Recent Developments in
Device Reliability Modeling:
The Bias Temperature Instability

Tibor Grasser

Institute for Microelectronics, TU Vienna
Gußhausstraße 27–29, A-1040 Wien, Austria
TU Wien, Vienna, Austria
The Negative Bias Temperature Instability

Negative bias temperature stress of pMOSFETs

Large negative gate voltage ($\approx 5 - 8$ MV/cm), all other terminals grounded
Elevated temperatures (typically $100^\circ C - 200^\circ C$, but also at room temperature)

Degradation of critical device parameters

Threshold voltage
Subthreshold slope
Transconductance
Mobility
Drain current
...

Occurs in all four configurations

Strongest in pMOS with negative bias

Serious reliability concern in pMOSFETs

[1] Schroder and Babcock, JAP '03
[2] Alam and Mahapatra, MR '05
[3] Huard et al., MR '06
The Negative Bias Temperature Instability

When does the NBTI scenario occur?

NBTI: $V_G \ll 0 \text{ V}, \ V_S = V_D = 0 \text{ V}$

Example: inverter with $V_{\text{in}} = 0 \text{ V}$

Similar scenarios in ring-oscillators, SRAM cells, etc.

What happens to the pMOS transistor?

Kimizuka et al., VLSI Symp. '00
What happens during negative bias temperature stress?

Creation of SiO$_2$/Si interface defects (dangling Si bonds, $P_b$ centers)

- Pre-existing, but passivated by hydrogen anneal
- Si–H bonds can be broken
- Results in trapping sites inside the Si bandgap
- Universally acknowledged\textsuperscript{[1]}\textsuperscript{[2]}
- Different defect in SiON and high-k? \textsuperscript{[3]}

Creation of oxide charge

- Most likely $E'$ centers
- Charge exchange mechanism?
- Controversial! \textsuperscript{[4]}

\textsuperscript{[1]} Mahapatra \textit{et al.}, IRPS '07 \textsuperscript{[2]} Huard \textit{et al.}, MR '06 \textsuperscript{[3]} Campbell \textit{et al.}, TDMR '07 \textsuperscript{[4]} Mahapatra \textit{et al.}, IRPS '07
NBTI Measurement Techniques

Main problem: it is impossible to perfectly measure NBTI

As soon as stress is removed, extremely fast recovery is observed\textsuperscript{[1][2]}

Strong bias dependence, in particular to positive bias\textsuperscript{[3][4][5]}

A number of techniques have been suggest and used

Conventional Measure/Stress/Measure\textsuperscript{[6]}

On-the-fly (during stress, no interruption)\textsuperscript{[7]}

Charge-pumping and DCIV techniques\textsuperscript{[8]}

Various problems

Delays lead to recovery

How to quantify the degradation ($\Delta V_{th}$, $\Delta I_D$, ???)

Biggest problem: results do not match!!!

No exact theory available that unanimously links and explains all the data

\textsuperscript{[1]} Ershov \textit{et al.}, IRPS '03 \textsuperscript{[2]} Reisinger \textit{et al.}, IRPS '06 \textsuperscript{[3]} Ang, EDL '06 \textsuperscript{[4]} Huard \textit{et al.}, MR '06

\textsuperscript{[5]} Grasser \textit{et al.}, IEDM '07 \textsuperscript{[6]} Kaczer \textit{et al.}, IRPS '05 \textsuperscript{[7]} Denais \textit{et al.}, IEDM '04

\textsuperscript{[8]} Neugroschel \textit{et al.}, IEDM '06
Influence of Delay

Measurement delay has a significant impact on measurement.\textsuperscript{[1][2][3]}

Curvature in data becomes more obvious, larger (time-dependent) 'slope'

Impact of delay does not disappear at longer stress times

Impact of delay is temperature dependent

\textsuperscript{[1]} Ershov \textit{et al.}, IRPS '03 \textsuperscript{[2]} Denais \textit{et al.}, IEDM '04 \textsuperscript{[3]} Kaczer \textit{et al.}, IRPS '05
Standard Model: Reaction-Diffusion Model

Successful in describing constant bias stress\textsuperscript{[1][2]}

Cannot describe relaxation\textsuperscript{[3][4][5]}

Relaxation sets in too late and is then too fast, bias independent
Wrong duty-factor dependence in AC stress: 80% (theory) vs. 50% (measured)

