Charge Trapping in Oxides

From RTN to BTI

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Outline

Motivation

Fundamentals of Stochastic Processes

Experimental Determination of the Capture and Emission Times

Distribution of the Capture and Emission Times

Physical Models for the Capture and Emission Times

Stochastic BTI
Motivation

Take a MOSFET with 5 oxide defects
Each defect will have random capture and emission times
Each defect will have a different impact on $\Delta V_{th}$

Interface states are too fast
They do not cause RTN or BTI, visible e.g. in charge-pumping
Motivation

Now monitor $V_{G@I_{D,th}}$ or $I_{D@V_{th}}$

Defect responses: independent stationary noise processes
Lead to random telegraph noise (RTN) in $\Delta V_G$ or $\Delta I_D$

$V_G = -0.5V$

Simulation with TDDS defect parameters, see Grasser et al., PRB '10
Motivation

Now apply a stress bias

Capture times depend exponentially on bias, say by 4 orders

Conventionally known as bias temperature instability (BTI)

\[ V_G = -1.8V \]
Motivation

Now remove the stress bias

Defects go back to their equilibrium occupancies

Known as recovery of bias temperature instability

\[ V_G = -0.5V \]
Motivation

Defects have a wide distribution of time constants
  Due to the amorphous nature of the oxide

The same defects are responsible for RTN and BTI
  Only a few ‘lucky’ defects cause RTN
  A much larger number of defects contributes to BTI
  Same for pMOS/NBTI (holes) and nMOS/PBTI (electrons)

Charge exchange is a thermally activated process
  Nonradiative multiphonon process
  Due to changes in the defect structure
  Defects can have metastable states

In small area devices BTI is a stochastic process
  Lifetime becomes a stochastic quantity

A more detailed account of the material presented here will be available soon in Grasser et al., Microelectronics Reliability, 2011
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Stochastic BTI
**Two-State Stochastic Process**

Simple defect with two states

Example: state 1 is neutral, state 2 is positively charged

Transitions can be described by a Markov process

Transition at time $t$ only depends on current state

System has no memory

Occuccancies of each state

$X_i(t) = 1$ when the defect is in state $i$ at time $t$

$X_i(t) = 0$ when the defect is *not* in state $i$ at time $t$
Two-State Stochastic Process

Assume system is in state 1 at time \( t \)
Probability of going from 1 to 2 within infinitesimal time-step \( h \)
\[
P\{X_2(t + h) = 1 \mid X_1(t) = 1\} = k_{12} h
\]

Assume system is in state 2 at time \( t \)
Probability of staying in 2 within \( h \)
\[
P\{X_2(t + h) = 1 \mid X_2(t) = 1\} = 1 - k_{21} h
\]

Shorthand for probability of being in state \( i \) at time \( t \)
\[
p_i(t) = P\{X_i(t) = 1\}
\]

The above conditional probabilities define \( p_2(t) \)
Probability of being in state 2 at time \( t + h \)
\[
p_2(t + h) = P\{X_2(t + h) = 1 \mid X_1(t) = 1\} p_1(t) + P\{X_2(t + h) = 1 \mid X_2(t) = 1\} p_2(t)
\]
\[
= k_{12} h p_1(t) + (1 - k_{21} h) p_2(t)
\]
Two-State Stochastic Process

This equation determines $p_2(t)$

$$p_2(t + h) = k_{12} h p_1(t) + (1 - k_{21} h) p_2(t)$$

Rearrange

$$\frac{p_2(t + h) - p_2(t)}{h} = k_{12} p_1(t) - k_{21} p_2(t)$$

At any time $t$, the process has to be in either 1 or 2

$$p_1(t) + p_2(t) = 1$$

For $h \to 0$ we obtain the Master equation of the process

$$\frac{dp_1(t)}{dt} = k_{21} (1 - p_1(t)) - k_{12} p_1(t)$$
$$\frac{dp_2(t)}{dt} = k_{12} (1 - p_2(t)) - k_{21} p_2(t)$$
Two-State Stochastic Process

Solution of the Master equation

\[ p_1(t) = p_1(\infty) + (p_1(0) - p_1(\infty)) e^{-t/\tau} \]
\[ p_2(t) = p_2(\infty) + (p_2(0) - p_2(\infty)) e^{-t/\tau} \]

\[ p_1(\infty) = \frac{k_{21}}{k_{12} + k_{21}} \]
\[ p_2(\infty) = \frac{k_{12}}{k_{12} + k_{21}} \]
\[ \tau = \frac{1}{k_{12} + k_{21}} \]
First Passage Times

How long does it take to go from state \( i \) to state \( j \)?

Known as \textit{first passage time} (FPT) from \( i \) to \( j \)

Obviously, the first passage time is a stochastic quantity

Capture time: how long does it take to go from 1 to 2?

Modified problem, independent of \( k_{21} \)

\[ k_{12} \]

\[ 1 \]

\[ 2 \]

Modified Master equation

\[ k_{21} = 0 \text{ and } p_1(0) = 1 \]

\[ \frac{dp_1(t)}{dt} = -k_{12} p_1(t) \quad \Rightarrow \quad p_1(t) = \exp(-k_{12}t) \]
First Passage Times

Probability that at time $t$ we are in state 2 is given by $p_2(t)$

This tells us that $\tau_c < t$, which defines the c.d.f.\footnote{cumulative distribution function}

$$F(\tau_c) = P\{\tau_c \leq t\} = p_2(\tau_c) = 1 - \exp(-k_{12}\tau_c).$$

The p.d.f.\footnote{probability density function} of $\tau_c$ is thus

$$f(\tau_c) = \frac{dF(\tau_c)}{d\tau_c} = k_{12} \exp(-k_{12}\tau_c)$$

The random variable $\tau_c$ is exponentially distributed with mean

$$\bar{\tau}_c \overset{\Delta}{=} \mathbb{E}\{\tau_c\} = \int_0^\infty \tau_c f(\tau_c) \, d\tau_c = \frac{1}{k_{12}}$$

Analogous procedure for the emission time

Emission time $\tau_e$ is exponentially distributed, $\bar{\tau}_e = 1/k_{21}$

Perfectly general procedure

Works also for multi-state defects
Exponential Distribution

P.d.f. on a linear scale

\[ f(\tau) = \frac{1}{\bar{\tau}} \exp\left(-\frac{\tau}{\bar{\tau}}\right) \]

