Charge Trapping in Oxides
From RTN to BTI

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Acknowledgments

My reliability Ph.D. students

F. Schanovsky, W. Gös, P.-J. Wagner, Ph. Hehenberger, ...

Collaborators and colleagues

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Who burnt 6 CPU and 2 Ph.D. months creating nice animations

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

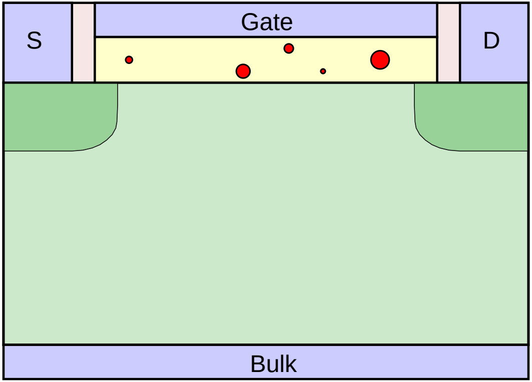
Motivation

Take a MOSFET with 5 oxide defects

- Each defect will have random capture and emission times
- Each defect will have a different impact on ΔV_{th}

Interface states are too fast

- They do not cause RTN or BTI, visible e.g. in charge-pumping

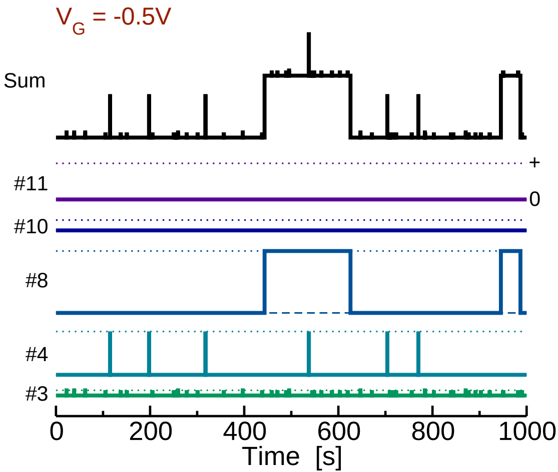


Motivation

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

Defect responses: independent stationary noise processes[1]

Lead to random telegraph noise (RTN) in ΔV_G or ΔI_D



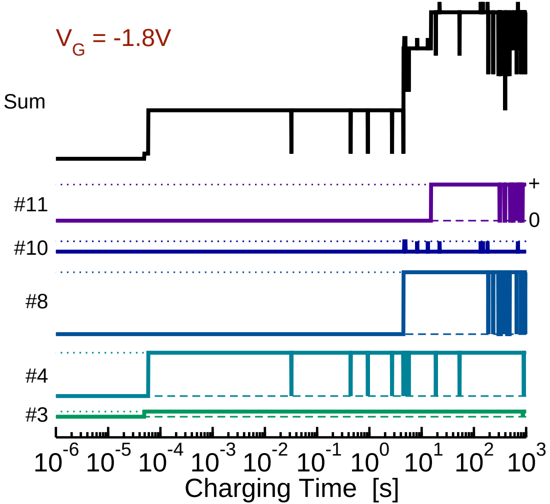
[1] Simulation with TDDS defect parameters, see Grasser *et al.*, PRB '10

Motivation

Now apply a stress bias

Capture times depend exponentially on bias, say by 4 orders

Conventionally known as bias temperature instability (BTI)

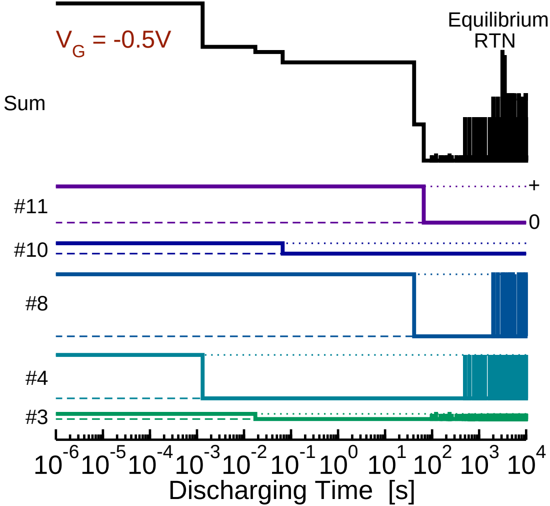


Motivation

Now remove the stress bias

Defects go back to their equilibrium occupancies

Known as recovery of bias temperature instability



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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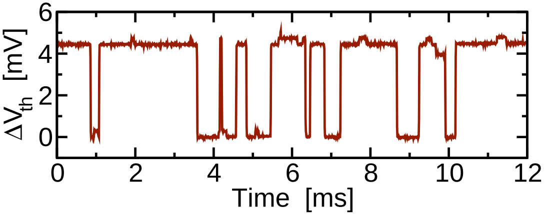
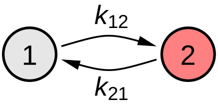
Stochastic BTI

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

Occupancies 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 $t+h$

$$\begin{aligned} p_2(t+h) &= P\{X_2(t+h)=1 \mid X_1(t)=1\}\, p_1(t) + \\ &\quad P\{X_2(t+h)=1 \mid X_2(t)=1\}\, p_2(t) \\ &= k_{12}h\, p_1(t) + (1-k_{21}h)\, p_2(t) \end{aligned}$$

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

$$\boxed{\begin{aligned} \frac{\mathrm{d}p_1(t)}{\mathrm{d}t} &= k_{21}\,(1 - p_1(t)) - k_{12}\, p_1(t) \\ \frac{\mathrm{d}p_2(t)}{\mathrm{d}t} &= k_{12}\,(1 - p_2(t)) - k_{21}\, p_2(t) \end{aligned}}$$

Two-State Stochastic Process

Solution of the Master equation

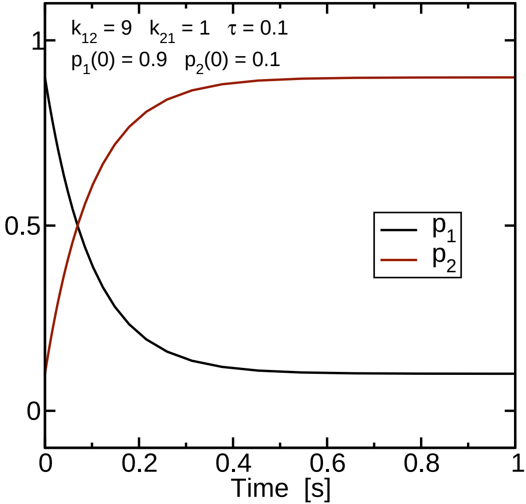
$$p_1(t) = p_1(\infty) + (p_1(0) - p_1(\infty))\, \mathrm{e}^{-t/\tau}$$

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

$$p_1(\infty) = \frac{k_{21}}{k_{12} + k_{21}}$$

$$p_2(\infty) = \frac{k_{12}}{k_{12} + k_{21}}$$

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



First Passage Times

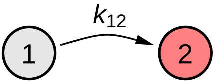
How long does it take to go from state *i* to state *j*?

Known as *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}



Modified Master equation

$k_{21} = 0$ and $p_1(0) = 1$

$$\frac{\mathrm{d}p_1(t)}{\mathrm{d}t} = -k_{12}\, p_1(t) \qquad \Rightarrow \qquad p_1(t) = \exp(-k_{12} t)$$

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.[1]

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

The p.d.f.[2] of τ_c is thus

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

The random variable τ_c is exponentially distributed with mean

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

Analogous procedure for the emission time

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

Perfectly general procedure

Works also for multi-state defects

[1] cumulative distribution function

[2] probability density function

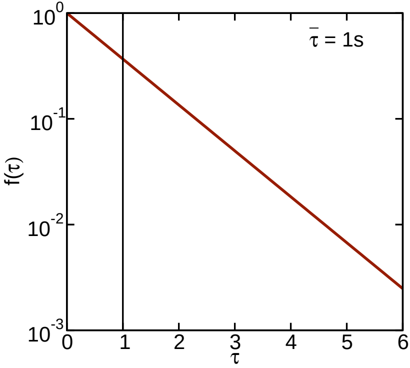
Exponential Distribution

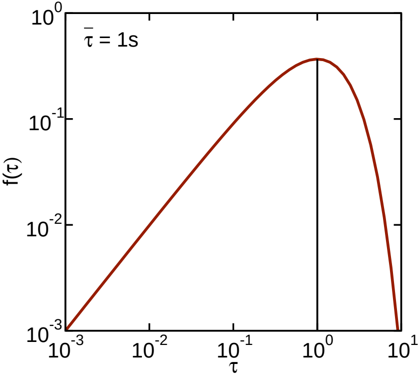
P.d.f. on a linear scale

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

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

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

Mean: (what we see on average)

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

Variance: (related to the noise power)

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

Under stationary conditions as used for RTN analysis

Simple two-state defect

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

$$\sigma_2^2(\infty) = \frac{k_{12}k_{21}}{(k_{12} + k_{21})^2}$$

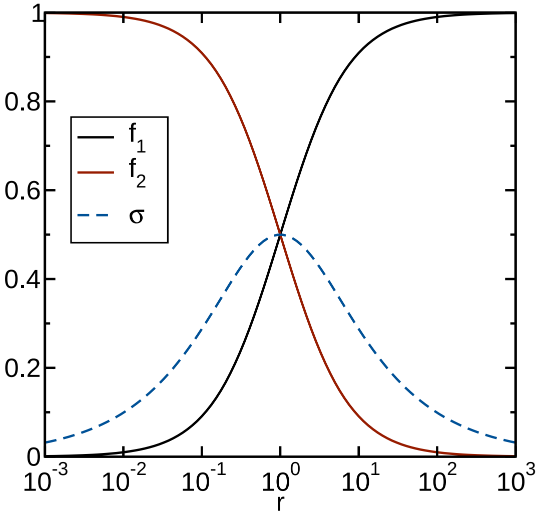
Stationary Moments of a Two-State Defect

Introduce $r = k_{21}/k_{12}$

$$f_1 = \frac{r}{1+r}$$

$$f_2 = \frac{1}{1+r}$$

$$\sigma_1^2 = \sigma_2^2 = \frac{r}{(1+r)^2}$$



Maximum std.dev.

$$r = 1 \Rightarrow \sigma = 1/2$$

Detection optimum

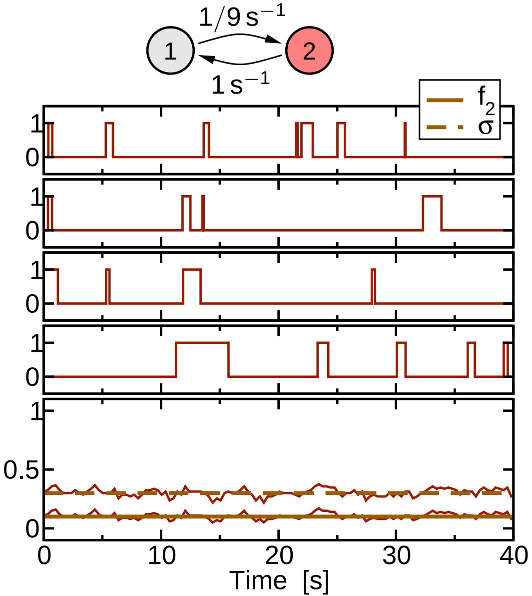
Provided

$$1\,\mu\text{s} \lesssim \frac{1}{k_{12}}, \frac{1}{k_{21}} \lesssim 1\,\text{ks}$$

Stationary Realization of a Two-State Defect

Easy to detect

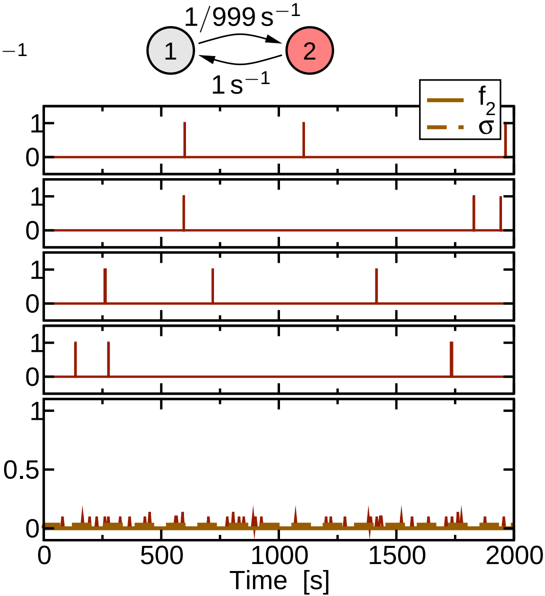
$$k_{12} = 1/9\,\mathrm{s}^{-1}$$
$$k_{21} = 1\,\mathrm{s}^{-1}$$
$$r = 9$$
$$f_1 = 9/10$$
$$f_2 = 1/10$$
$$\sigma = 3/10$$



Stationary Realization of a Two-State Defect

Hard to detect

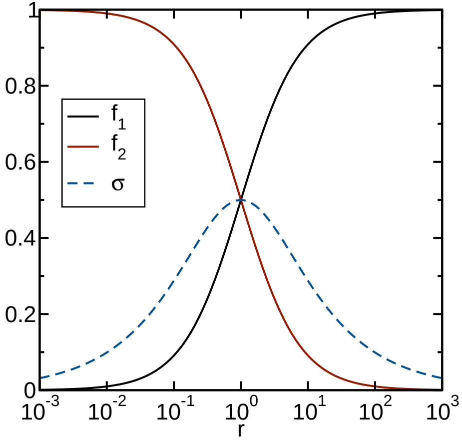
$$k_{12} = 1/999\,\mathrm{s}^{-1}$$
$$k_{21} = 1\,\mathrm{s}^{-1}$$
$$r = 999$$
$$f_1 = 0.999$$
$$f_2 = 0.001$$
$$\sigma \approx 0.032$$



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 ($|V_\mathrm{G}^\mathrm{L}| < |V_\mathrm{G}^\mathrm{H}|$)

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

Detects the most important defects

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

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 $p_2(0)$

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

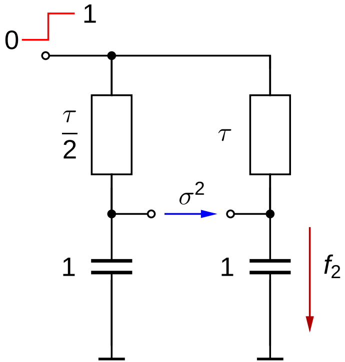
Consider the special case of $p_2(0) \approx 0$ and $p_2(\infty) \approx 1$

The first two moments

$$f_2(t) = 1 - e^{-t/\tau}$$
$$\sigma^2(t) = e^{-t/\tau} - e^{-2t/\tau}$$
$$\tau = \frac{1}{k_{12} + k_{21}}$$