Model is wrong!!!\textsuperscript{[6][7][8][9][10]}

\[5\] Huard et al., IEDM '07 \quad [6] Grasser et al., IEDM '10 \quad [7] Grasser et al., IRPS '10 \quad [8] Reisinger et al., IRPS '10
\[9\] Kaczer et al., IRPS '10 \quad [10] Huard et al., IRPS '10
Overview

Introduction
Stochastic NBTI on small-area devices: link NBTI and RTN

New measurement technique
The time dependent defect spectroscopy

Anomalous defect behavior
Present in all defects

Stochastic model
Additional metastable states, multiphonon theory

Compact modeling attempt
RC ladders

Implications on lifetimes

Conclusions
What is Really Going On?

Study of NBTI recovery on small-area devices

Stochastic and discrete charge emission events, no diffusion

Recoverable NBTI due to the same Defects as RTN

Quasi-equilibrium:
Some defects neutral, others positive, a few produce random telegraph noise (RTN)

Stress:
Defects switch to new equilibrium (mostly positive), a few may produce RTN

Recovery:
Slow transition (broad distribution of timescales) to initial quasi-equilibrium
The Time Dependent Defect Spectroscopy (TDDS) …

Analyzes contributions from multiple traps via spectral maps \([1][2]\)

\[ t_s = 1\text{ms} \]
\[ T = 100^{\circ}\text{C} \]
\[ V_G = -1.7\text{V} \]

[1] Grasser \textit{et al.}, IRPS '10  
[2] For a discussion on the step heights see Kaczer \textit{et al.}, IRPS '10
The Time Dependent Defect Spectroscopy (TDDS) Analyzes contributions from multiple traps via spectral maps.

\[ t_s = 1\text{ms} \]
\[ T = 100^\circ\text{C} \]
\[ V_G = -1.7\text{V} \]
The Time Dependent Defect Spectroscopy (TDDS) analyzes contributions from multiple traps via spectral maps.

Time Domain

\( t_s = 1\text{ms} \)
\( T = 100^\circ\text{C} \)
\( V_G = -1.7\text{V} \)

<table>
<thead>
<tr>
<th>Emission Time [s]</th>
<th>Step Height [mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 10^{-5} )</td>
<td>0</td>
</tr>
<tr>
<td>( 10^{-4} )</td>
<td>2</td>
</tr>
<tr>
<td>( 10^{-3} )</td>
<td>4</td>
</tr>
<tr>
<td>( 10^{-2} )</td>
<td>6</td>
</tr>
<tr>
<td>( 10^{-1} )</td>
<td>8</td>
</tr>
<tr>
<td>( 10^{0} )</td>
<td>10</td>
</tr>
<tr>
<td>( 10^{1} )</td>
<td>12</td>
</tr>
<tr>
<td>( 10^{2} )</td>
<td>14</td>
</tr>
</tbody>
</table>

Spectrum
The Time Dependent Defect Spectroscopy (TDDS) analyzes contributions from multiple traps via spectral maps.

$$\Delta V_h \text{ [mV]}$$

$$t_s = 1\text{ms}$$
$$T = 100^\circ\text{C}$$
$$V_G = -1.7\text{V}$$
The Time Dependent Defect Spectroscopy

Function of stress time $t_s$

75 $^\circ$C $V_s=-2.1V$ $V_r=-0.409V$

$t_s=10 \mu s/t_r=342s$ 160x
The Time Dependent Defect Spectroscopy

Function of stress time $t_s$

75°C $V_s=-2.1V$ $V_r=-0.409V$
$t_s=100 \mu s/t_r=342s$ 160x
The Time Dependent Defect Spectroscopy

Function of stress time $t_s$

75°C $V_S=-2.1V$ $V_r=-0.409V$
$t_s=1$ ms/$t_r=342s$ 160x

Step Height [mV] vs. Emission Time [s]
The Time Dependent Defect Spectroscopy

Function of stress time $t_s$

$75 \degree C \ V_s=-2.1V \ V_r=-0.409V$

$t_s=10 \text{ ms} \ / \ t_r=342s \ 160x$
The Time Dependent Defect Spectroscopy

Function of temperature

100°C  \( V_s = -1.7V \)  \( V_r = -0.568V \)
\( t_s = 10 \text{ ms} \)  \( t_r = 89s \)  100x

Step Height [mV]