P.d.f. on a logarithmic scale

\[ \tilde{f}(\tau) = \tau f(\tau) = \frac{\tau}{\bar{\tau}} \exp\left(-\frac{\tau}{\bar{\tau}}\right) \]
Moments

The moments of $p_i(t)$ are trivially obtained since realization of $X_i(t)$ can only be 0 or 1

$$E\{X_i^k(t)\} = \sum_{x=0}^{1} x^k P\{X_i(t) = x\} = p_i(t)$$

Mean: (what we see on average)

$$f_i(t) = E\{X_i(t)\} = p_i(t)$$

Variance: (related to the noise power)

$$\sigma_i^2(t) = E\{(X_i(t) - f_i(t))^2\} = p_i(t) - p_i^2(t)$$

Under stationary conditions as used for RTN analysis

Simple two-state defect

$$f_2(\infty) = \frac{k_{12}}{k_{12} + k_{21}}$$

$$\sigma_2^2(\infty) = \frac{k_{12}k_{21}}{(k_{12} + k_{21})^2}$$
Stationary Moments of a Two-State Defect

Introduce \( r = k_{21}/k_{12} \)

\[
\begin{align*}
    f_1 &= \frac{r}{1 + r} \\
    f_2 &= \frac{1}{1 + r} \\
    \sigma_1^2 &= \sigma_2^2 = \frac{r}{(1 + r)^2}
\end{align*}
\]

Maximum std.dev.

\( r = 1 \Rightarrow \sigma = 1/2 \)

Detection optimum

Provided

\[
1 \mu s \lesssim \frac{1}{k_{12}}, \quad \frac{1}{k_{21}} \lesssim 1 \text{ ks}
\]
Stationary Realization of a Two-State Defect

Easy to detect

\[ k_{12} = 1/9 \text{s}^{-1} \]
\[ k_{21} = 1 \text{s}^{-1} \]
\[ r = 9 \]
\[ f_1 = 9/10 \]
\[ f_2 = 1/10 \]
\[ \sigma = 3/10 \]
Stationary Realization of a Two-State Defect

Hard to detect

\[ k_{12} = 1/999 \text{ s}^{-1} \]

\[ k_{21} = 1 \text{ s}^{-1} \]

\[ r = 999 \]

\[ f_1 = 0.999 \]

\[ f_2 = 0.001 \]

\[ \sigma \approx 0.032 \]
Detection of Defects

Serious problem

Large variance required for detection
Defects have a very wide distribution of $r = k_{21}/k_{12}$
Only defects with $r$ reasonably close to 1 detectable
RTN analysis misses most defects!
Detection of Defects

Solution: bias switches between $V_{G}^{L}$ and $V_{G}^{H}$ ($|V_{G}^{L}| < |V_{G}^{H}|$)

Capture time depends exponentially on $|V_{G}|$

Detects the most important defects

Defects with $r(V_{G}^{L}) \ll 1$ and $r(V_{G}^{H}) \gg 1$

These defects are uncharged at $V_{G}^{L}$ and become charged at $V_{G}^{H}$

At both $V_{G}^{L}$ and $V_{G}^{H}$ the std.dev. will be small, $\sigma \ll 1/2$

$\Rightarrow$ cause PBTI in nMOS and NBTI in pMOS transistors

Switch to high-level

Defects become charged

During charging std.dev. will become a maximum, $\sigma = 1/2$

Switch to low-level

Defects become discharged

During discharging std.dev. will become a maximum, $\sigma = 1/2$
Two-State Stochastic Process

Probability of being in state 2

At time $t = 0$, we are in state 2 with probability $p_2(0)$

$$p_2(t) = p_2(\infty) + (p_2(0) - p_2(\infty)) e^{-t/\tau}$$

Consider the special case of $p_2(0) \approx 0$ and $p_2(\infty) \approx 1$

The first two moments

$$f_2(t) = 1 - e^{-t/\tau}$$
$$\sigma^2(t) = e^{-t/\tau} - e^{-2t/\tau}$$

$$\tau = \frac{1}{k_{12} + k_{21}}$$

Maximum of $\sigma$

$$f_1(t_{\text{max}}) = f_2(t_{\text{max}}) = \sigma(t_{\text{max}})$$
$$t_{\text{max}} = \tau \ln(2)$$
Two-State Stochastic Process

Charging of a two-state defect

\[ \tau = 1 \]

\[ \sigma = f_2 = 1/2 \quad @ \quad t = \tau \ln(2) \]
Charging of a Two-State Defect

\[ \frac{1}{9} \text{s}^{-1} \quad 1 \text{s}^{-1} \quad \frac{9}{1} \text{s}^{-1} \quad 1 \text{s}^{-1} \]

![Graph showing charging process over time](image-url)
Charging of a Two-State Defect

1/9 s\(^{-1}\)  
1 s\(^{-1}\)  

9 s\(^{-1}\)  
1 s\(^{-1}\)  

\[ f_2 \]

\[ \sigma \]
Charging of a Two-State Defect

\[ \frac{1}{999} \text{s}^{-1} \quad 1 \text{s}^{-1} \quad 99 \text{s}^{-1} \quad 1 \text{s}^{-1} \]

\[ f_2 \quad \sigma \]

Time [s]

-0.06 -0.04 -0.02 0 0.02 0.04 0.06
Charging/Discharging of a Two-State Defect

Can be generalized to arbitrary switching sequences

Switching between $V_L$ and $V_H$

For $t < t_0$

$$p_2(t) = p_2^L$$

For $t_0 < t < t_1$ (stress)

$$p_2(t) = p_2^H + (p_2^L - p_2^H) e^{-t_s/\tau^H}$$

For $t > t_1$ (recovery)

$$p_2(t) = p_2^L + (P_c - p_2^L) e^{-t_r/\tau^L}$$

$$P_c = p_2(t_1)$$
Charging of a single defect in a pMOS

Charging probability: 30%

From $1 - \exp(-t_s/\tau_c) = 0.3$ we get $\tau_c \gtrsim 3$ ms

Defect discharges around $\tau_e = 4$ s

Averaging results in the correct $\exp(-t/\tau_e)$ behavior
Charging of a single defect in a pMOS