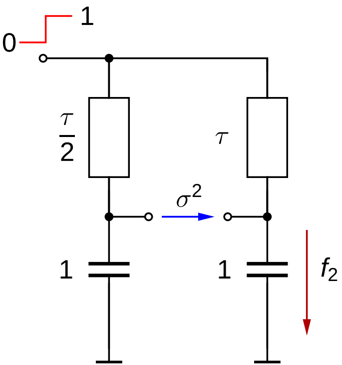
Maximum of σ

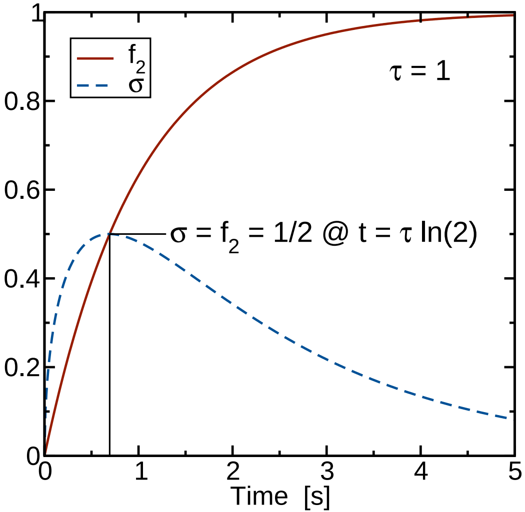
$$f_1(t_{max}) = f_2(t_{max}) = \sigma(t_{max})$$
$$t_{max} = \tau \ln(2)$$



Two-State Stochastic Process

Charging of a two-state defect





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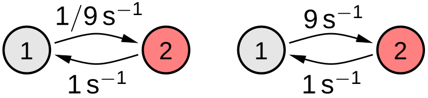

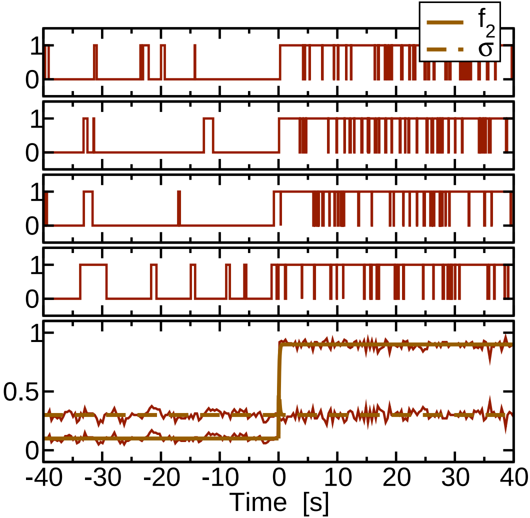

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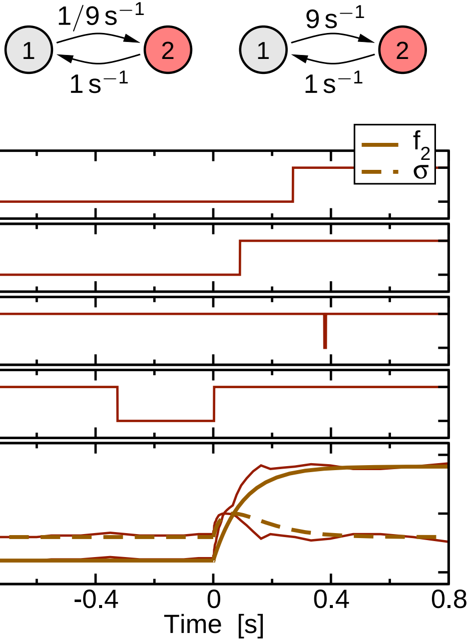

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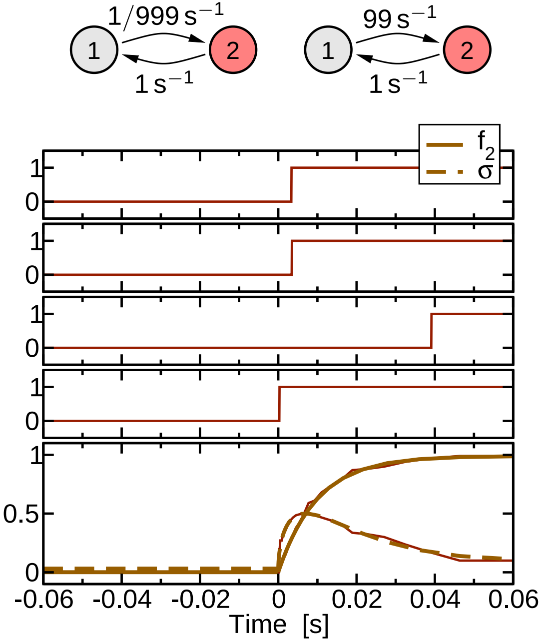


Charging/Discharging of a Two-State Defect

Can be generalized to arbitrary switching sequences

Switching between V_L and V_H

For $t < t_0$

$$p_2(t) = p_2^\mathrm{L}$$

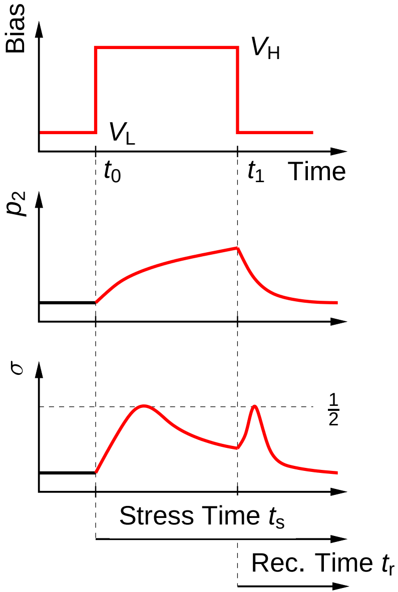
For $t_0 < t < t_1$ (stress)

$$p_2(t) = p_2^\mathrm{H} + (p_2^\mathrm{L} - p_2^\mathrm{H})\,\mathrm{e}^{-t_\mathrm{s}/\tau^\mathrm{H}}$$

For $t > t_1$ (recovery)

$$p_2(t) = p_2^\mathrm{L} + (P_\mathrm{c} - p_2^\mathrm{L})\,\mathrm{e}^{-t_\mathrm{r}/\tau^\mathrm{L}}$$

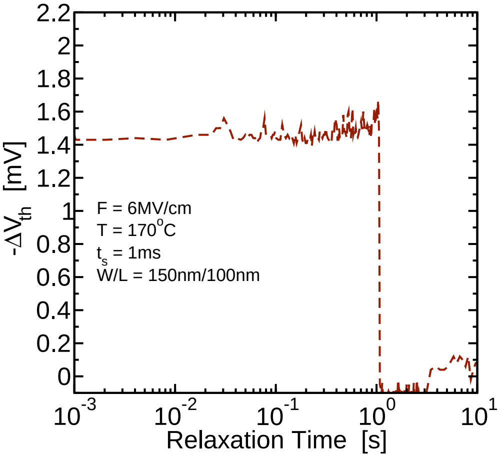
$$P_\mathrm{c} = p_2(t_1)$$



Experimental

Charging of a single defect in a pMOS

- Charging probability: 30%
  - From $1 - \exp(-t_\mathrm{s}/\bar{\tau}_\mathrm{c}) = 0.3$ we get $\bar{\tau}_\mathrm{c} \gtrsim 3\,\mathrm{ms}$
- Defect discharges around $\bar{\tau}_\mathrm{e} = 4\,\mathrm{s}$
- Averaging results in the correct $\exp(-t/\bar{\tau}_\mathrm{e})$ behavior



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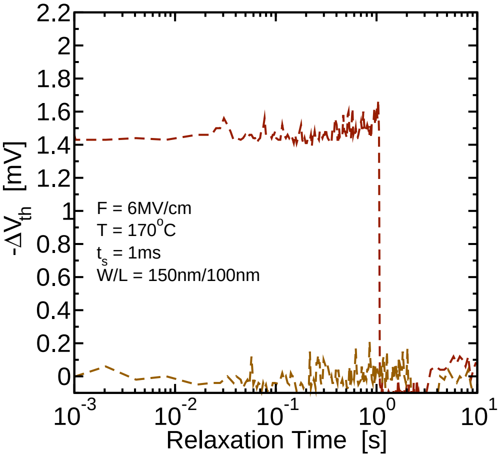

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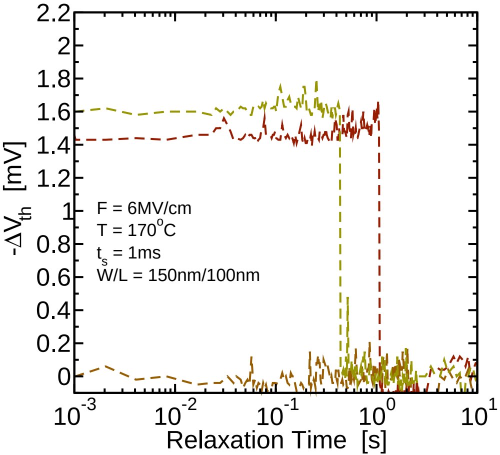

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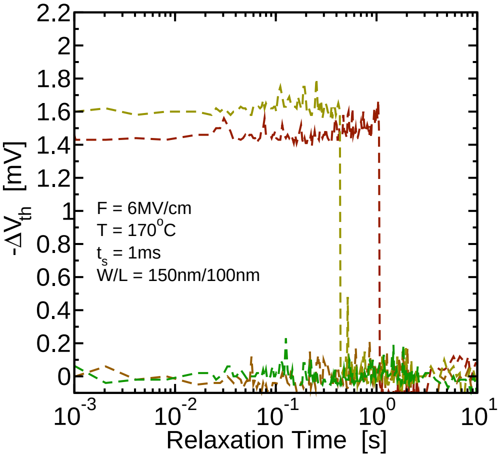

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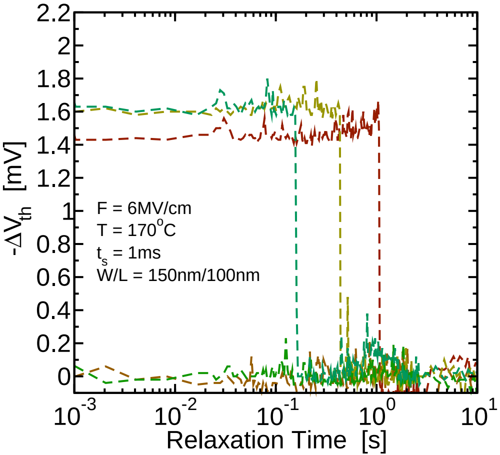

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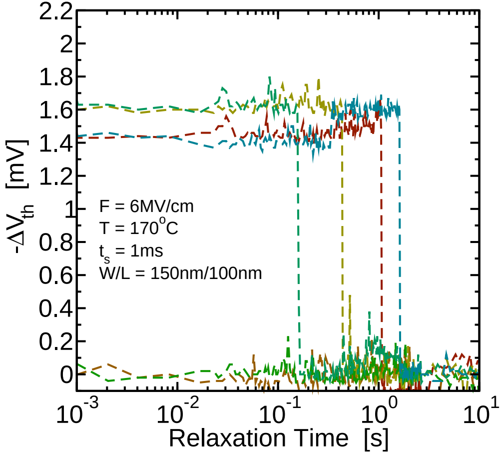

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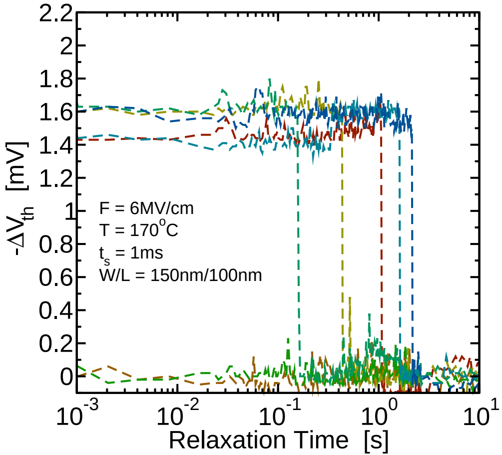

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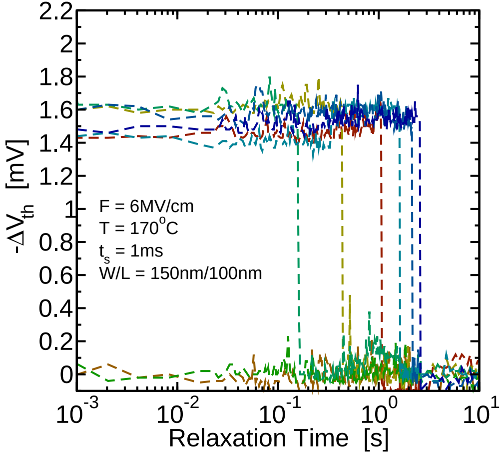

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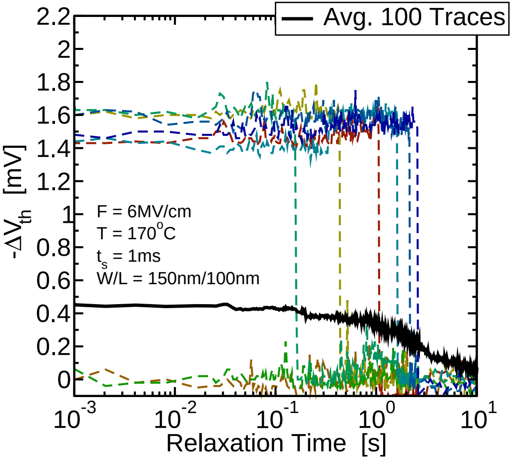

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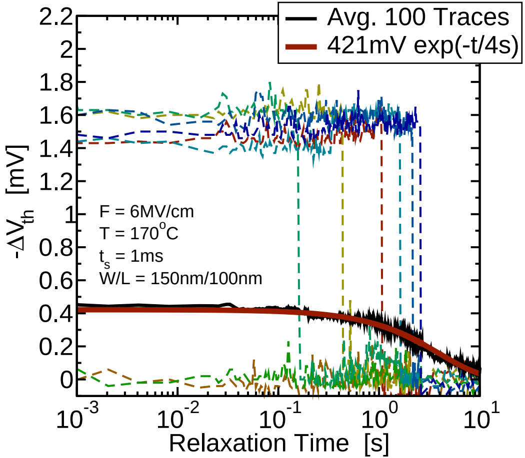
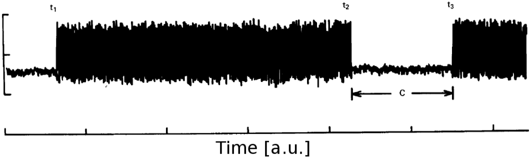


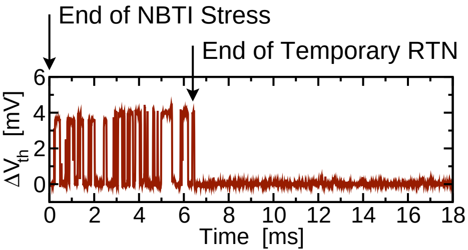
General Defect Model

Defects can have more than two states

Anomalous RTN, where RTN is turned on/off[1]



Temporary RTN following NBTI stress[2]



[1] Uren *et al.*, PRB ’88
[2] Grasser *et al.*, IRPS ’10 and PRB ’10

General Defect Model

Generalization of this procedure gives[1]