Emission Time [s]
Function of temperature

125°C $V_S = -1.7\, V$ $V_r = -0.556\, V$
$t_S = 10\, ms/t_r = 89\, s\, 100x$
The Time Dependent Defect Spectroscopy

Function of temperature

150°C $V_S=-1.7V$ $V_r=-0.55V$
$t_S=10\text{ ms}/t_r=89s$ 100x
The Time Dependent Defect Spectroscopy

Function of temperature

175°C  \( V_s = -1.7 \text{V} \quad V_r = -0.54 \text{V} \)
\( t_s = 10 \text{ ms} / t_r = 90\text{s} \quad 100x \)
The Time Dependent Defect Spectroscopy

Different non-linear field dependence of the capture time constants
Different bias dependence of emission time constant: two defect types?

Compare SRH-like model:
\[ \tau_c = \tau_0 e^{\beta \Delta E_B} \frac{N_v}{p} \]

\[ \tau_e = \tau_0 e^{\beta \Delta E_B} e^{\beta \Delta E_T} e^{x F / V_T} \]
Anomalous Defect Behavior

Defects disappear temporarily from the map (#7)

Long term stability: defect #6 missing for a few months now
Anomalous Defect Behavior

Temporary random telegraph noise (tRTN)

Trace 23: 
- $T = 150^\circ C / t_s = 1s / V_s = -1.7V$
- $V_r = -0.668V$

Trace 16: 
- $T = 125^\circ C / t_s = 100ms / V_s = -1.5V$
- $V_r = -0.556V$

Trace 14: 
- No Modulation
- $V_r = -0.459V$
Tewksbury Model

Tewksbury model\footnote{Tewksbury and Lee, SSC '94} charging and discharging of traps via elastic tunneling

Equilibrium

Stress

Recovery

\[ V_{OX} \]

\[ \Delta V_e \]

\[ \Delta V_p \]

\[ -V_{\text{BIAS}} \]

\[ E_F^0 \]

\[ T \]

\[ T \]

\[ T \]

\[ x \Delta V_{OX} \]

\[ \phi_C \]

\[ E_c \]

\[ E_F^0 \]

\[ E_v \]

\[ \phi_V \]

How Can We Model All That Properly?
Model suggested by Kirton & Uren\[^{[1]}\]

Noticed that elastic tunneling cannot be 'it'

Also used lattice-relaxation multiphonon emission (LRME)

Time constants depend on activation energy $\Delta E_B$ and depth $x$

\[
\tau_c = \tau_0 e^{\beta \Delta E_B} \frac{N_v}{p} \quad \text{and} \quad \tau_0^{-1} = N_v \nu_{th} \sigma e^{-x/x_0} \\
\tau_e = \tau_0 e^{\beta \Delta E_B} e^{\beta \Delta E_T} e^{xF/V_T}
\]
Lattice Relaxation and Metastability

Density functional calculations (DFT) of $E'$ center 'charging & puckering'
Lattice Relaxation and Metastability

Density functional calculations (DFT) of $E'$ center 'charging & puckering'
Lattice Relaxation and Metastability

Density functional calculations (DFT) of $E'$ center 'charging & puckering'
Lattice Relaxation and Metastability

Density functional calculations (DFT) of $E'$ center 'charging & puckering'
Lattice Relaxation and Metastability

Density functional calculations (DFT) of \( E' \) center 'charging & puckering'

- Silicon
- Oxygen
Density functional calculations (DFT) of $E'$ center 'charging & puckering'
Lattice Relaxation and Metastability

Density functional calculations (DFT) of $E'$ center 'charging & puckering'
Lattice Relaxation and Metastability

Density functional calculations (DFT) of $E'$ center 'charging & puckering'
Lattice Relaxation and Metastability

Density functional calculations (DFT) of $E'$ center 'charging & puckering'
Lattice Relaxation and Metastability

Density functional calculations (DFT) of \( E' \) center 'charging & puckering'
Density functional calculations (DFT) of $E'$ center 'charging & puckering'
Lattice Relaxation and Metastability

Density functional calculations (DFT) of $E'$ center 'charging & puckering'
Detailed Defect Model Required

Charge Exchange with Substrate

Positive Metastable

Structural Relaxation

Neutral Stable

1

2

Positive Stable

Structural Relaxation

Charge Exchange with Substrate

Neutral Metastable

1'