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From $1 - \exp(-t_s/\bar{\tau}_c) = 0.3$ we get $\bar{\tau}_c \gtrsim 3$ ms

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Averaging results in the correct $\exp(-t/\bar{\tau}_e)$ behavior

![Graph showing relaxation time and threshold voltage change](image-url)
Charging of a single defect in a pMOS

Charging probability: 30%

From $1 - \exp(-t_s/\bar{\tau}_c) = 0.3$ we get $\bar{\tau}_c \gtrsim 3$ ms

Defect discharges around $\bar{\tau}_e = 4$ s

Averaging results in the correct $\exp(-t/\bar{\tau}_e)$ behavior

![Graph showing relaxation time vs. $\Delta V_{th}$]

- $F = 6$ MV/cm
- $T = 170^\circ$C
- $t_s = 1$ ms
- $W/L = 150$ nm/100 nm
Charging of a single defect in a pMOS

Charging probability: 30%

From \(1 - \exp(-t_s/\bar{\tau}_c) = 0.3\) we get \(\bar{\tau}_c \gtrsim 3\) ms

Defect discharges around \(\bar{\tau}_e = 4\) s

Averaging results in the correct \(\exp(-t/\bar{\tau}_e)\) behavior
Charging of a single defect in a pMOS

Charging probability: 30%

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Defect discharges around $\bar{\tau}_e = 4 \text{ s}$

Averaging results in the correct $\exp(-t/\bar{\tau}_e)$ behavior

![Diagram showing relaxation time vs. ∆V_th]

- $F = 6\text{MV/cm}$
- $T = 170^\circ\text{C}$
- $t_s = 1\text{ms}$
- $W/L = 150\text{nm}/100\text{nm}$
Experimental

Charging of a single defect in a pMOS

Charging probability: 30%

From $1 - \exp(-t_s/\bar{\tau}_c) = 0.3$ we get $\bar{\tau}_c \gtrsim 3$ ms

Defect discharges around $\bar{\tau}_e = 4$ s

Averaging results in the correct $\exp(-t/\bar{\tau}_e)$ behavior

![Graph showing relaxation time vs. $\Delta V_{th}$]

- $F = 6$ MV/cm
- $T = 170^\circ$ C
- $t_s = 1$ ms
- $W/L = 150$ nm/100 nm
Experimental

Charging of a single defect in a pMOS

Charging probability: 30%

From $1 - \exp(-t_s/\bar{\tau}_c) = 0.3$ we get $\bar{\tau}_c \gtrsim 3$ ms

Defect discharges around $\bar{\tau}_e = 4$ s

Averaging results in the correct $\exp(-t/\bar{\tau}_e)$ behavior

![Graph showing relaxation time vs. threshold voltage change for various conditions (F = 6MV/cm, T = 170°C, t_s = 1ms, W/L = 150nm/100nm)]
Charging of a single defect in a pMOS

Charging probability: 30%

From $1 - \exp\left(-\frac{t_s}{\bar{\tau}_c}\right) = 0.3$ we get $\bar{\tau}_c \gtrsim 3$ ms

Defect discharges around $\bar{\tau}_e = 4$ s

Averaging results in the correct $\exp\left(-\frac{t}{\bar{\tau}_e}\right)$ behavior
General Defect Model

Defects can have more than two states

Anomalous RTN, where RTN is turned on/off

Temporary RTN following NBTI stress

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1 Uren et al., PRB ’88
2 Grasser et al., IRPS ’10 and PRB ’10
General Defect Model

Generalization of this procedure gives

\[ P\{X_j(t + h) = 1 \mid X_i(t) = 1\} = k_{ij} h, \]
\[ P\{X_i(t + h) = 1 \mid X_i(t) = 1\} = 1 - \sum_{j \neq i} k_{ij} h \]

From this one obtains the Master equation

\[ \frac{dp_i(t)}{dt} = -p_i(t) \sum_{i \neq j} k_{ij} + \sum_{i \neq j} k_{ji} p_j(t) \]

Note

Since \( \sum_i p_i(t) = 1 \), only \( N - 1 \) equations are linearly independent

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Example: Anomalous RTN

- **RTN**: 20 s⁻¹
- **Pause**: 3 s⁻¹

Diagram showing the RTN and pause transition with rates and time intervals.
Example: Temporary RTN

Equilibrium $\leftrightarrow$ tRTN

- $1 \leftrightarrow 1'$
- $10^{-6} \text{ s}^{-1}$
- $0.5 \text{ s}^{-1}$
- $1000 \text{ s}^{-1}$
- $200 \text{ s}^{-1}$

Graphical representation showing the time evolution of

- $X_2(\cdot)$
- $X_1'(\cdot)$
- $X_1(\cdot)$
- $\Sigma(\cdot)$

against time $[\text{s}]$ from 0 to 4.
Charge Capture for a Three-State Defect

1 2 2' 140 s\(^{-1}\) 0.5 s\(^{-1}\)

0.3 s\(^{-1}\) 10\(^{-6}\) s\(^{-1}\)

\[ X_2 (\pm) \]
\[ X_2' (0) \]
\[ X_1 (0) \]
\[ \Sigma (+) \]

Time [s]

10\(^{-5}\) 10\(^{-4}\) 10\(^{-3}\) 10\(^{-2}\) 10\(^{-1}\) 10\(^{0}\) 10\(^{1}\) 10\(^{2}\)
Multi-State Defect Model Reduction

Can the stochastic multi-state defect model be simplified?

