $T$ data

Estimation of long time, lower $V_G$, $T$ data

Estimation of AC/DC ratio

Long time degradation dominated by trap generation, negligible impact of hole trapping

Goel, IRPS’15
Outline

Mechanism of NBTI degradation

NBTI modeling – macroscopic framework

Stochastic effects

Compact model, SRAM circuit analysis
Small Area Device Variability

RTN and BTI are NOT same! They have different physical origins.

RTN does not change after BTI stress!

*Kerber, IRPS’15

<table>
<thead>
<tr>
<th>Time-zero</th>
<th>Time dependent</th>
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</thead>
<tbody>
<tr>
<td>RDF, MGG, LER….</td>
<td>Trap generation</td>
</tr>
<tr>
<td>RTN</td>
<td>Trapping</td>
</tr>
</tbody>
</table>

TCAD

Stochastic RD; Naphade IRPS’13 IEDM’13

Trapping only models
Stochastic BTI Framework

- Reaction-Diffusion (RD) Model
  - Distribution of new generated traps
- Distribution of trapping in pre-existing traps
- Energy level model

Randomize charge occupancy of generated traps

Transient Trap Occupancy Model (TTOM)

- Distribution of $V_T$ shift
- Distribution of post-stress $V_T$
- Pre-stress $V_T$ distribution

TCAD
Stochastic Simulation Framework

NBTI: Trap generation and hole trapping

Trap generation and recovery: KMC version of RD model

Naphade, IEDM’13
Stochastic Simulation Framework

NBTI: Trap generation and hole trapping

Trap generation and recovery: KMC version of RD model

Trapping/detrapping: 2 state model, log-normal time constant distribution

Naphade, IEDM’13
Stochastic Trap Generation / Recovery

Stress: Distribution of power law time exponent \( n \)

Recovery: Discrete steps, slow process
Stochastic Electron Capture Process

Recovery by RD simulation only

Recovery by electron capture in generated traps and RD simulation

Faster recovery when electron capture is considered
Stochastic Hole Trapping / Detrapping

Pre-existing traps - Poisson distributed

Fast saturation and recovery
Distribution of Overall $V_T$ Shift

Addition of trap generation and trapping (independent)

Porting of charges into TCAD to calculate $V_T$ shift

Gamma distribution better describes $V_T$ shift
Time-zero Process Variability

Impact of RDF, LER, MGG etc., Normal distribution

Well captured using standard TCAD

Tsunomura, VLSI 2008

Synopsys, s-IFM simulation
Simulated Distribution – Total $V_T$

TCAD: BTI $\Delta V_T$ and time-zero $V_{T0}$ (independent)

Relative dominance (time-zero versus BTI shift) determines final $V_T$ distribution

Mean shifts, shift in variance depends on time-zero dominance
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**Fixed Time Compact Model (FTCM)**

\[
\Delta V_{IT1,AC} = \gamma \times k_{DUTY} \times \Delta V_{IT,DC}
\]

Where \(k_{DUTY}\) is calculated from RD model and \(\gamma\) depends on \(V_{G,LOW}\)

\[
\Delta V_{IT2,AC} = (1 - \gamma) \times k_{DUTY} \times \Delta V_{IT,DC} \times \left(1 - e^{-\frac{t_{OFF}}{\tau_C}}\right) \times \left( e^{-\frac{t_{ON}}{\tau_E}}\right)
\]

\[
\Delta V_{HT,AC} = \Delta V_{HT,DC} \times \left(1 - e^{-\frac{t_{ON}}{\tau_{STR}}}\right) \times \left( e^{-\frac{t_{OFF}}{\tau_{REC}}}\right)
\]

\[
\Delta V_{T,AC} = \Delta V_{IT1,AC} + \Delta V_{IT2,AC} + \Delta V_{HT,AC}
\]

*Only predict AC to DC ratio at fixed stress time*

*Useful for high frequency, long stress time*
Comparison of TTOM and FTCM model

**TTOM:** Exact tracking in time

**FTOM:** Equivalent duty compact model

\[ V_{G,\text{HIGH}} / V_{G,\text{LOW}} = -1.5V / 0V, \ T = 130^\circ C \]

**Duty cycle dependence for Mode-A and B**

**Frequency dependence for Mode-A and B**

Goel IRPS 2015
Comparison of TTOM & FTCM models

Arbitrary AC pulse sequence of different duty

Red line: Exact tracking by transient model

Blue line: DC stress
Symbol: Equivalent prediction by effective duty compact model

Goel IRPS 2015
Error Analysis: TTOM vs. FTCM

Fixed stress time, AC stress
Randomized time for half periods
Start with on half cycle
End with off half cycle

TTOM – exact tracking till end of stress
FTCM – end of stress AC to DC ratio
Error within 7%
Distribution of $V_T$ Shift

Mean: Macroscopic compact model

Distribution: Gamma, independent Poisson process

Measured FinFET $\Delta V_T$ distribution predicted and extrapolation for 100k data points.

Measured data: C. Prasad et. al., "Bias temperature instability variation on SiON/Poly, HK/MG and trigate architectures," IRPS 2014

Goel IRPS 2015
AC activity ‘α’ on left pFET and complementary ‘1-α’ on right pFET

α=0 implies unstressed left p-FET and full DC stress on right p-FET

V_L and V_R are internal nodal voltages of left and right latch initialized to ‘0’ and ‘1’ respectively
HSPICE Simulation Framework

\[ \Delta V_T = A t^n \]

\( \Delta V_T \) DC mean using power law.
\( \Delta V_T \) AC mean refer Table-I

\( \Delta V_T \) distribution around mean

Monte-Carlo Simulation using foundry models

\( V_{T0} \) distribution

Redefined distribution

BTI distribution from compact model

Time-zero distribution – Foundry provided

Addition using independent distributions

Goel IRPS 2015
Read SNM distribution

Reduction in mean and increase in variance

Higher impact at for high stress VDD and lower operation VDD

Larger impact for HD cells
Impact of Activity - Read SNM

More imbalanced activity – one node get stressed more than other

Reduction in mean

Increase in sigma
Conclusions

NBTI explained by trap generation & recovery (RD model) with transient trap occupancy (dominant) and hole trapping & detrapping

Prediction of: time evolution of DC stress & recovery, HKMG process dependence, arbitrary multi-cycle DC and AC stress at different frequency & duty cycle dat

Development of stochastic framework for small area devices

Developed compact model can predict DC & AC data, used for circuit simulation