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

From this one obtains the Master equation

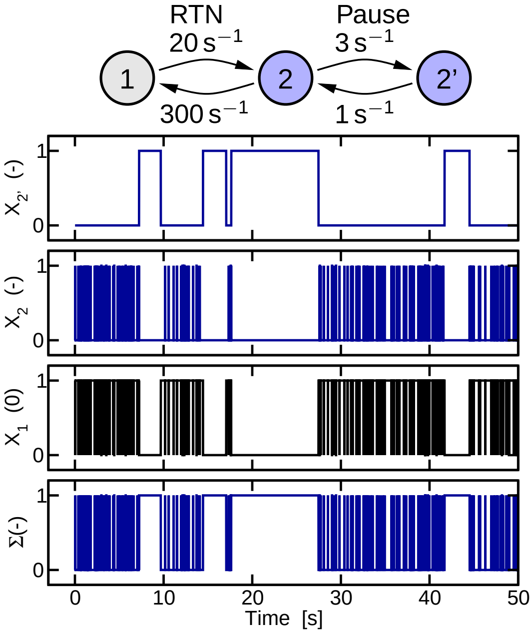
$$\frac{\mathrm{d}p_i(t)}{\mathrm{d}t}=-p_i(t)\sum_{i\neq j}k_{ij}+\sum_{i\neq j}k_{ji}p_j(t)$$

Note

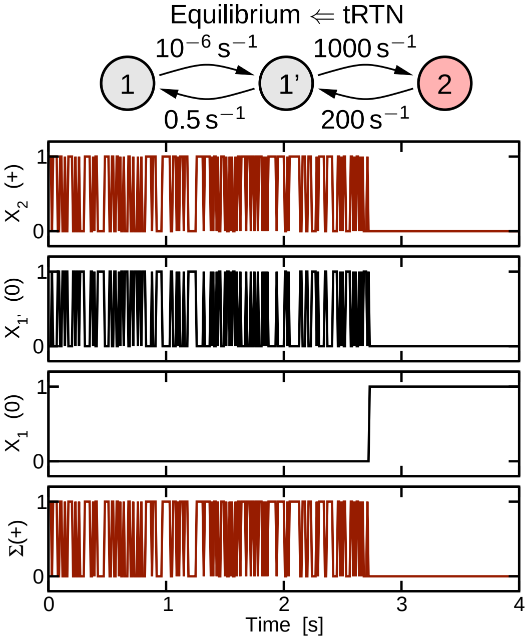
Since $\sum_i p_i(t)=1$, only $N-1$ equations are linearly independent

[1] Gillespie, *Markov Processes*, Academic Press, 1992

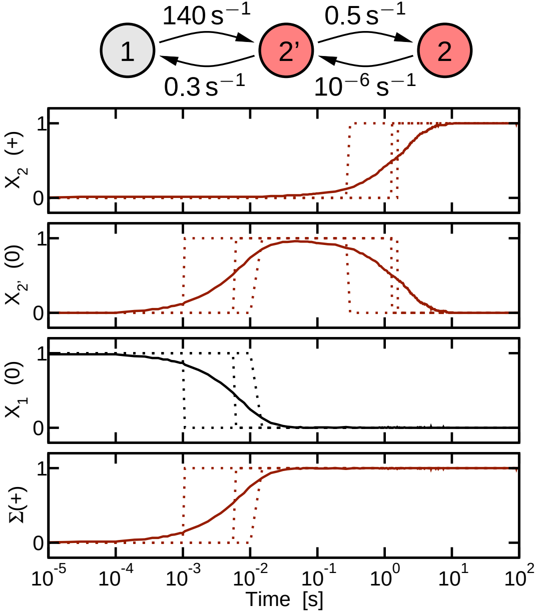
Example: Anomalous RTN



Example: Temporary RTN



Charge Capture for a Three-State Defect



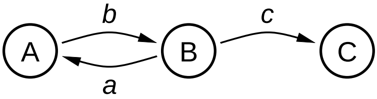
Multi-State Defect Model Reduction

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

$$\frac{\mathrm{d}p_{\mathrm{A}}}{\mathrm{d}t} = -b\,p_{\mathrm{A}} + a\,p_{\mathrm{B}}$$

$$\frac{\mathrm{d}p_{\mathrm{B}}}{\mathrm{d}t} = b\,p_{\mathrm{A}} - a\,p_{\mathrm{B}} - c\,p_{\mathrm{B}}$$

$$\frac{\mathrm{d}p_{\mathrm{C}}}{\mathrm{d}t} = c\,p_{\mathrm{B}}$$

Multi-State Defect Model Reduction

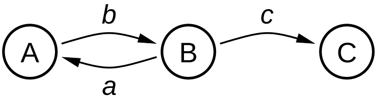
Solution of the modified Master equation

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

$$\tau_1 = 2(s + \sqrt{s^2 - 4bc})^{-1} \geqslant 1/b$$

$$\tau_2 = 2(s - \sqrt{s^2 - 4bc})^{-1} \geqslant 1/c$$

$$s = a + b + c$$



First passage time

'Normalized' difference of two exponential distributions

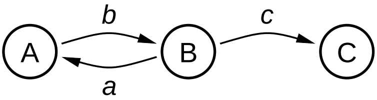
$$f(\tau) = \frac{\mathrm{d}p_C(\tau)}{\mathrm{d}\tau} = \frac{e^{-\tau/\tau_2} - e^{-\tau/\tau_1}}{\tau_2 - \tau_1}$$

Expectation value

$$\bar{\tau} = \mathrm{E}\{\tau\} = \int_0^\infty \tau f(\tau)\,\mathrm{d}\tau = \tau_1 + \tau_2 = \frac{a+b+c}{bc}$$

Three-State Defect: First Passage Time

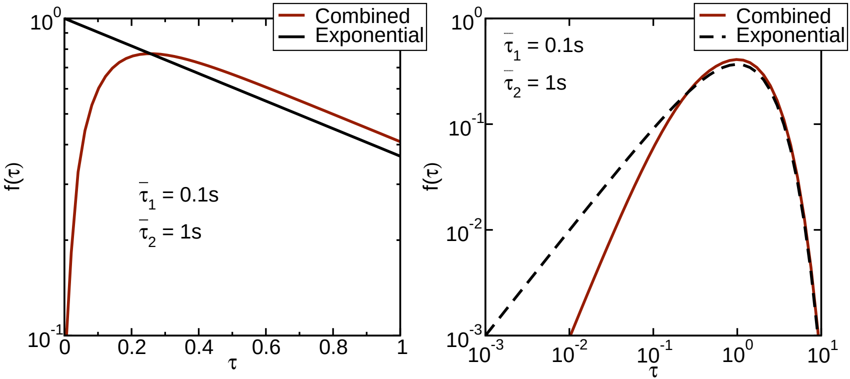
P.d.f. on a linear scale



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

P.d.f. on a logarithmic scale

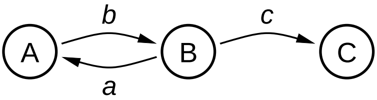
$$\tilde{f}(\tau) = \tau f(\tau) = \tau \frac{e^{-\tau/\tau_2} - e^{-\tau/\tau_1}}{\tau_2 - \tau_1}$$



Three-State Defect: First Passage Time

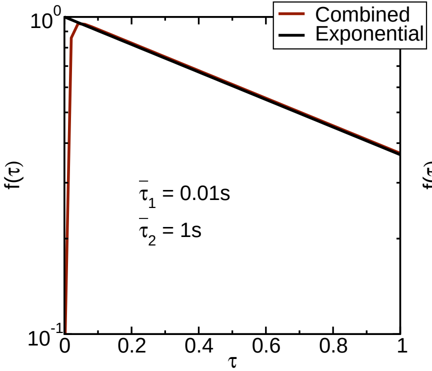
P.d.f. on a linear scale

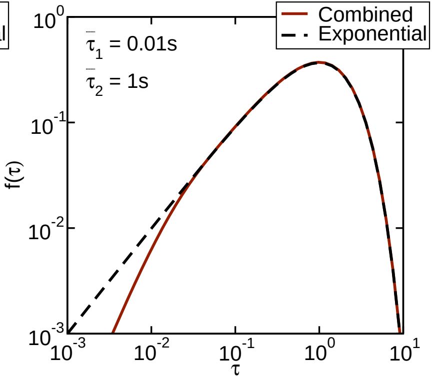
$$f(\tau) = \frac{e^{-\tau/\tau_2} - e^{-\tau/\tau_1}}{\tau_2 - \tau_1}$$



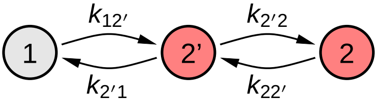
P.d.f. on a logarithmic scale

$$\tilde{f}(\tau) = \tau f(\tau) = \tau \frac{e^{-\tau/\tau_2} - e^{-\tau/\tau_1}}{\tau_2 - \tau_1}$$





Three-State Defect Capture Time



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

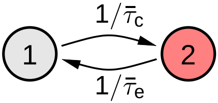
$$\bar{\tau}_\mathrm{c} = \frac{k_{2'1} + k_{12'} + k_{2'2}}{k_{12'}\,k_{2'2}}$$

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

$$\bar{\tau}_\mathrm{e} = \frac{k_{2'2} + k_{22'} + k_{2'1}}{k_{22'}\,k_{2'1}}$$

Approximation for three-state defect

Mean value exact, variance may differ slightly



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

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 σ can be analyzed
- Only devices with a few defects can be analyzed
- Defects with larger $\bar{\tau}_c$ are missed ($\Rightarrow$ cause BTI)

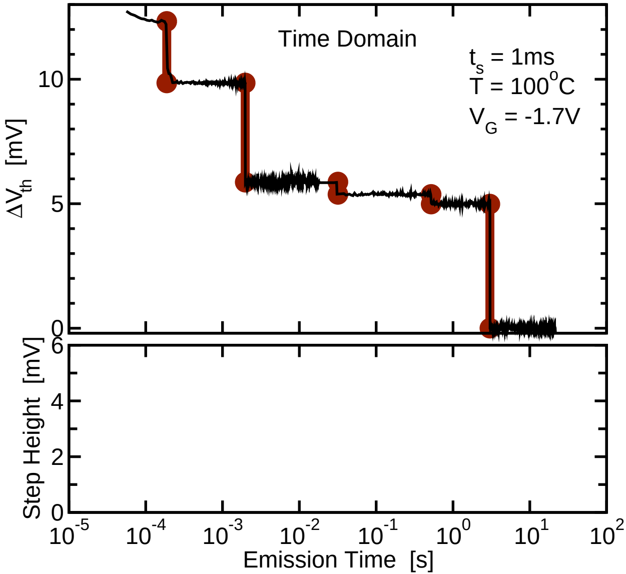
Time-dependent defect spectroscopy (TDDS)

- 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*



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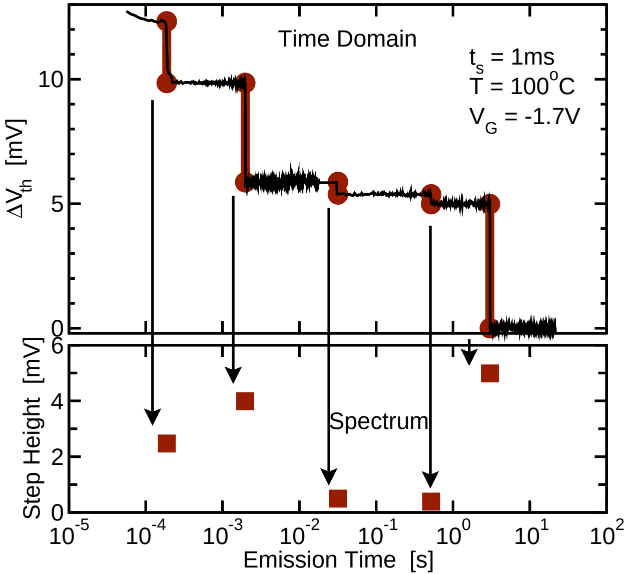

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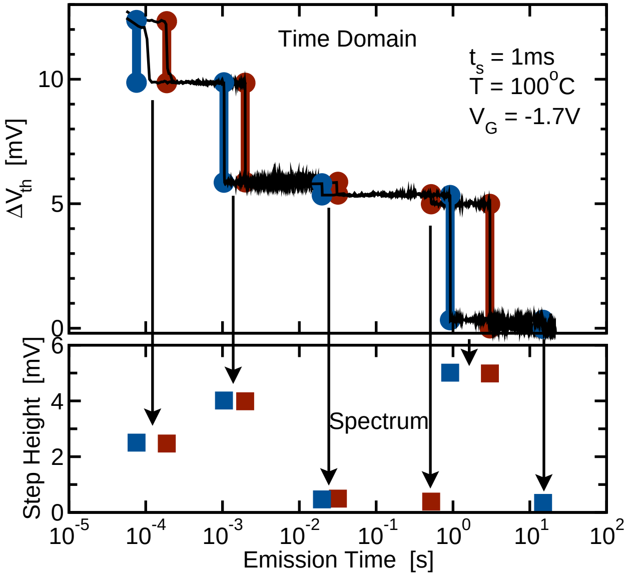

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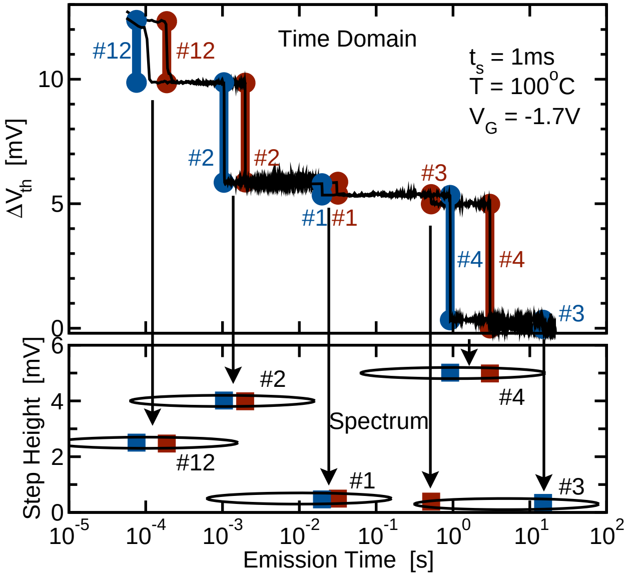
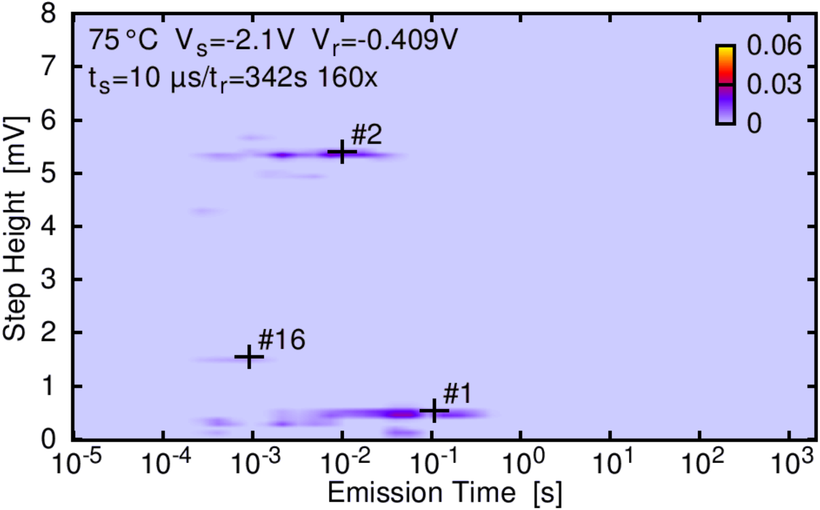