Yes, under certain conditions a model reduction is possible

Consider the first passage time from A to C

Modified state-transition diagram

Modified Master equation

\[ \frac{dp_A}{dt} = -b \, p_A + a \, p_B \]
\[ \frac{dp_B}{dt} = b \, p_A - a \, p_B - c \, p_B \]
\[ \frac{dp_C}{dt} = c \, p_B \]
Multi-State Defect Model Reduction

Solution of the modified Master equation

\[ p_C(t) = 1 - \frac{1}{\tau_2 - \tau_1}(\tau_2 e^{-\tau/\tau_2} - \tau_1 e^{-\tau/\tau_1}) \]

\[
\begin{align*}
\tau_1 &= 2(s + \sqrt{s^2 - 4bc})^{-1} \geq 1/b \\
\tau_2 &= 2(s - \sqrt{s^2 - 4bc})^{-1} \geq 1/c \\
s &= a + b + c
\end{align*}
\]

First passage time

‘Normalized’ difference of two exponential distributions

\[ f(\tau) = \frac{dp_C(\tau)}{d\tau} = \frac{e^{-\tau/\tau_2} - e^{-\tau/\tau_1}}{\tau_2 - \tau_1} \]

Expectation value

\[ \tilde{\tau} = E\{\tau\} = \int_0^\infty \tau f(\tau) \, d\tau = \tau_1 + \tau_2 = \frac{a + b + c}{bc} \]
Three-State Defect: First Passage Time

P.d.f. on a linear scale

\[ f(\tau) = \frac{e^{-\tau/\tau_2} - e^{-\tau/\tau_1}}{\tau_2 - \tau_1} \]

P.d.f. on a logarithmic scale

\[ \tilde{f}(\tau) = \tau f(\tau) = \tau \frac{e^{-\tau/\tau_2} - e^{-\tau/\tau_1}}{\tau_2 - \tau_1} \]
Three-State Defect: First Passage Time

P.d.f. on a linear scale

\[ f(\tau) = \frac{e^{-\tau/\tau_2} - e^{-\tau/\tau_1}}{\tau_2 - \tau_1} \]

P.d.f. on a logarithmic scale

\[ \tilde{f}(\tau) = \tau f(\tau) = \tau \frac{e^{-\tau/\tau_2} - e^{-\tau/\tau_1}}{\tau_2 - \tau_1} \]
Three-State Defect Capture Time

Average capture time (for transition $1 \rightarrow 2$)

$$\bar{\tau}_c = \frac{k_{2'1} + k_{12'} + k_{2'2}}{k_{12'} k_{2'2}}$$

Average emission time (for transition $2 \rightarrow 1$)

$$\bar{\tau}_e = \frac{k_{2'2} + k_{22'} + k_{2'1}}{k_{22'} k_{2'1}}$$

Approximation for three-state defect

Mean value exact, variance may differ slightly
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Stochastic BTI
**Experimental Aspects**

**Experimental determination of $\bar{\tau}_c$ and $\bar{\tau}_e$**

Conventional: analysis of RTN signals$^1$

Recently: time-dependent defect spectroscopy (TDDS)$^2$

**Drawbacks of RTN analysis**

Only defects with reasonably large $\sigma$ can be analyzed

Only devices with a few defects can be analyzed

Defects with larger $\bar{\tau}_c$ are missed ($\Rightarrow$ cause BTI)

**Time-dependent defect spectroscopy (TDDS)**

Analyzes discrete recovery traces following BTI stress

Many more relevant defects with $\bar{\tau}_c \gg \bar{\tau}_e$ can be analyzed

Works for a wide temperature-range

Works from threshold to oxide breakdown

$^1$ Ralls *et al.*, PRL ’84; Nagumo *et al.*, IEDM ’09 & ’10

$^2$ Grasser *et al.*, IRPS ’10 and PRB ’10
Time-Dependent Defect Spectroscopy (TDDS)

Deconvolutes multiple traps via *spectral maps*

![Graph showing Time Domain](image)

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

*Graph depicting time-domain analysis with data points and labels.*
Time-Dependent Defect Spectroscopy (TDDS)

Deconvolutes multiple traps via spectral maps

Time Domain

\[ t_s = 1\text{ms} \]
\[ T = 100^\circ\text{C} \]
\[ V_G = -1.7V \]
Time-Dependent Defect Spectroscopy (TDDS)

Deconvolutes multiple traps via *spectral maps*

\[ V_G = -1.7V \]
\[ T = 100^\circ C \]
\[ t_s = 1ms \]
Time-Dependent Defect Spectroscopy (TDDS)

Deconvolutes multiple traps via *spectral maps*

![Graph showing time-domain and spectrum analysis of trap deconvolution.](image)

- Time Domain: $t_s = 1\,\text{ms}$, $T = 100^\circ\text{C}$, $V_G = -1.7\,\text{V}$
- Spectral Maps: #1, #2, #3, #4
Time-Dependent Defect Spectroscopy (TDDS)

Spectral maps as a function of stress time

75 °C  \( V_s = -2.1 \text{V} \)  \( V_r = -0.409 \text{V} \)
\( t_s = 10 \ \mu \text{s} / t_r = 342 \text{s} \) 160x
Time-Dependent Defect Spectroscopy (TDDS)

Spectral maps as a function of stress time

75°C $V_S=-2.1\text{V}$ $V_r=-0.409\text{V}$
$t_s=100\ \mu\text{s}/t_r=342\text{s} \ 160\times$

- #2
- #1
- #16
- #4
- #3

Step Height [mV]

Emission Time [s]
Time-Dependent Defect Spectroscopy (TDDS)

Spectral maps as a function of stress time

75 °C $V_s = -2.1\, \text{V} \quad V_r = -0.409\, \text{V}$
$t_s = 1\, \text{ms} / t_r = 342\, \text{s} \quad 160\times$

- Step Height [mV]
- Emission Time [s]

- #1
- #2
- #3
- #4
- #16
Time-Dependent Defect Spectroscopy (TDDS)

Spectral maps as a function of stress time

75°C  $V_s=-2.1\,V$  $V_r=-0.409\,V$
$t_s=10\,\text{ms}/t_r=342\,\text{s} \times 160$
Time-Dependent Defect Spectroscopy (TDDS)

Spectral maps as a function of temperature

100°C  $V_s=-1.7V$  $V_r=-0.568V$
$t_s=10$ ms/$t_r=89s$  100x
Time-Dependent Defect Spectroscopy (TDDS)

Spectral maps as a function of temperature

125°C  \( V_S = -1.7V \)  \( V_r = -0.556V \)
\( t_s = 10 \text{ ms} / t_r = 89s \)  100x
Time-Dependent Defect Spectroscopy (TDDS)

Spectral maps as a function of temperature

150°C  $V_s=-1.7V$  $V_r=-0.55V$  
$t_s=10\text{ ms}/t_r=89\text{ s}$  100x
Time-Dependent Defect Spectroscopy (TDDS)

Spectral maps as a function of temperature

175°C  $V_S=-1.7V$  $V_r=-0.54V$

$t_s=10$ ms  $t_r=90s$  $100x$
Time-Dependent Defect Spectroscopy (TDDS)

Spectral maps agree with two-state Markov process

Recall: exponential distribution is on a logarithmic scale
Capture and emission times are widely distributed
A Few Notes on the Step-Height

Each defect causes a different contribution to $\Delta V_{\text{th}}$

Courtesy: Glasgow University
RTN/BTI step-heights are exponentially distributed\textsuperscript{1}

\[ \eta = 4.4\text{mV} \]

\[ W/L = 90\text{nm}/35\text{nm} \]

\[ 0.8\text{nm HfO}_2 \]

\[ \text{Charge-Sheet: 1.2mV} \]

\[ \text{Lifetime Criterion} \]

\[ \text{Tail of the Distribution} \]

\textsuperscript{1} Kaczer et al., IRPS '10
Time-Dependent Defect Spectroscopy (TDDS)

Would a three-state defect be visible?