2'
Model

Different adiabatic potentials for the neutral and positive defect

Metastable states 2’ and 1’ are secondary minima

Thermal transitions to ground states 1 and 2

Stochastic Markov-model for defect kinetics based on multiphonon theory
Normal random telegraph noise (RTN)

Very similar energetical position of the minimas 1 and 2

Kirton and Uren, Adv. Phys. '89
Anomalous RTN

Very similar energetical position of the three minima 1, 2, and 1’

Uren et al., PRB ’88
Temporary random telegraph noise (tRTN)

Very similar energetical position of the minima 2 and 1′
Quantitative Model Evaluation

Excellent agreement for both capture and emission time constants

- Capture time: particularly important for back-extrapolation of stress data
- Emission time: determines recovery behavior

Does the defect act like a switching trap?

- Depends on the defect configuration
How to Model This with SPICE?
Compact Modeling

First attempt: approximate multi-state model by two-state model [1][2]

Try to capture the notoriously difficult dynamics first
Effective capture and emission time constants

Differential equation for a two-state model
Corresponds to an RC equivalent circuit
Two branches: charging vs. discharging

Compact Modeling

Example: modeling of recovery\textsuperscript{[1]}

Crude approximation: 1 RC element every 3 decades

\textsuperscript{[1]} Reisinger et al., IRPS ’10
Compact Modeling

Example: modeling of recovery\textsuperscript{[1]}

Finer approximation: 2 RC elements every 3 decades

\textsuperscript{[1]} Reisinger et al., IRPS '10
Compact Modeling

Extraction of the time constants

[1] Reisinger et al., IRPS '10
Compact Modeling

Application examples

T=130°C
Vstress = -2.0V

T=175°C
Vstress = -1.7V

[1] Reisinger et al., IRPS ’10
Notorious: duty factor dependence

[1] Grasser et al., IEDM ’07
[2] Grasser et al., IRPS Tutorial ’08
[3] Reisinger et al., IRPS ’10
Why Would We Care?
Why Would We Care?

Defects determine the lifetime of the device

Statistics of individual defects become important in nanoscale MOSFETs
- Random number of traps
- Random distribution of traps in space
- Random defect properties
- Interaction with random discrete dopants
- Discrete stochastic charge capture and emission events

Fundamental implications on device reliability
- Lifetime is a stochastic quantity
- Lifetime will have a huge variance
How to Determine the Lifetime?

Small area devices: lifetime is a stochastic quantity\cite{1}\cite{2}

- Charge capture/emission stochastic events
- Capture and emission times distributed

For details see Grasser et al. IEDM '10

\cite{1} Kaczer et al. IRPS '09 \cite{2} Grasser et al. IEDM '10
Conclusions

NBTI/PBTI is a challenging problem to understand and model

Dynamics are of utmost importance
  
  For example: DC vs. AC stress, duty factor dependence, bias dependence, etc.
  What happens in a circuit?
  Cannot be captured by existing models

Measurement method: time dependent defect spectroscopy (TDDS)
  Operates on nanoscale MOSFETs with a handful of defects
  Allows extraction of $\bar{\tau}_e$, $\bar{\tau}_c$, and step-height over very wide range
  Allows simultaneous analysis of multiple defects

New defect model
  Metastable defect states, nonradiative multiphonon theory, stochastic behavior

First attempts towards compact modeling
  Equivalent RC circuits which deliver $\Delta V_{th}$
  Can capture the main features, e.g. DC vs. AC

Lifetime becomes a stochastic quantity
This work would have been impossible without the support of … …

The Institute for Microelectronics
   E. Langer, S. Selberherr, …
   My Ph.D. students W. Gös, Ph. Hehenberger, F. Schanovsky, and P.-J. Wagner

B. Kaczer and G. Groeseneken (IMEC)
   Longstanding collaboration, tons of measurement data, discussion/theory

M. Nelhiebel, Th. Aichinger, J. Fugger, and O. Häberlen (Infineon Villach)
   Financial support, measurement data, and discussion

R. Minixhofer and H. Enichlmair (austriamicrosystems)
   Financial support, measurement data, and discussion

H. Reisinger, C. Schlünder, and W. Gustin (Infineon Munich)
   Ultra fast measurement data, discussion/theory

‘Reliability community’
   P. Lenahan, J. Campbell, G. Bersuker, V. Huard, N. Mielke, A.T. Krishnan, …

Funding by
   EU FP7 contract n°216436 (ATHENIS), ENIAC project n°820379 (MODERN), CDG