Time-Dependent Defect Spectroscopy (TDDS)

Spectral maps as a function of stress time



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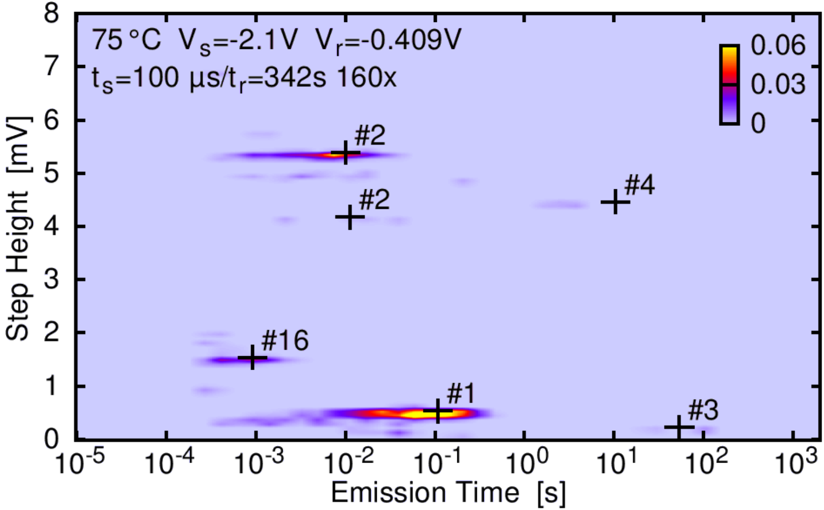

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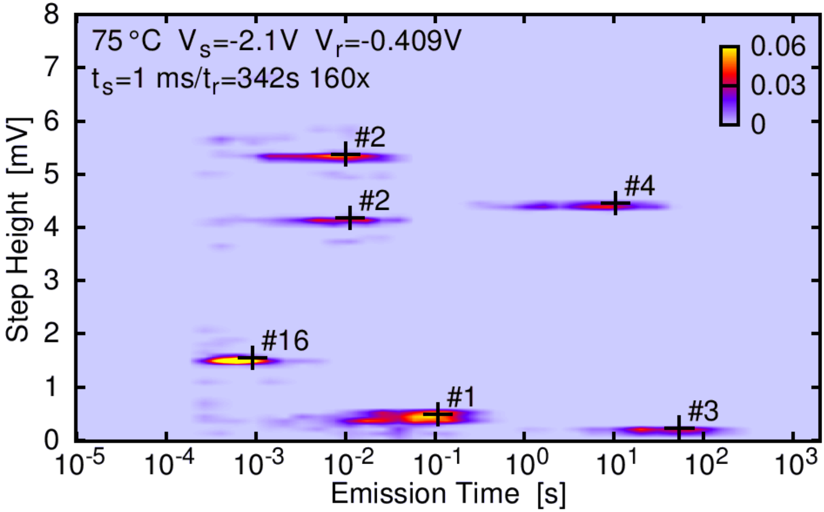

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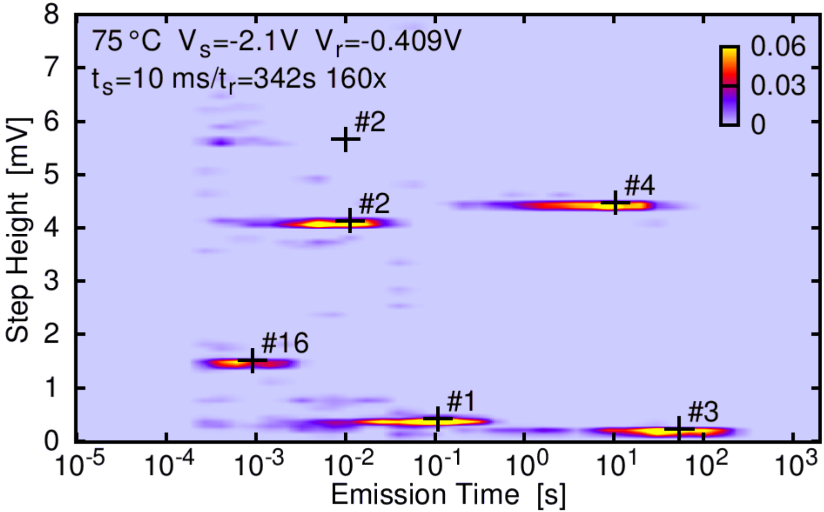
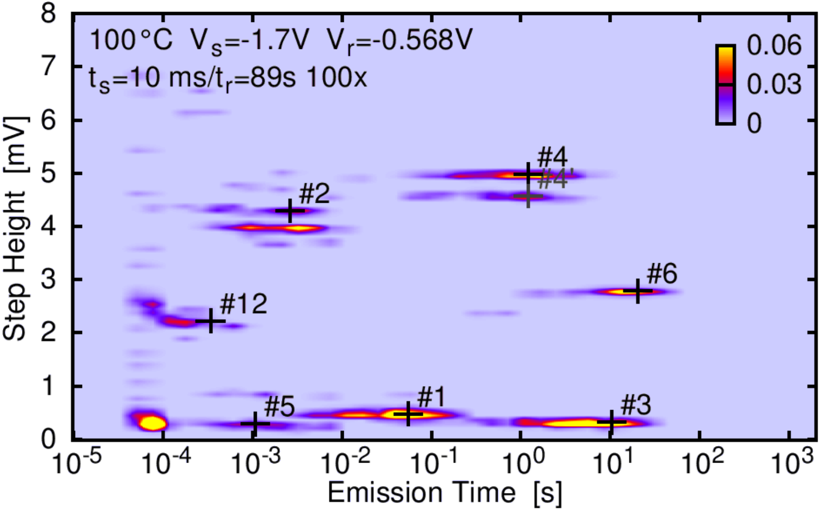
Spectral maps as a function of stress time



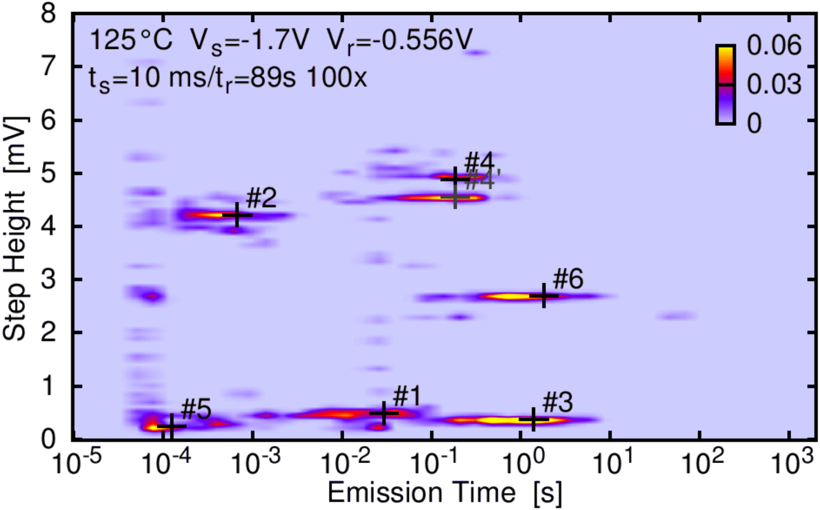
Time-Dependent Defect Spectroscopy (TDDS)

Spectral maps as a function of temperature



Time-Dependent Defect Spectroscopy (TDDS)

Spectral maps as a function of temperature



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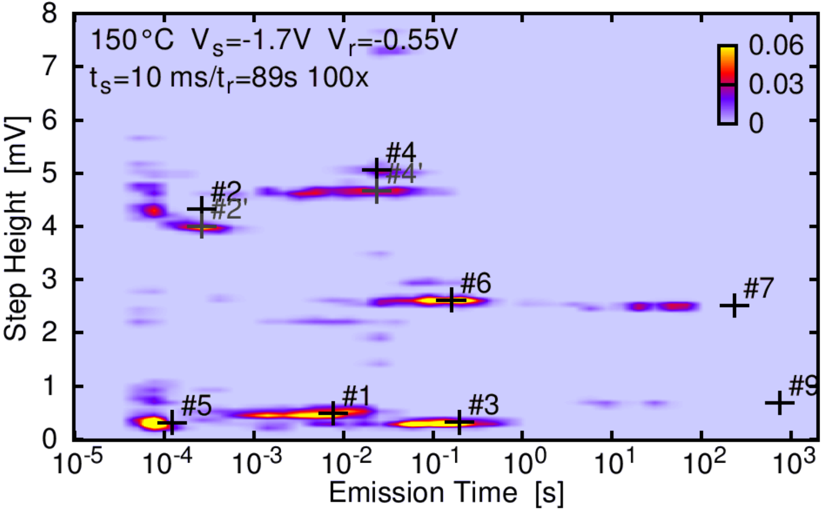
Spectral maps as a function of temperature



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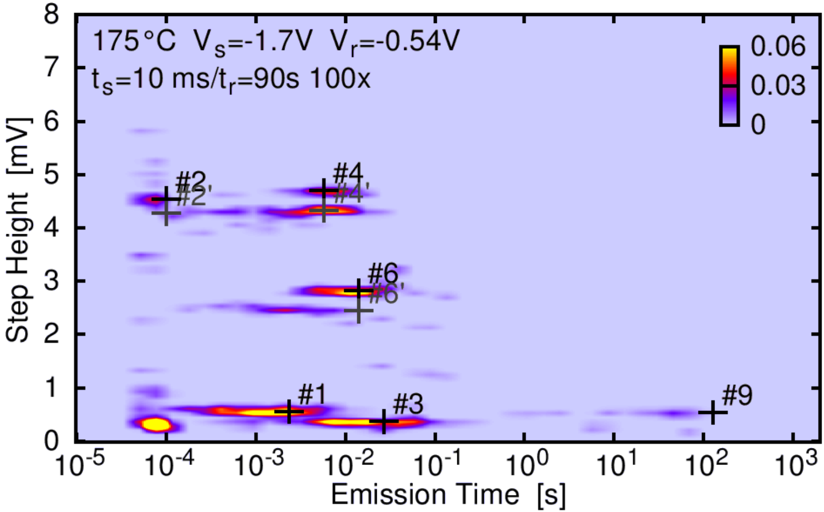
Spectral maps as a function of temperature

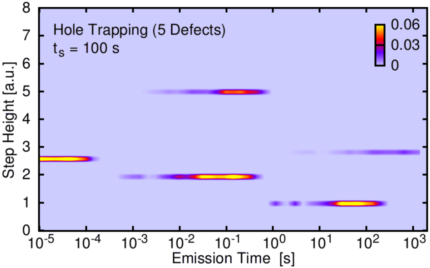


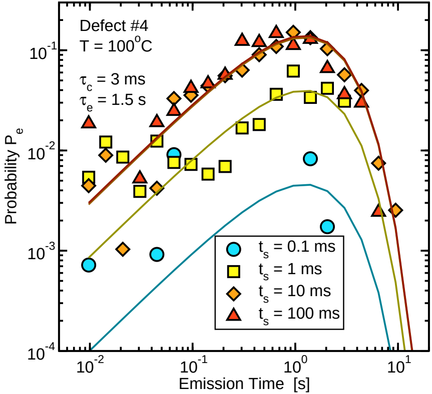
Time-Dependent Defect Spectroscopy (TDDS)

Spectral maps agree with two-state Markov process

Recall: exponential distribution is on a *logarithmic scale*

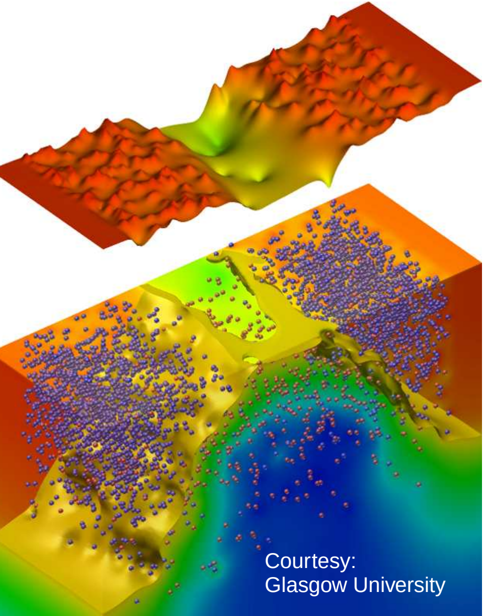
Capture and emission times are widely distributed

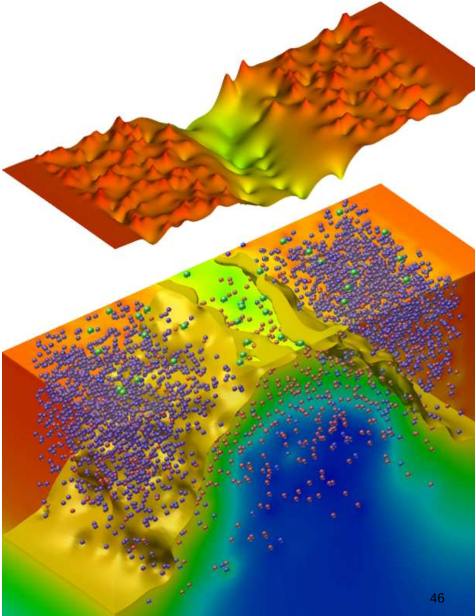




A Few Notes on the Step-Height

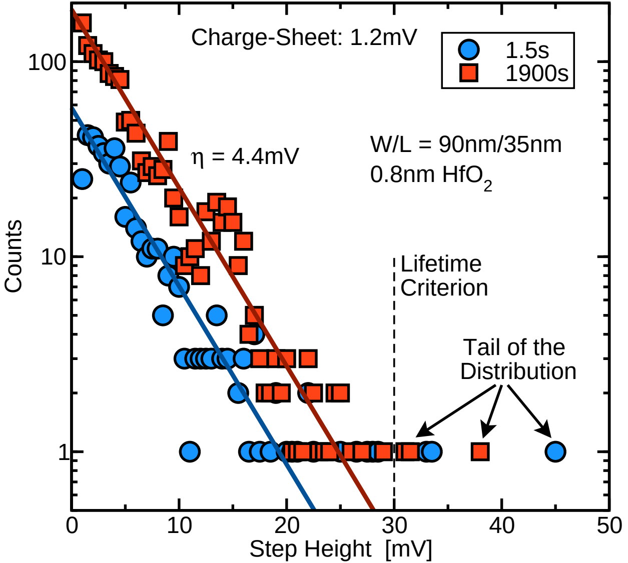
Each defect causes a different contribution to ΔV_{th}





A Few Notes on the Step-Height

RTN/BTI step-heights are exponentially distributed[1]

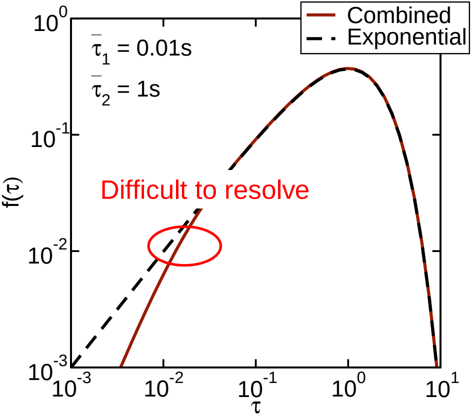


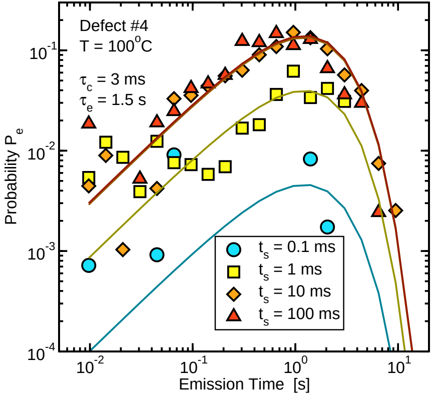
[1] Kaczer *et al.*, IRPS '10

Time-Dependent Defect Spectroscopy (TDDS)

Would a three-state defect be visible?