Capture via intermediate state experimentally challenging

\[ f(τ) \]

\[ \tau_1 = 0.01\text{s} \]
\[ \tau_2 = 1\text{s} \]

Difficult to resolve

\[ T = 100^\circ\text{C} \]
\[ τ_c = 3\text{ ms} \]
\[ τ_e = 1.5\text{ s} \]
Time-Dependent Defect Spectroscopy (TDDS)

Metastable states visible as ‘disappearing defects’
Time-Dependent Defect Spectroscopy (TDDS)

Metastable states visible as temporary RTN

\[ T = 150^\circ C / t_s = 1s / V_s = -1.7V \]
Outline

Motivation

Fundamentals of Stochastic Processes

Experimental Determination of the Capture and Emission Times

Distribution of the Capture and Emission Times

Physical Models for the Capture and Emission Times

Stochastic BTI
Discrete Distribution

Discrete capture/emission time map (CET) of $\bar{\tau}_c$ and $\bar{\tau}_e$

Strong bias dependence of $\bar{\tau}_c$

Strong temperature dependence of both $\bar{\tau}_c$ and $\bar{\tau}_e$

Note: $\bar{\tau}_c = \bar{\tau}_c(V_H)$ and $\bar{\tau}_e = \bar{\tau}_e(V_L)$

![Graph 1](image1.png)

$125^\circ C$

$V_G = -0.7 \ldots -2.5 V$

$|V_G|$

$10^5$

$10^4$

$10^3$

$10^2$

$10^1$

$10^0$

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$10^{-5}$

$10^{-6}$

$10^{-7}$

$\tau_e [s] @ -560 mV$

$10^5$

$10^4$

$10^3$

$10^2$

$10^1$

$10^0$

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$10^{-5}$

$10^{-6}$

$10^{-7}$

$\tau_e [s] @ -560 mV$

![Graph 2](image2.png)

$175^\circ C$

$V_G = -0.7 \ldots -2.5 V$

$|V_G|$

$10^5$

$10^4$

$10^3$

$10^2$

$10^1$

$10^0$

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$10^{-5}$

$10^{-6}$

$10^{-7}$

$\tau_e [s] @ -560 mV$
What is the use of the capture/emission time map (CET)?

Reconstruct the temporal behavior (just like Fourier transform)
Macroscopic version (expectation value)

\[
\Delta V_{th}(t_s, t_r) = \sum_{k}^{N} d_k a_k h_k(t_s, t_r; \tau_{c,k}, \tau_{e,k})
\]

\(N\) \hspace{1cm} \text{... Number of defects}

\(d_k\) \hspace{1cm} \text{... step-height}

\(a_k\) \in [0 ... 1] \hspace{1cm} \text{... maximum occupancy}

\(h_k(t_s, t_r) = (1 - e^{-t_s/\tau_{c,k}}) e^{-t_r/\tau_{e,k}}\) \hspace{1cm} \text{... dynamics}

Stochastic version also possible
Continuous Distribution

Continuous capture/emission time (CET) map

$$\Delta V_{th}(t_s, t_r) \approx \int_0^\infty d\tau_c \int_0^\infty d\tau_e \quad g(\tau_c, \tau_e) \quad h(t_s, t_r; \tau_c, \tau_e)$$

$$\approx \int_0^{t_s} d\tau_c \int_{t_r}^\infty d\tau_e \quad g(\tau_c, \tau_e)$$

Simple extraction scheme for $g$ using measured $\Delta V_{th}$

$$g(\tau_c, \tau_e) = -\frac{\partial^2 \Delta V_{th}(\tau_c, \tau_e)}{\partial \tau_c \partial \tau_e}$$

$^1$ Reisinger et al., IRPS ’10
Continuous Distribution

Example CET map for an SiON pMOS with EOT=2.2 nm

\[ g(\tau_c, \tau_e) = -\frac{\partial^2 \Delta V_{th}(\tau_c, \tau_e)}{\partial \tau_c \partial \tau_e} \]
CET Maps from Theory: RD Model

Analytical solution of the reaction-diffusion model

\[ \Delta V_{th}(t_s, t_r) = \frac{t_s^n}{1 + \sqrt{t_r/t_s}} \]

Analytical CET map becomes negative

\[ g(\tau_c, \tau_e) = -\frac{\partial^2 \Delta V_{th}(\tau_c, \tau_e)}{\partial \tau_c \partial \tau_e} = \frac{2n - 1 + (2n + 1)\sqrt{\tau_e/\tau_c}}{4\sqrt{\tau_e/\tau_c}(1 + \sqrt{\tau_e/\tau_c})^3} \frac{1}{\tau_c^{2-n}} \]
CET Maps from Theory: Hole Trapping

Analytical solution of a simple hole-trapping model

\[ \Delta V_{th}(t_s, t_r) = A \log(1 + B t_r / t_s) \quad \text{for } t_s < t_s^{max}. \]

Analytical CET map

\[ g(\tau_c, \tau_e) = \frac{AB}{(B + \tau_e/\tau_c)^2} \frac{1}{\tau_c^2} \]

\[ B = 1 \]

\[ B = 10 \]
CET Maps from Theory: Universal Recovery

Empirical universal recovery expression

\[
\Delta V_{th}(t_s, t_r) = \frac{At_s^a}{1 + B(t_r/t_s)^b} + Pt_s^n
\]

Analytical CET map

\[
g(\tau_c, \tau_e) = \frac{-\partial^2 \Delta V_{th}(\tau_c, \tau_e)}{\partial \tau_c \partial \tau_e} = \frac{a - b + (a + b)B(\tau_e/\tau_c)^b}{(1 + B(\tau_e/\tau_c)^b)^3} \frac{bAB}{\tau_c^{2-a}(\tau_e/\tau_c)^{1-b}}
\]

\[a = 1/6, \ b = 0.15, \ B = 2\]

1 Grasser et al., IEDM '07
Motivation

Fundamentals of Stochastic Processes

Experimental Determination of the Capture and Emission Times

Distribution of the Capture and Emission Times

Physical Models for the Capture and Emission Times

Stochastic BTI
Conventional Model: Extended SRH Theory

SRH theory

Developed for bulk defects, defect level $E_1$ inside the bandgap
No ‘explicit’ assumption on capture and emission mechanism
Assumption: capture rate is represented by an averaged value
Gives Boltzmann factor in the emission rate, $\exp(-\beta(E_2 - E_1))$

Extension to oxide defects

WKB factor to account for tunneling, $\exp(-x/x_0)$
Defect level may lie outside the Si bandgap

Defect is described by a two-state Markov process
Example: hole trap, neutral in state 1, positive in state 2

\[
\begin{array}{c}
1 \\
\hline
k_{12} \\
\hline
k_{21} \\
2
\end{array}
\]

1 McWhorter ’57; Masuduzzaman, T-ED ’08
Conventional Model: Extended SRH Theory

Defect level inside Si bandgap

Hole capture: no barrier
Hole emission: Boltzmann factor $e^{-\beta E_{12}}$
Conventional Model: Extended SRH Theory

Defect level *outside* Si bandgap

Hole capture: Boltzmann factor $e^{-\beta E_{21}}$

Hole emission: no barrier

\[
\begin{align*}
E_1 & \quad \text{Defect} \\
E_2 & \quad \text{Reservoir} \\
E_1 & \quad \text{Defect} \\
E_2 & \quad \text{Reservoir}
\end{align*}
\]
Conventional Model: Extended SRH Theory

Electronic defect level depends on oxide field

Depending on field, defect level changes relative to $E_2 \approx E_v$
Conventional Model: Extended SRH Theory

Model results in a ‘tunneling front’ due to WKB factor

Charging: only defects which moved from below to above $E_F$
Discharging: only defects that had just been charged
Both charging and discharging are independent of defect level
Tunneling front reaches 1 nm in about 10 ms
Conventional Model: Extended SRH Theory

Model results in a ‘tunneling front’ due to WKB factor

Charging: only defects which moved from below to above $E_F$
Discharging: only defects that had just been charged
Both charging and discharging are independent of defect level
Tunneling front reaches 1 nm in about 10 ms
Problems with Extended SRH Theory

Too fast

Tunneling front reaches 1 nm in about 10 ms
Experimental $\bar{\tau}_c$ and $\bar{\tau}_e$ can be considerably larger (h, m, w, y?)

Capture rate temperature independent

Experimental $\bar{\tau}_c$ can have $E_A \approx 1$ eV

Bias dependence of $\bar{\tau}_c$ weak

Depends dominantly on surface hole concentration, $\bar{\tau}_c \sim 1/p$
Experimental $\bar{\tau}_c$ depends exponentially on oxide field
Problems with Extended SRH Theory

No similarity with experimental CET map (right)

\[ \bar{\tau}_c \text{ correlated with } \bar{\tau}_e \]

The SRH model cannot describe oxide defects
How are Charges Really Trapped in Oxides?

Where does the charge go?
How are Charges Really Trapped in Oxides?

Neutral defect
How are Charges Really Trapped in Oxides?

Positive defect
The Total Potential Energy

The charge-state determines the atomic positions
  Known as electron-phonon coupling

The atomic positions determine the electronic levels
  Adiabatic approximation: electrons are much faster than atoms

The vibronic properties determine the barriers
  This effect dominates the transition rates

We need to consider two contributions to the ‘total energy’
  Electronic energy: the information displayed in the band-diagram
  Vibronic energy: the information missing in the band-diagram
This Phenomenon is Everywhere!

Chemistry
   Electron transfer reactions (intra- and intermolecular)
   Marcus theory (Nobel Prize in Chemistry 1992)

Spectroscopy
   Certain types of fluorescence
   Broadening of absorption and emission peaks to bands

Physics
   Vibronic solid-state lasers
   Organic semiconductors
   Non-radiative capture/emission in semiconductors (deep centers)

Biology
   Photosynthesis
   Sense of smell
   Lightsensitivity (the very reason you can read this)
This Phenomenon is Everywhere!

The year is 2011 AD. The whole world is considering vibronic transitions. Well, not entirely ... One small group of indomitable reliability engineers still holds out against the invaders.
100 Femtoseconds in the Life of an E’ center
100 Femtoseconds in the Life of an E’ center
Coordinate Transformation onto Si-Si Bond
The Total Potential Energy

Vibronic energy model: quantum harmonic oscillator

Energy levels

\[ \mathcal{E}_n = \hbar \omega (n + \frac{1}{2}) \]

Level occupancy

\[ \frac{P(\mathcal{E}_n)}{P(\mathcal{E}_0)} = \frac{e^{-\beta \mathcal{E}_n}}{e^{-\beta \mathcal{E}_0}} \]
The Total Potential Energy

Total energy contains vibronic + electronic energy\(^1\)

Harmonic oscillator in each state (parabolic potential)
Equilibrium \(q\) depends on defect state (adiabatic approximation)

\[
V_1(q) = \frac{1}{2} M \omega_1^2 (q - q_1)^2 + E_1 \\
V_2(q) = \frac{1}{2} M \omega_2^2 (q - q_2)^2 + E_2
\]

Optical transition
Occur at constant \(q\) from min \(V_i(q)\)
(Franck-Condon principle)\(^2\)

Nonradiative transition
Occur at \(V_1(q) = V_2(q)\)
(Classical limit)

---

\(^1\) Abakumov et al., Nonradiative Recombination in Semic. North-Holland ’1991

Optical Transitions

Optical transitions (radiative transitions)

Occur at constant $q$ from min $V_i(q)$ (Franck-Condon principle)