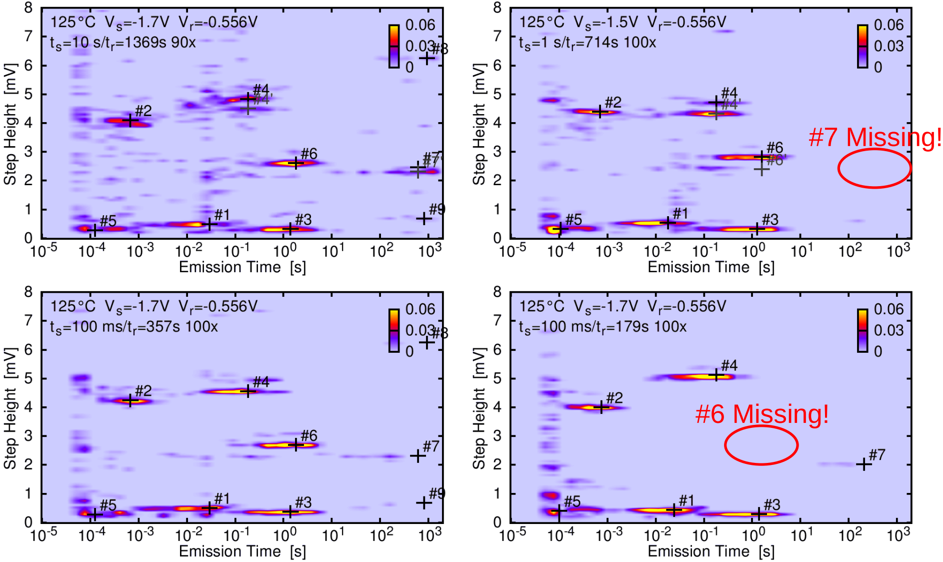
Capture via intermediate state experimentally challenging





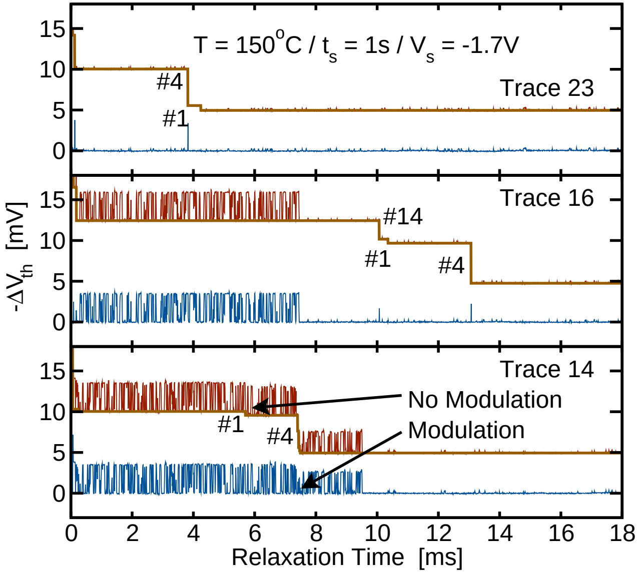
Time-Dependent Defect Spectroscopy (TDDS)

Metastable states visible as 'disappearing defects'



Time-Dependent Defect Spectroscopy (TDDS)

Metastable states visible as temporary RTN



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Physical Models for the Capture and Emission Times

Stochastic BTI

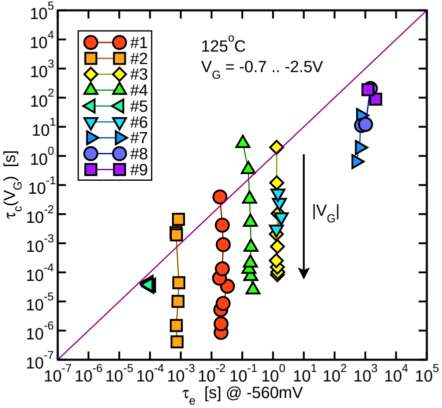
Discrete Distribution

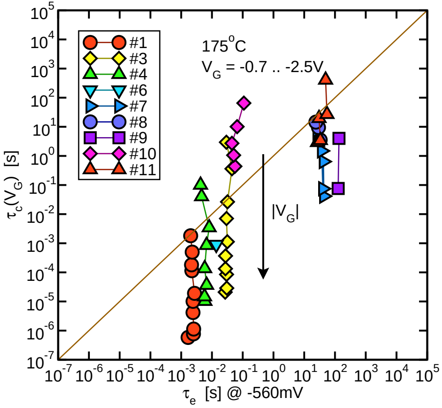
Discrete capture/emission time map (CET) of $\bar{\tau}_c$ and $\bar{\tau}_e$

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 $\bar{\tau}_e = \bar{\tau}_e(V_L)$





Discrete Capture/Emission Time Map (CET)

What is the use of the capture/emission time map (CET)?

Reconstruct the temporal behavior (just like Fourier transform)

Macroscopic version (expectation value)

$$\Delta V_{\mathrm{th}}(t_{\mathrm{s}}, t_{\mathrm{r}}) = \sum_{k}^{N} d_k \, a_k \, h_k(t_{\mathrm{s}}, t_{\mathrm{r}}; \tau_{\mathrm{c},k}, \tau_{\mathrm{e},k})$$

N		... Number of defects
d_k		... step-height
a_k	$\in [0 \ldots 1]$	... maximum occupancy
$h_k(t_{\mathrm{s}}, t_{\mathrm{r}})$	$= (1 - \mathrm{e}^{-t_{\mathrm{s}}/\tau_{\mathrm{c},k}})\, \mathrm{e}^{-t_{\mathrm{r}}/\tau_{\mathrm{e},k}}$	... dynamics

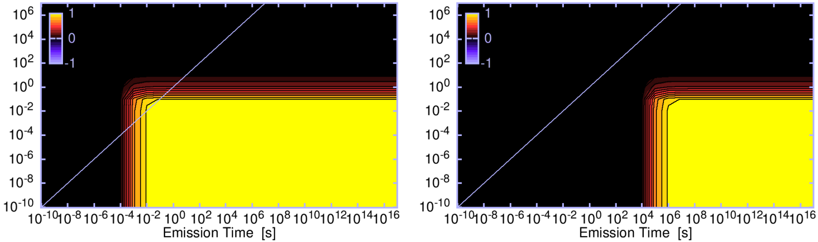
Stochastic version also possible

Continuous Distribution

Continuous capture/emission time (CET) map[1]

$$\Delta V_{\mathrm{th}}(t_{\mathrm{s}}, t_{\mathrm{r}}) \approx \int_0^\infty \mathrm{d}\tau_{\mathrm{c}} \int_0^\infty \mathrm{d}\tau_{\mathrm{e}}\, g(\tau_{\mathrm{c}}, \tau_{\mathrm{e}})\, h(t_{\mathrm{s}}, t_{\mathrm{r}}; \tau_{\mathrm{c}}, \tau_{\mathrm{e}})$$

$$\approx \int_0^{t_{\mathrm{s}}} \mathrm{d}\tau_{\mathrm{c}} \int_{t_{\mathrm{r}}}^\infty \mathrm{d}\tau_{\mathrm{e}}\, g(\tau_{\mathrm{c}}, \tau_{\mathrm{e}})$$



Simple extraction scheme for g using measured ΔV_{th}

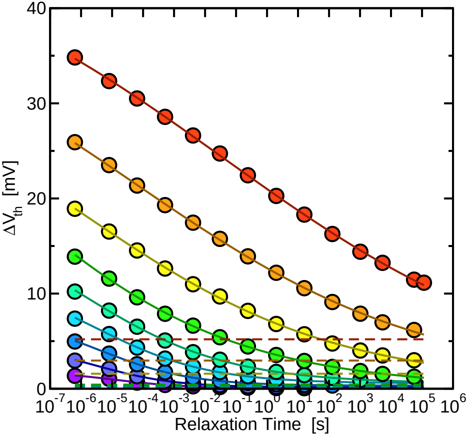
$$g(\tau_{\mathrm{c}}, \tau_{\mathrm{e}}) = -\frac{\partial^2 \Delta V_{\mathrm{th}}(\tau_{\mathrm{c}}, \tau_{\mathrm{e}})}{\partial \tau_{\mathrm{c}}\, \partial \tau_{\mathrm{e}}}$$

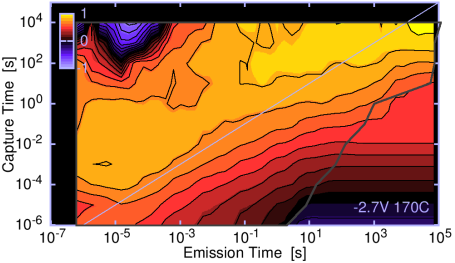
[1] Reisinger *et al.*, IRPS '10

Continuous Distribution

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

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





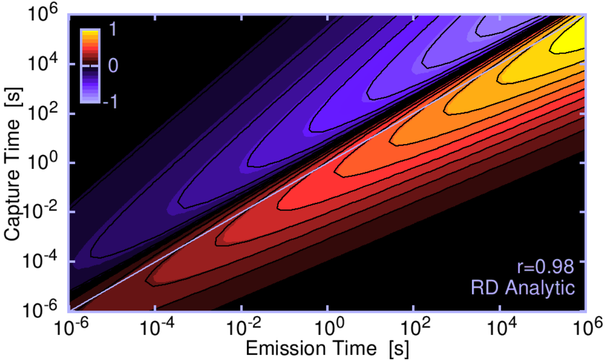
CET Maps from Theory: RD Model

Analytical solution of the reaction-diffusion model

$$\Delta V_{\mathrm{th}}(t_{\mathrm{s}}, t_{\mathrm{r}}) = \frac{t_{\mathrm{s}}^{n}}{1 + \sqrt{t_{\mathrm{r}}/t_{\mathrm{s}}}}$$

Analytical CET map becomes negative

$$g(\tau_{\mathrm{c}}, \tau_{\mathrm{e}}) = -\frac{\partial^2 \Delta V_{\mathrm{th}}(\tau_{\mathrm{c}}, \tau_{\mathrm{e}})}{\partial \tau_{\mathrm{c}} \partial \tau_{\mathrm{e}}} = \frac{2n - 1 + (2n+1)\sqrt{\tau_{\mathrm{e}}/\tau_{\mathrm{c}}}}{4\sqrt{\tau_{\mathrm{e}}/\tau_{\mathrm{c}}}(1 + \sqrt{\tau_{\mathrm{e}}/\tau_{\mathrm{c}}})^3} \frac{1}{\tau_{\mathrm{c}}^{2-n}}$$



CET Maps from Theory: Hole Trapping

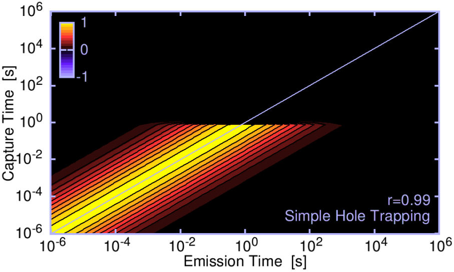
Analytical solution of a simple hole-trapping model

$$\Delta V_{\mathrm{th}}(t_{\mathrm{s}}, t_{\mathrm{r}}) = A \log(1 + B t_{\mathrm{r}}/t_{\mathrm{s}}) \qquad \text{for } t_{\mathrm{s}} < t_{\mathrm{s}}^{\max}.$$

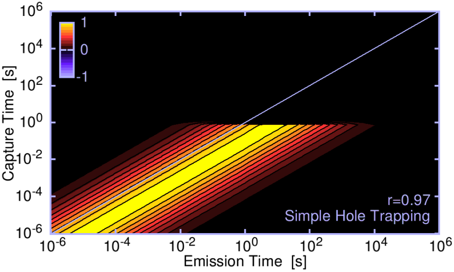
Analytical CET map

$$g(\tau_{\mathrm{c}}, \tau_{\mathrm{e}}) = \frac{AB}{(B + \tau_{\mathrm{e}}/\tau_{\mathrm{c}})^2} \frac{1}{\tau_{\mathrm{c}}^2}$$

$B = 1$



$B = 10$



CET Maps from Theory: Universal Recovery

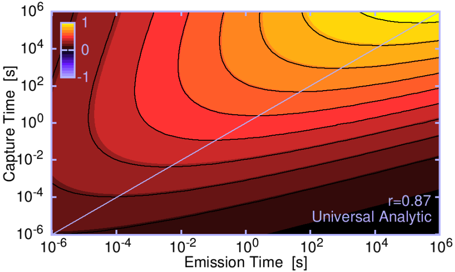
Empirical universal recovery expression [1]

$$\Delta V_{\mathrm{th}}(t_{\mathrm{s}}, t_{\mathrm{r}}) = \frac{A t_{\mathrm{s}}^{a}}{1 + B(t_{\mathrm{r}}/t_{\mathrm{s}})^{b}} + P t_{\mathrm{s}}^{n}$$

Analytical CET map

$$g(\tau_{\mathrm{c}}, \tau_{\mathrm{e}}) = -\frac{\partial^2 \Delta V_{\mathrm{th}}(\tau_{\mathrm{c}}, \tau_{\mathrm{e}})}{\partial \tau_{\mathrm{c}} \partial \tau_{\mathrm{e}}} = \frac{a - b + (a+b)B(\tau_{\mathrm{e}}/\tau_{\mathrm{c}})^{b}}{(1 + B(\tau_{\mathrm{e}}/\tau_{\mathrm{c}})^{b})^{3}} \frac{bAB}{\tau_{\mathrm{c}}^{2-a}(\tau_{\mathrm{e}}/\tau_{\mathrm{c}})^{1-b}}$$

$$a = 1/6,\ b = 0.15,\ B = 2$$



[1] Grasser *et al.*, IEDM '07

Outline

Conventional Model: Extended SRH Theory

SRH theory

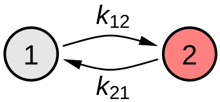
- Developed for bulk defects, defect level E_1 inside the bandgap
- No 'explicit' assumption on capture and emission mechanism
- Assumption: capture rate is represented by an averaged value
- Gives Boltzmann factor in the emission rate, $\exp(-\beta(E_2 - E_1))$

Extension to oxide defects[1]