Photon absorption ($1 \rightarrow 2$)

$$\varepsilon_{12} = V_2(q_1) - V_1(q_1)$$

Photon emission ($2 \rightarrow 1$)

$$\varepsilon_{21} = V_2(q_2) - V_1(q_2)$$

Photon energies differ, $\varepsilon_{12} \neq \varepsilon_{21}$

Difference due to lattice relaxation

$$\varepsilon_{12} = E_{21} + E_R$$

$$\varepsilon_{21} = E_{12} - E_R$$

$E_R$ is the relaxation energy\(^1\)

---

\(^1\) Stoneham, Rep.Prog.Phys. ’81
Nonradiative Transitions

Nonradiative transitions

No photons are absorbed or emitted

Occur in the classical limit at $V_1(q) = V_2(q)$ (‘over the barrier’)

![Diagram showing energy levels and nonradiative transitions](image)
The Total Energy

Three model parameters: \( M\omega_1^2/M\omega_2^2, q_2 - q_1, E_2 - E_1 \)

\[
V_1(q) = \frac{1}{2} M\omega_1^2(q - q_1)^2 + E_1 \\
V_2(q) = \frac{1}{2} M\omega_2^2(q - q_2)^2 + E_2
\]

Classical barrier: \( V_2(q) = V_1(q) \)

Two important cases, depending on \( R = \omega_1/\omega_2 \)

Linear electron-phonon coupling: \(^1\) \( R = 1 \) \( (\omega_1 = \omega_2) \)

\[
\Rightarrow V_2(q) - V_1(q) \text{ is linear in } q
\]

\[
E_{12} = \frac{(E_R + E_{21})^2}{4E_R}
\]

\[
E_R = M\omega^2(q_2 - q_1)^2/2
\]

\[ S = E_R/\hbar\omega \text{ is the Huang-Rhys factor}^{2} \]

Number of phonons required to reach \( E_R \)

---

\(^1\) For quadratic electron-phonon coupling see Grasser et al., MR ’11

\(^2\) Huang and Rhys, Proc. Roy. Soc. ’50
The Final Rates

The total rate consists of two contributions

The vibrational matrix element in the high-temperature limit

\[ \approx e^{-\beta \varepsilon_{12}} \]

The electronic matrix element is approximately

\[ \approx \sigma v_{\text{th}} \rho \]

To account for tunneling: WKB factor in \( \sigma \)

\[ \sigma = \sigma_0 \exp(-x/x_0) \quad x_0 = \hbar/(2\sqrt{2m\phi}) \]

So in total we have

\[ k_{12} = \sigma v_{\text{th}} \rho \quad e^{-\beta \varepsilon_{12}} \]

\[ k_{21} \approx \sigma v_{\text{th}} N_v \quad e^{-\beta \varepsilon_{21}} \quad (\text{Maxwell-Boltzmann statistics}) \]

Compare to SRH model (defect inside Si bandgap)

\[ k_{12} = \sigma v_{\text{th}} \rho \]

\[ k_{21} \approx \sigma v_{\text{th}} N_v \quad e^{-\beta E_{12}} \quad (\text{Maxwell-Boltzmann statistics}) \]
Charge Trapping in an E’ Center
Charge Trapping in an E’ Center
Amorphous Oxide

All defects are different
Charging of a Large Number of Defects

Nonradiative multiphonon model

There is no longer a tunneling front
Capture and emission times uncorrelated with $x^1$

1 See detailed RTN study of Nagumo et al., IEDM ’10
Charging of a Large Number of Defects

Nonradiative multiphonon model

There is no longer a tunneling front
Capture and emission times uncorrelated with $x^1$

1 See detailed RTN study of Nagumo et al., IEDM ’10
Field-Dependence

What is the meaning of the electronic energy levels?

- $E_1$ is the electronic defect level (a.k.a $E_T$)
- $E_2$ is the electronic energy level of the reservoir (e.g. $E_C$ or $E_V$)

As in the SRH model, $E_{21} = E_2 - E_1$ depends linearly on $F$

$$E_{21} = E_{20} - E_{10} - qxF$$
Field-Dependence

\[ E_{21} = E_2 - E_1 \] depends linearly on \( F \)

\[ E_{21} = E_{20} - E_{10} - qxF \]

Application of a field reduces \( E_{12} \) and increases \( E_{21} \)

Results in exponential sensitivity of the rates to \( F \)
Bias Dependence of the Rates

The electronic matrix element

Below $V_{th}$, strong bias sensitivity due to $\rho$
Above $V_{th}$, weak bias dependence of $\rho$
Weak bias dependence of the (complete) WKB factor

The vibrational matrix element

Depends on the electric field $F$

$$\exp(-\beta \varepsilon_{12}) = \exp(-\beta \left( \frac{(E_R + E_{20} - E_{10} - qxF)^2}{4E_R} \right))$$

Below $V_{th}$, weak bias dependence of $F$
Above $V_{th}$, exponential bias dependence

⇒ the vibrational properties dominate the bias-dependence
Bias Dependence: Weak Coupling

Weak-coupling limit

\[
E_R \ll E_{20} - E_{10} - qxF
\]

Quadratic field-dependence

\[
\mathcal{E}_{12} = \left( \frac{E_R + E_{21}}{4E_R} \right)^2 \approx \frac{E_{21}^2}{4E_R} + \frac{1}{2} E_{21}
\]
Bias Dependence: Weak Coupling

Crazy trap?

Well, something like this has been reported\(^1\)

---

\(\tau_c\)  \(\tau_e\)  \(10^{20}\text{cm}^{-3}/p\)

---

1 Schulz, JAP '93
**Bias Dependence: Strong Coupling**

**Strong-coupling limit**

\[ E_R \gg E_{20} - E_{10} - qxF \]

**Linear field-dependence**

\[ \varepsilon_{12} = \frac{(E_R + E_{21})^2}{4E_R} \approx \frac{E_R}{4} + \frac{E_{21}}{2} \]
Bias Dependence: Strong Coupling

Compare the bias dependence to experimental data

Model: $\tau_c$ and $\tau_e$ are symmetric
Data: $\tau_e$ can be flat/sudden drop
Model: $\tau_c$ is nearly linear in $F$
Data: $\tau_c$ has curvature

Reason

Metastable defect states

\[ \text{Defect #1} \]

\[ \text{Defect #4} \]