- 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



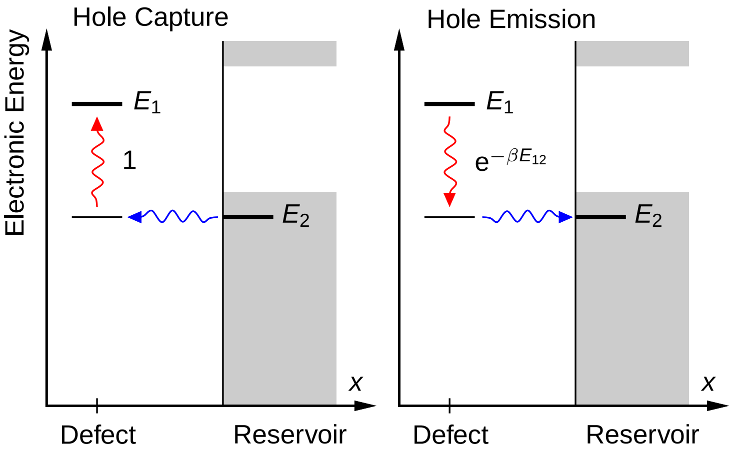
[1] McWhorter '57; Masuduzzaman, T-ED '08

Conventional Model: Extended SRH Theory

Defect level inside Si bandgap

Hole capture: no barrier

Hole emission: Boltzmann factor $e^{-\beta E_{12}}$

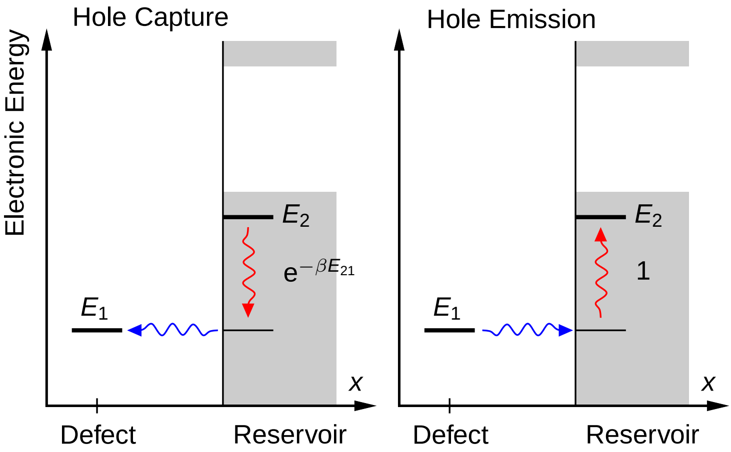


Conventional Model: Extended SRH Theory

Defect level *outside* Si bandgap

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

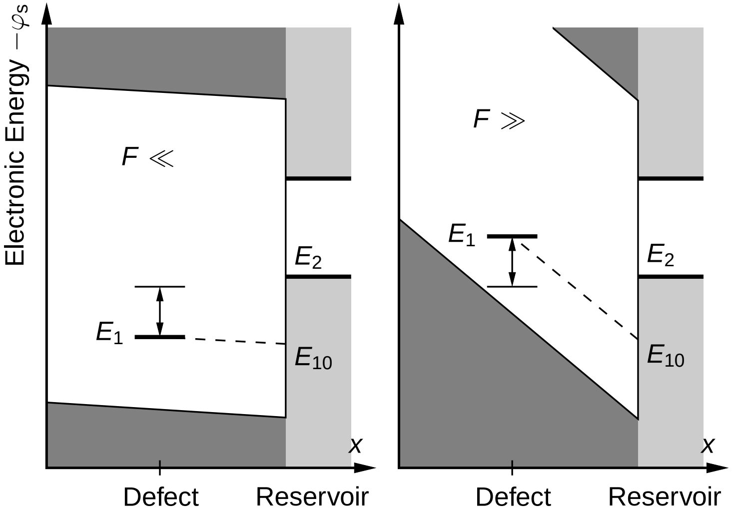
Hole emission: no barrier



Conventional Model: Extended SRH Theory

Electronic defect level depends on oxide field

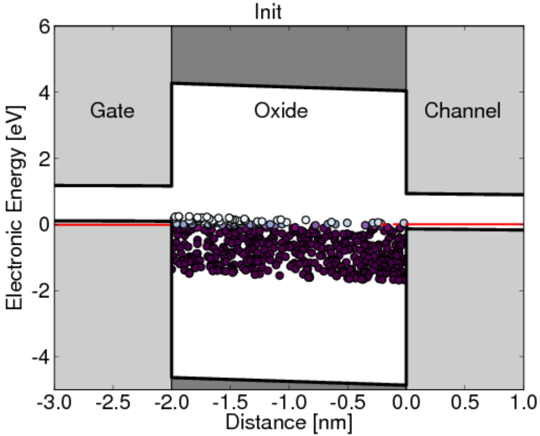
Depending on field, defect level changes relative to $E_2 \approx E_v$



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



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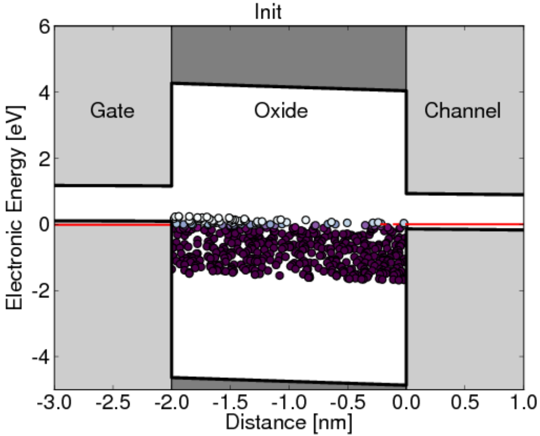


Problems with Extended SRH Theory

Too fast

Tunneling front reaches 1 nm in about 10 ms

Experimental $\bar{\tau}_\mathrm{c}$ and $\bar{\tau}_\mathrm{e}$ can be considerably larger (h, m, w, y?)

Capture rate temperature independent

Experimental $\bar{\tau}_\mathrm{c}$ can have $E_\mathrm{A} \approx 1\,\mathrm{eV}$

Bias dependence of $\bar{\tau}_\mathrm{c}$ weak

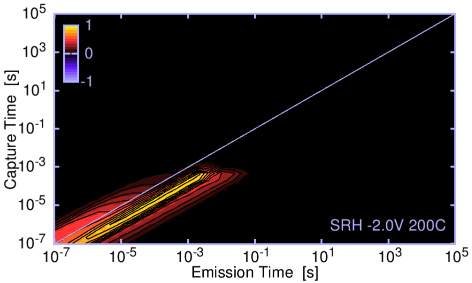
Depends dominantly on surface hole concentration, $\bar{\tau}_\mathrm{c} \sim 1/p$

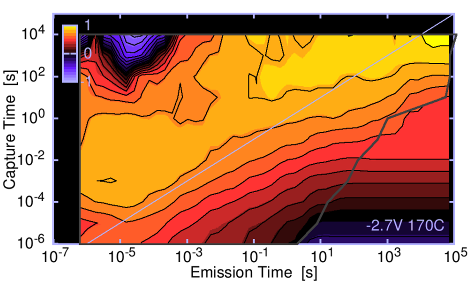
Experimental $\bar{\tau}_\mathrm{c}$ depends exponentially on oxide field

Problems with Extended SRH Theory

No similarity with experimental CET map (right)

$\bar{\tau}_c$ correlated with $\bar{\tau}_e$

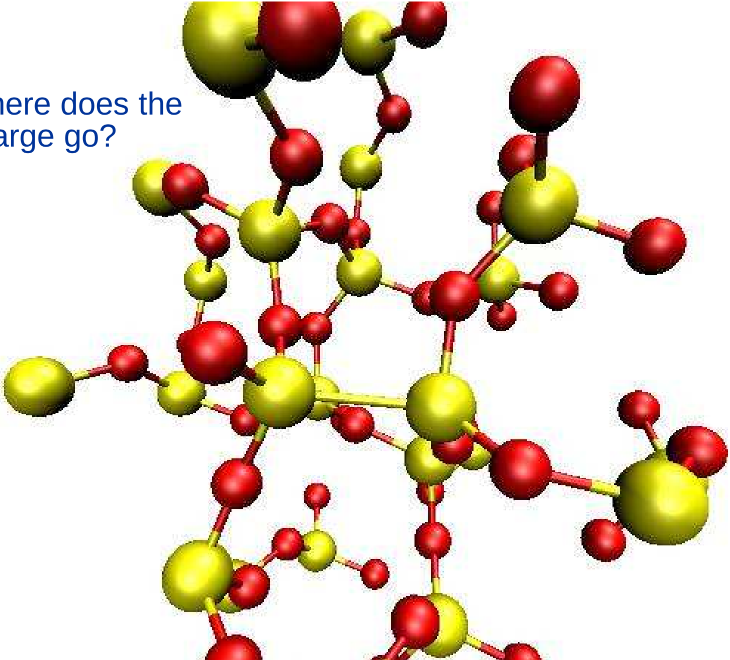




The SRH model cannot describe oxide defects

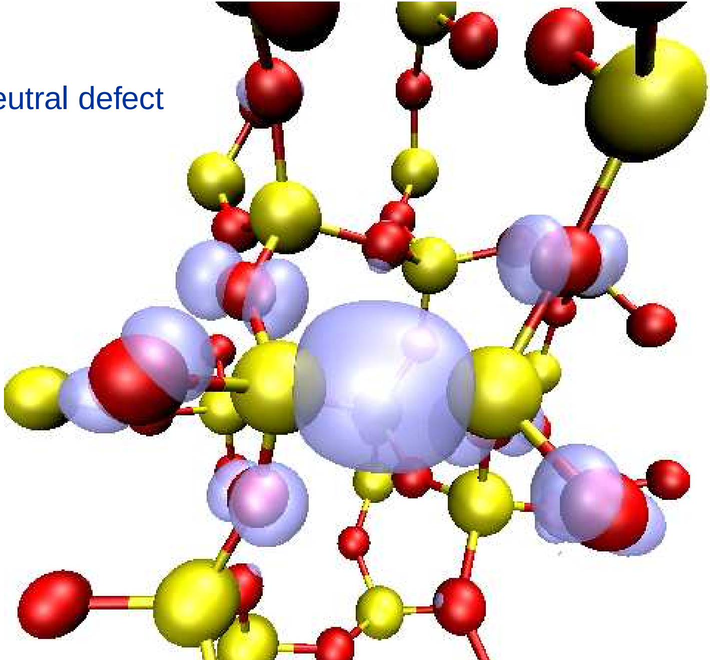
How are Charges Really Trapped in Oxides?

Where does the charge go?



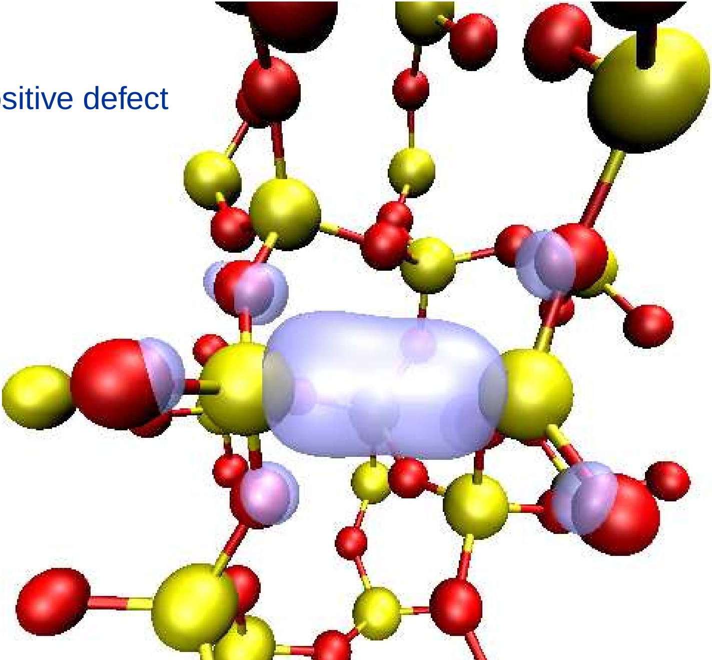
How are Charges Really Trapped in Oxides?

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)

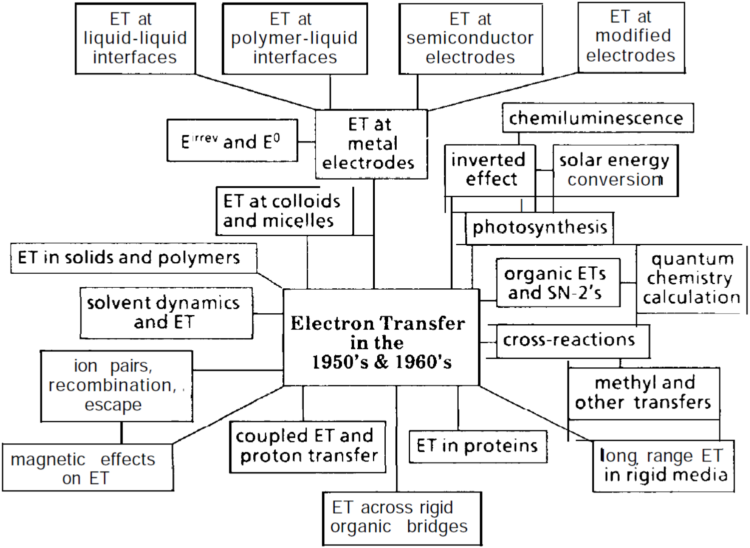
Biology

Photosynthesis

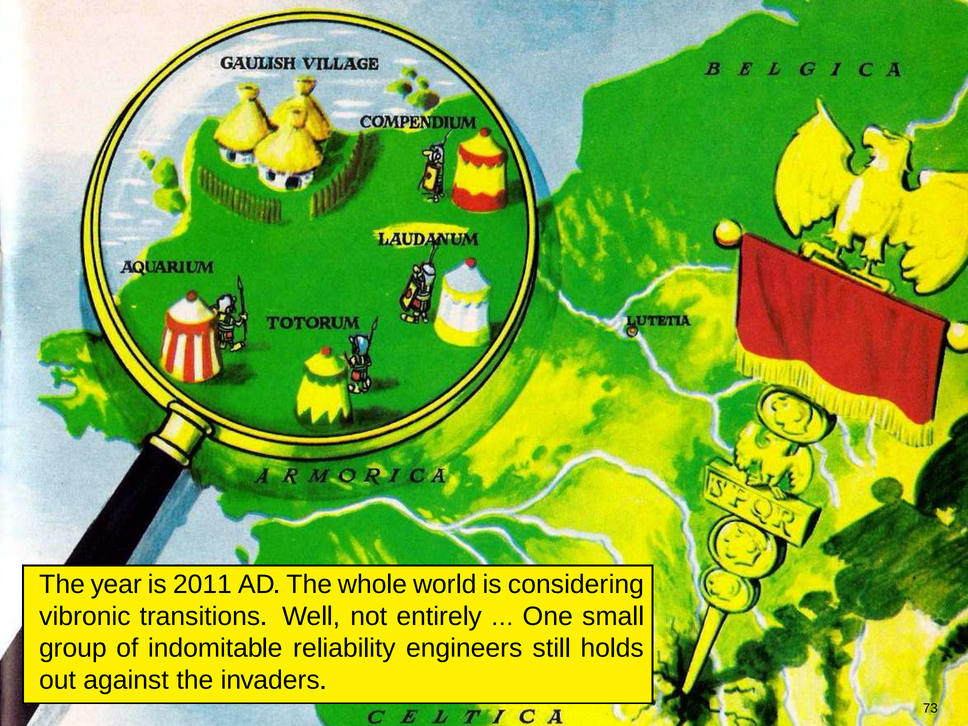
Sense of smell

Lightsensitivity (the very reason you can read this)

This Phenomenon is Everywhere!

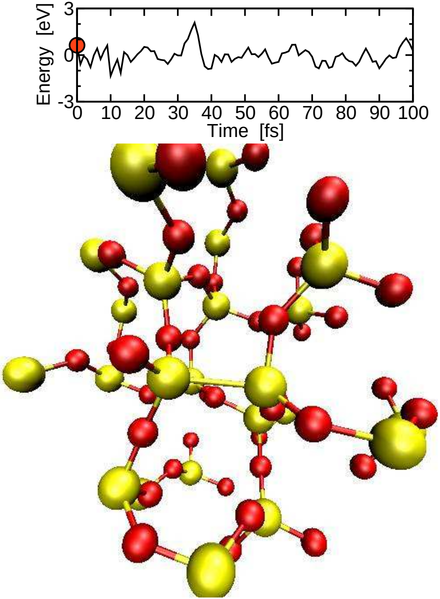


From: R.A. Marcus, "Electron Transfer Reactions in Chemistry", Nobel Lecture, 1992.

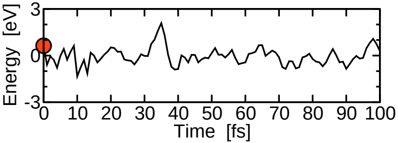


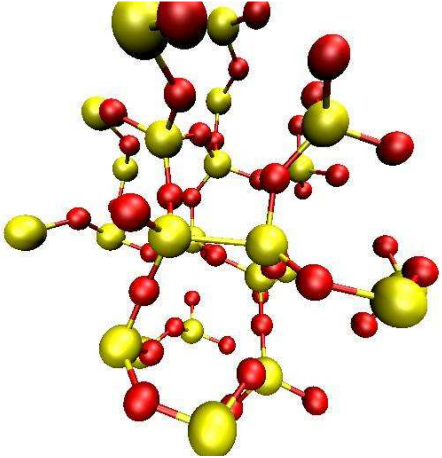
The year is 2011 AD. The whole world is considering vibronic transitions. Well, not entirely ... One small group of indomitable reliability engineers still holds out against the invaders.

100 Femtoseconds in the Life of an E' center

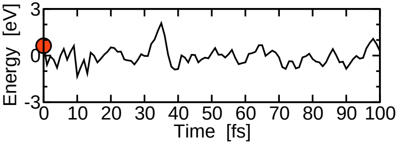


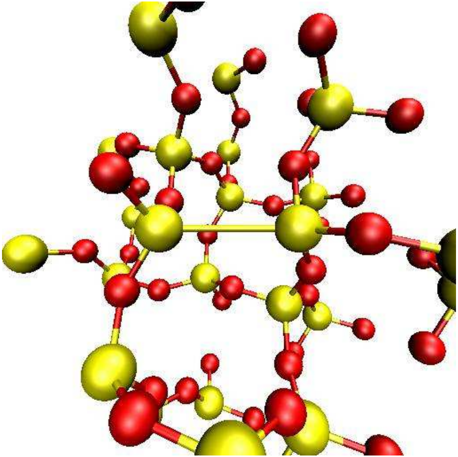
100 Femtoseconds in the Life of an E’ center





Coordinate Transformation onto Si-Si Bond





The Total Potential Energy

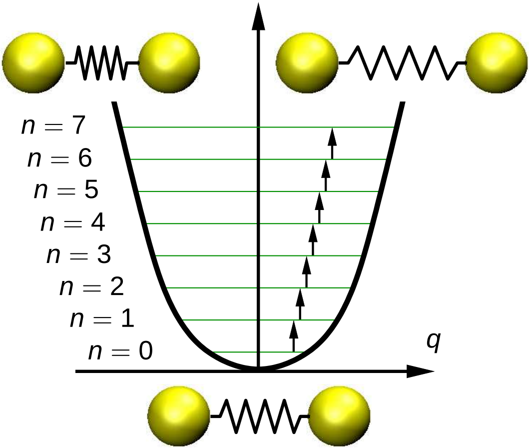
Vibronic energy model: quantum harmonic oscillator

Energy levels

$$\mathcal{E}_n = \hbar\omega(n + \tfrac{1}{2})$$

Level occupancy

$$\frac{P(\mathcal{E}_n)}{P(\mathcal{E}_0)} = \frac{e^{-\beta\mathcal{E}_n}}{e^{-\beta\mathcal{E}_0}}$$



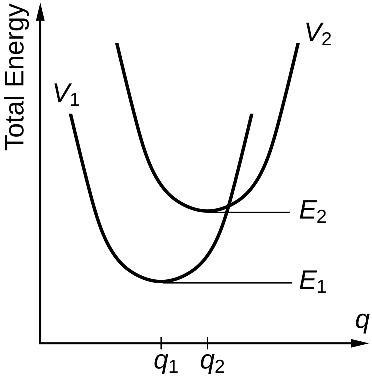
The Total Potential Energy

Total energy contains vibronic + electronic energy[1]

Harmonic oscillator in each state (parabolic potential)

Equilibrium q depends on defect state (adiabatic approximation)

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



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

[2] Franck, Trans.Far.Soc. '25; Condon, Phys.Rev. '28

Optical Transitions

Optical transitions (radiative transitions)

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

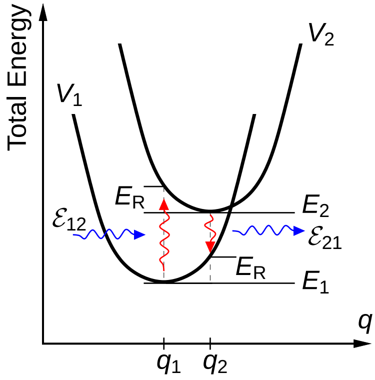
Photon absorption ($1 \rightarrow 2$)

$$\mathcal{E}_{12} = V_2(q_1) - V_1(q_1)$$

Photon emission ($2 \rightarrow 1$)

$$\mathcal{E}_{21} = V_2(q_2) - V_1(q_2)$$

Photon energies differ, $\mathcal{E}_{12} \neq \mathcal{E}_{21}$



Difference due to lattice relaxation

$$\mathcal{E}_{12} = E_{21} + E_R$$

$$\mathcal{E}_{21} = E_{12} - E_R$$

E_R is the relaxation energy[1]

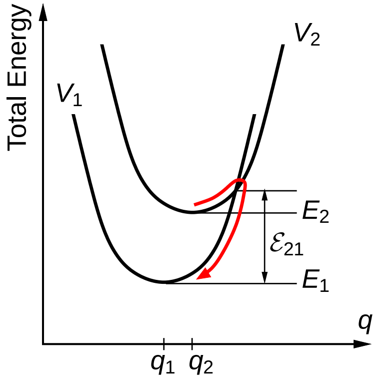
[1] Stoneham, Rep.Prog.Phys. '81

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')



The Total Energy

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

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

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

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

Linear electron-phonon coupling:[1] $R = 1$ $(\omega_1 = \omega_2)$

$\Rightarrow V_2(q) - V_1(q)$ is linear in q

$$\mathcal{E}_{12} = \frac{(E_\mathrm{R} + E_{21})^2}{4E_\mathrm{R}}$$
$$E_\mathrm{R} = M\omega^2(q_2 - q_1)^2/2$$

$S = E_\mathrm{R}/\hbar\omega$ 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

$$\approx \mathrm{e}^{-\beta \mathcal{E}_{12}}$$

The electronic matrix element is approximately

$$\approx \sigma v_{\mathrm{th}} p$$

To account for tunneling: WKB factor in σ

$$\sigma = \sigma_0 \exp(-x/x_0) \qquad x_0 = \hbar/(2\sqrt{2m\phi})$$

So in total we have

$$k_{12} = \sigma v_{\mathrm{th}} p \quad \mathrm{e}^{-\beta \mathcal{E}_{12}}$$

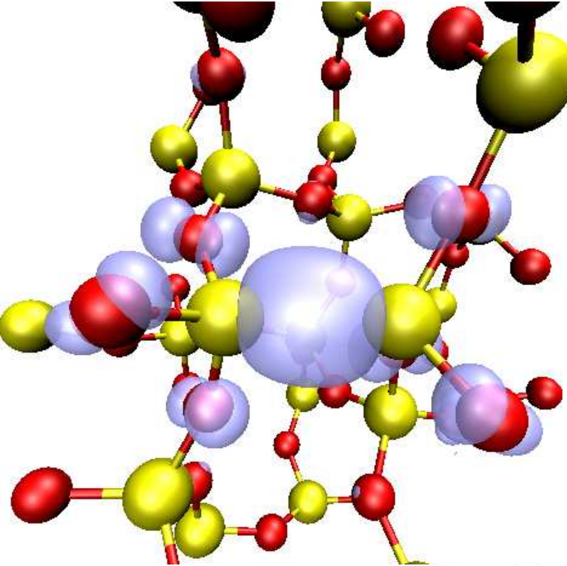
$$k_{21} \approx \sigma v_{\mathrm{th}} N_{\mathrm{v}} \, \mathrm{e}^{-\beta \mathcal{E}_{21}} \qquad \text{(Maxwell-Boltzmann statistics)}$$

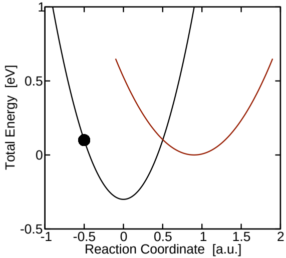
Compare to SRH model (defect inside Si bandgap)

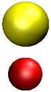
$$k_{12} = \sigma v_{\mathrm{th}} p$$

$$k_{21} \approx \sigma v_{\mathrm{th}} N_{\mathrm{v}} \, \mathrm{e}^{-\beta E_{12}} \qquad \text{(Maxwell-Boltzmann statistics)}$$

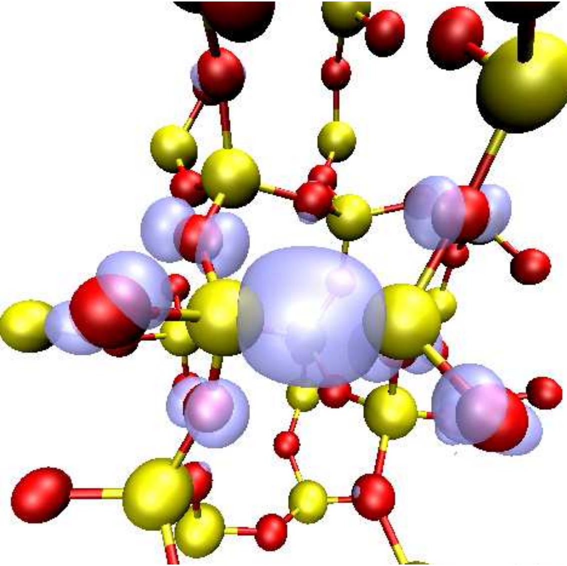
Charge Trapping in an E' Center

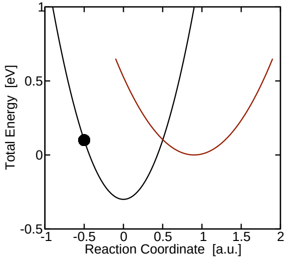


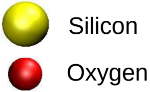




Charge Trapping in an E' Center

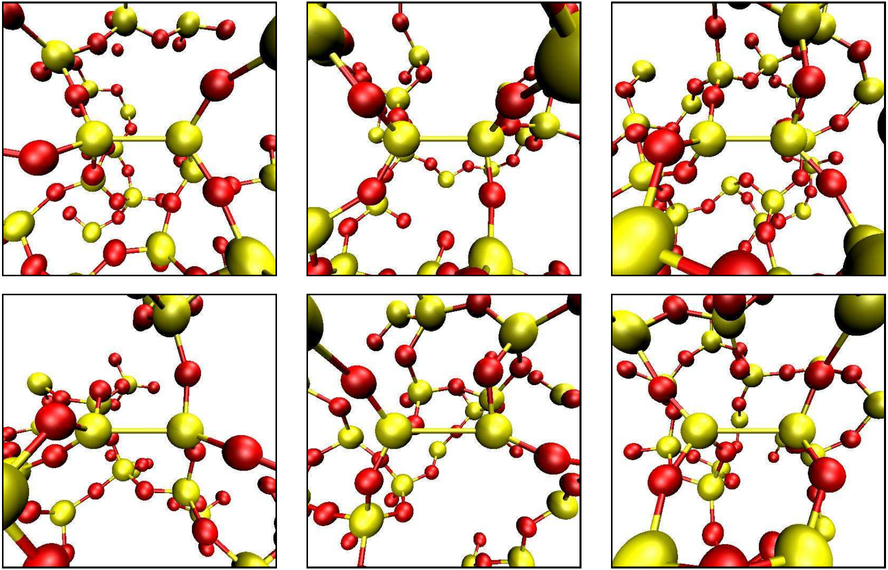






Amorphous Oxide

All defects are different

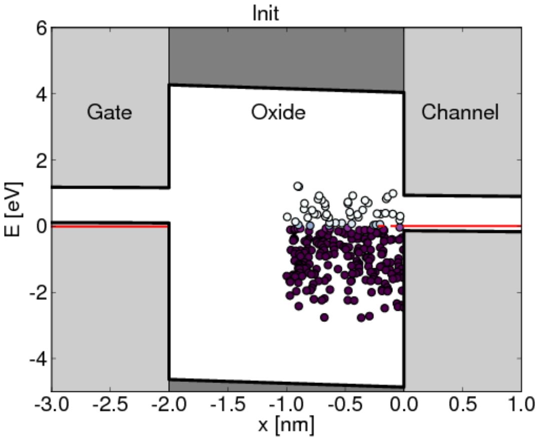


Charging of a Large Number of Defects

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

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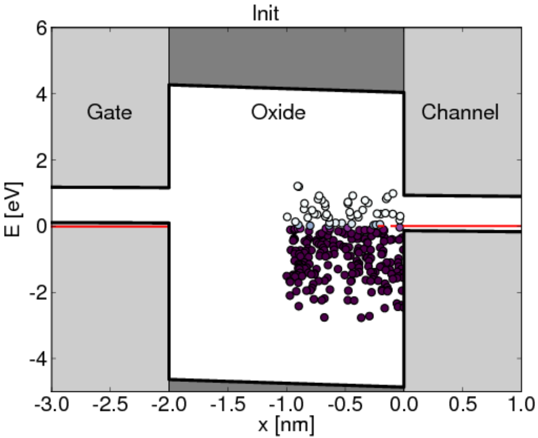


[1] See detailed RTN study of Nagumo *et al.*, IEDM '10

Field-Dependence

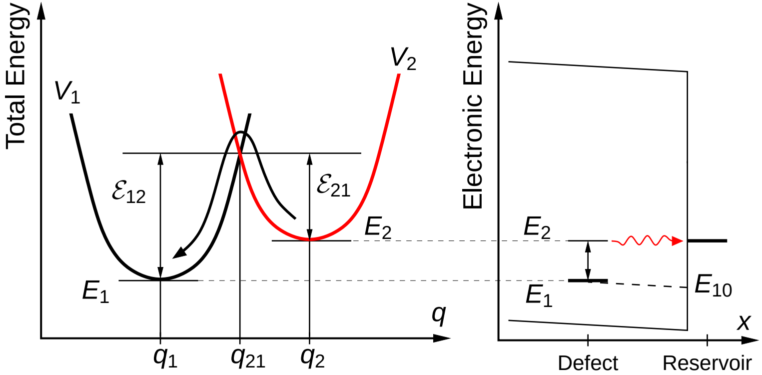
What is the meaning of the electronic energy levels?