$1$ Grasser et al., IRPS ’10
Problems with the Simple NMP Model

Model captures the ‘essence’, important details missing

Symmetric $\tau_c$ and $\tau_e$ (linear electron-phonon coupling)
Cannot describe the rapid drop of $\tau_e$ below $V_{th}$
Nearly linear $F$ dependence of $\tau_c$
No full decorrelation between $\tau_c$ and $\tau_e$ possible
Reminder: Metastable States

Defects can have more than two states

Anomalous RTN, where RTN is turned on/off

Temporary RTN following NBTI stress

---

1 Uren et al., PRB ’88
2 Grasser et al., IRPS ’10 and PRB ’10
Metastable States: Puckering of an E’ Center

[3D molecular diagram showing puckering motion with a reaction coordinate graph showing energy changes.]
Metastable States: Puckering of an E’ Center
Improved Defect Model: Metastable States

Defect model must include metastable states

RTN: anomalous RTN, curvature in $\tau_c$, flat vs. drop in $\tau_e$

BTI: temporary RTN, bias-dependence of recovery

Pre- and post-stress $f/T$ dependence/hysteresis of $I_{CP}$

$^{1}$ Hehenberger et al., IRPS ’09; Grasser et al., IRPS ’11
Charge Trapping vs. Defect Generation

Switching traps have a density of states in the bandgap

⇒ React to changes in $V_{\text{read}}$

Trapped charges couldn’t be bothered

Switching traps recover faster under more positive bias

Trapped charges couldn’t be bothered

\[
\begin{array}{cccc}
\text{Time [s]} & 10^{-3} & 10^{-2} & 10^{-1} & 10^{0} & 10^{1} \\
\Delta V_{\text{th}} [\text{mV}] & 100 & 80 & 60 & 40 & 20 & 0 \\
\end{array}
\]

- $V_{\text{read}} = -0.4V$
- $V_{\text{read}} = -0.2V$
- $V_{\text{read}} = -0.1V$
- $V_{\text{read}} = +0.2V$
- $V_{\text{read}} = +0.5V$

$E_C$, $E_F$, $E_V$
Charge Trapping vs. Defect Generation

Switching traps have a density of states in the bandgap
- React to changes in $V_{\text{read}}$
- Recover faster under more positive bias
- Cause a change in the subthreshold-slope

Trapped charges do not have states in the bandgap
- The charge is independent of $V_{\text{read}}$
- Cause a rigid shift of the $I_D - V_G$ curves

![Graph showing relaxation time and trapped charge for different stress levels.](image)
Model Summary

All features can be explained with a general defect model

Different defect potentials in the amorphous oxide

- Standard RTN
- Anomalous RTN

- Relax
- Stress
- Neutral
- Positively charged

Standard NBTI

NBTI Switching Trap/Temporary RTN
Outline

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Experimental Determination of the Capture and Emission Times

Distribution of the Capture and Emission Times

Physical Models for the Capture and Emission Times

Stochastic BTI
Small area devices: lifetime is a stochastic quantity

Charge capture/emission stochastic events
Capture and emission times distributed
Number of defects follow Poisson distribution

\[ N_i = 100 \]
\[ N_m = 5000 \]
\[ \text{Sample} = 0 \]

\[ \Delta V_{th} \] [mV]
\[ 10 \quad 100 \]
\[ 10^2 \quad 10^4 \quad 10^6 \quad 10^8 \]

\[ \text{Stress Time [s]} \]

\[ N_i = 12 \]
\[ N_m = 5000 \]
\[ \text{Sample} = 2 \]

\[ \Delta V_{th} \] [mV]
\[ 10 \quad 100 \]
\[ 10^0 \quad 10^2 \quad 10^4 \]

\[ \text{Stress Time [s]} \]

1 Rauch, TDMR ’07; Kaczer et al., IRPS ’10; Grasser et al., IEDM ’10
Stochastic Lifetimes

Small area devices: lifetime is a stochastic quantity

Charge capture/emission stochastic events
Capture and emission times distributed
Number of defects follow Poisson distribution

\[ N_i = 100 \]
\[ N_m = 1 \]
Sample = 0-4999

\[ \Delta V_{th} \text{ [mV]} \]

\[ N_i = 12 \]
\[ N_m = 1 \]
Sample = 0-4999

\[ \Delta V_{th} \text{ [mV]} \]

\[ \sigma \]

\[ E \]

\[ E-3\sigma \]

\[ E+3\sigma \]

\[ 10^0 \quad 10^2 \quad 10^4 \quad 10^6 \quad 10^8 \quad 10^{10} \]

[Stress Time [s]]

[Stress Time [s]]

\[ 10 \quad 100 \]

[Kaczer et al., IRPS ’10; Grasser et al., IEDM ’10]
Stochastic Lifetimes

Distribution of lifetime

Variance increases with decreasing number of defects

PDF

Lifetime

1 Kaczer et al., IRPS ’11
Stochastic Impact on Circuit

Example circuit with inverter\(^1\)

Jitter vs. NBTI

\[ t_s = 10^{-8} \text{ s} \]

\(^1\) Kaczer et al., IRPS '11
Stochastic Impact on Circuit

Example circuit with inverter\(^1\)

Jitter vs. NBTI

\[ V_{in}(V) \]

\[ 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \text{ ns} \]

\[ V_{th}(V) \]

\[ 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \text{ ns} \]

\[ V_{in}, V_{out}(V) \]

\[ 495 \quad 515 \quad 4495 \quad 4515 \quad 8495 \quad 8515 \text{ ps} \]

\[ t_s = 10^8 \text{ s} \]

\(^1\) Kaczer et al., IRPS ’11
Conclusions

Defects have a wide distribution of time constants
  Due to the amorphous nature of the oxide

The same defects are responsible for RTN and BTI
  Only a few ‘lucky’ defects cause RTN
  ‘Double-jackpot’ required for anomalous RTN
  A much larger number of defects contributes to BTI
  Same for NBTI/pMOS (holes) and PBTI/nMOS (electrons)

Charge exchange is a thermally activated process
  Nonradiative multiphonon process
  Due to changes in the defect structure
  Defects can have metastable states

In small area devices BTI is a stochastic process
  Lifetime becomes a stochastic quantity

A more detailed account of the material presented here will be available soon in Grasser et al., Microelectronics Reliability, 2011