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

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

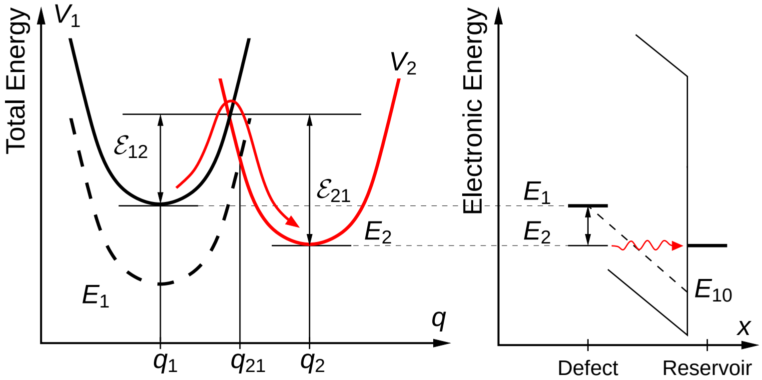


Field-Dependence

$E_{21} = E_2 - E_1$ depends linearly on F

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

Application of a field reduces $\mathcal{E}_{12}$ and increases $\mathcal{E}_{21}$
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 p

Above V_{th}, weak bias dependence of p

Weak bias dependence of the (complete) WKB factor

The vibrational matrix element

Depends on the electric field F

$$\exp(-\beta\mathcal{E}_{12}) = \exp\left(-\beta\left(\frac{(E_R + E_{20} - E_{10} - \mathrm{q}xF)^2}{4E_R}\right)\right)$$

Below V_{th}, weak bias dependence of F

Above V_{th}, exponential bias dependence

$\Rightarrow$ the vibrational properties dominate the bias-dependence

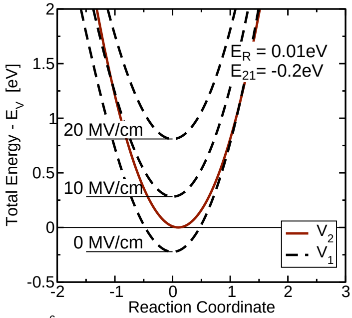
Bias Dependence: Weak Coupling

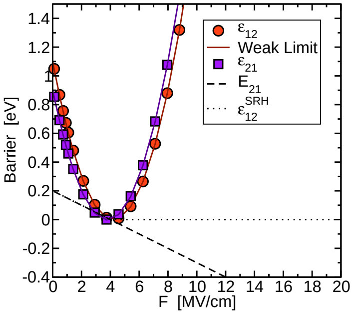
Weak-coupling limit

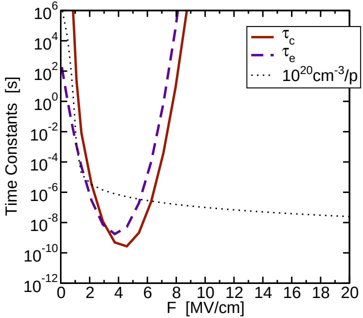
$$E_R \ll E_{20} - E_{10} - qxF$$

Quadratic field-dependence

$$\mathcal{E}_{12} = \frac{(E_R + E_{21})^2}{4E_R} \approx \frac{E_{21}^2}{4E_R} + \frac{1}{2}E_{21}$$



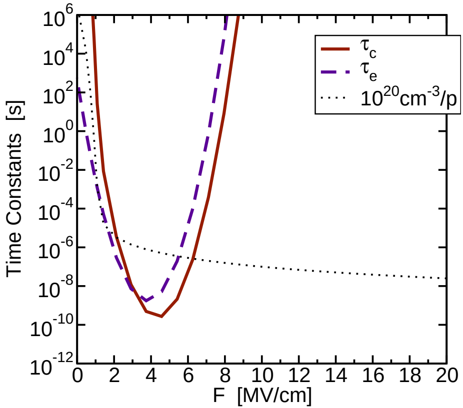


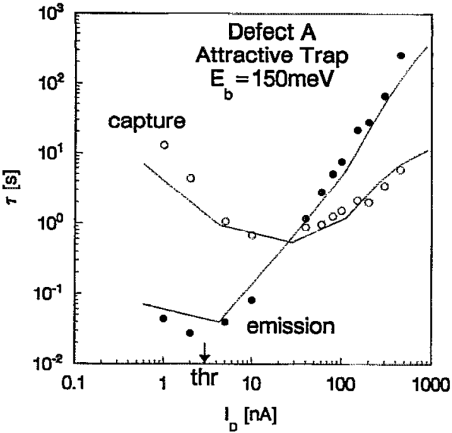


Bias Dependence: Weak Coupling

Crazy trap?

Well, something like this has been reported[1]





[1] Schulz, JAP '93

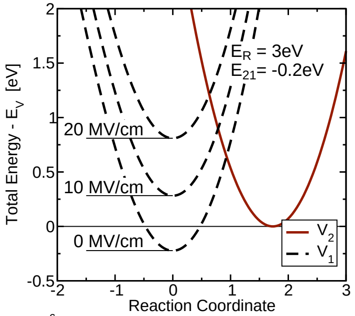
Bias Dependence: Strong Coupling

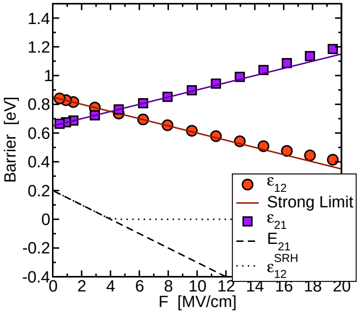
Strong-coupling limit

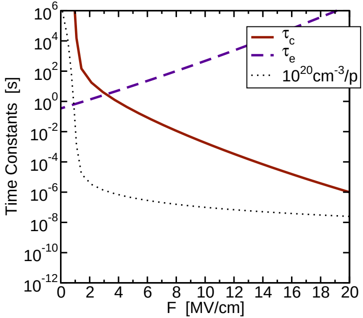
$$E_\mathrm{R} \gg E_{20} - E_{10} - \mathrm{q}xF$$

Linear field-dependence

$$\mathcal{E}_{12} = \frac{(E_\mathrm{R} + E_{21})^2}{4E_\mathrm{R}} \approx \frac{E_\mathrm{R}}{4} + \frac{E_{21}}{2}$$



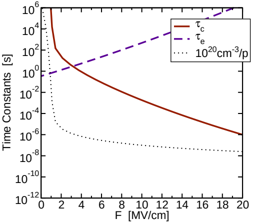




Bias Dependence: Strong Coupling

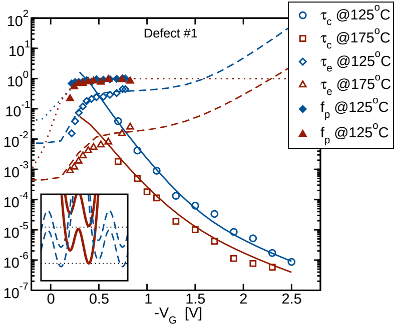
Compare the bias dependence to experimental data[1]

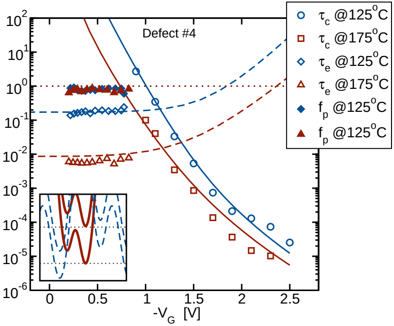
Model: τ_c and τ_e are symmetric
Data: τ_e can be flat/sudden drop
Model: τ_c is nearly linear in F
Data: τ_c has curvature



Reason

Metastable defect states



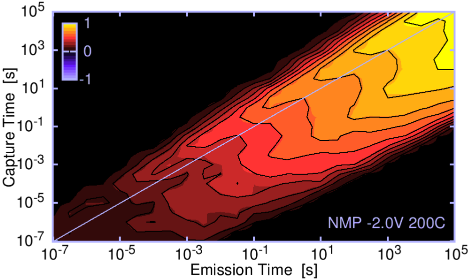


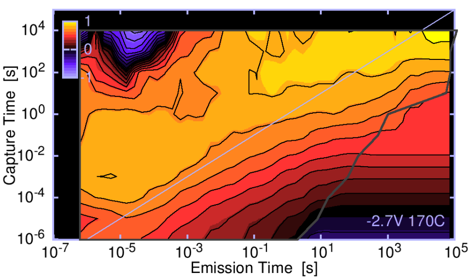
[1] Grasser *et al.*, IRPS '10

Problems with the Simple NMP Model

Model captures the 'essence', important details missing

- Symmetric τ_c and τ_e (linear electron-phonon coupling)
- Cannot describe the rapid drop of τ_e below V_{th}
- Nearly linear F dependence of τ_c
- No full decorrelation between τ_c and τ_e possible

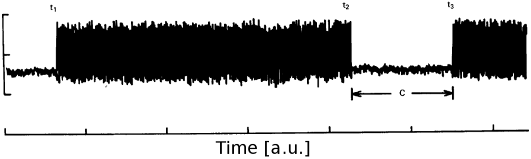




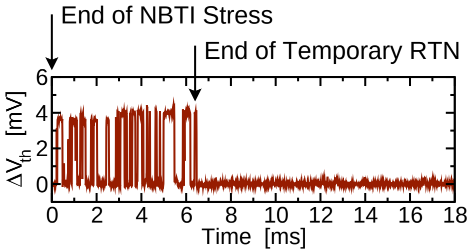
Reminder: Metastable States

Defects can have more than two states

Anomalous RTN, where RTN is turned on/off[1]



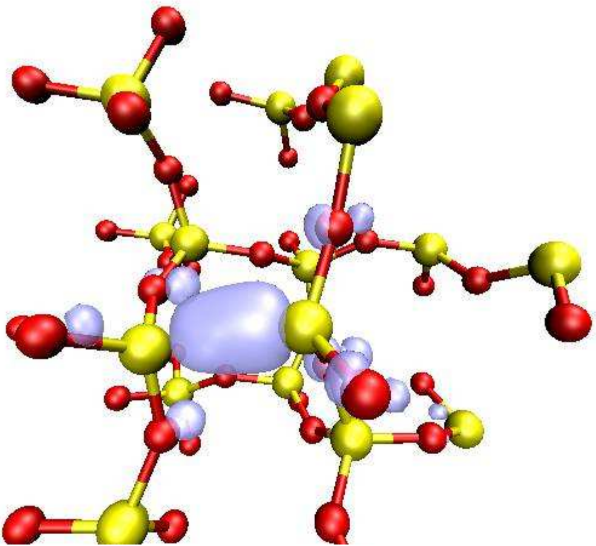
Temporary RTN following NBTI stress[2]

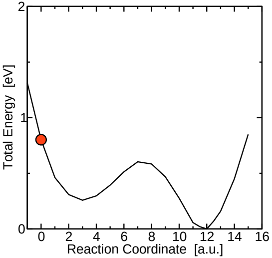


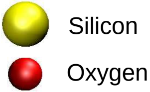
[1] Uren *et al.*, PRB ’88

[2] Grasser *et al.*, IRPS ’10 and PRB ’10

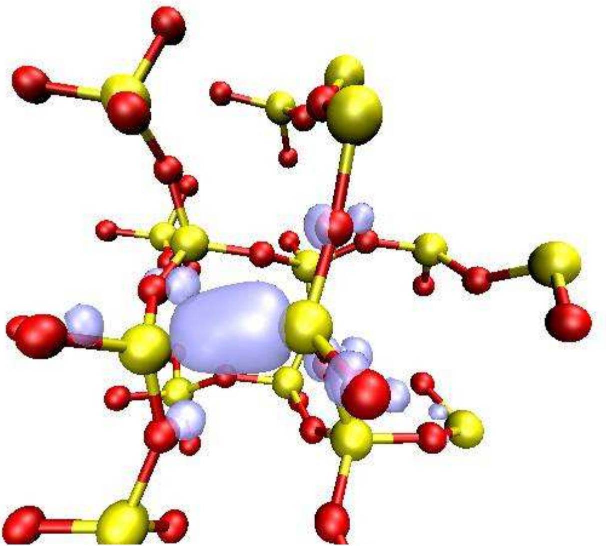
Metastable States: Puckering of an E' Center

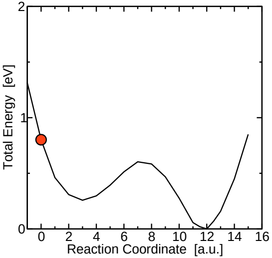


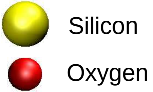




Metastable States: Puckering of an E' Center



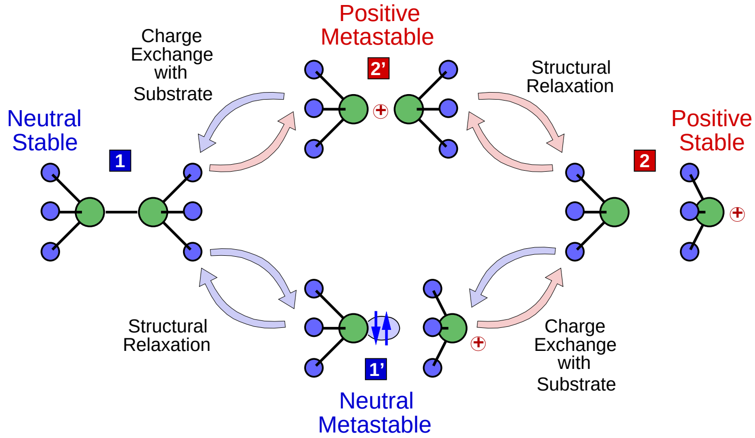




Improved Defect Model: Metastable States

Defect model must include metastable states

- RTN: anomalous RTN, curvature in τ_c, flat vs. drop in τ_e
- BTI: temporary RTN, bias-dependence of recovery
- Pre- and post-stress f/T dependence/hysteresis of I_{CP}[1]



[1] Hehenberger *et al.*, IRPS '09; Grasser *et al.*, IRPS '11

Charge Trapping vs. Defect Generation

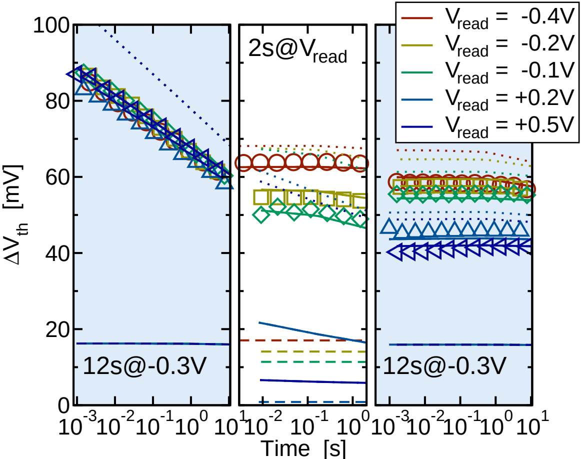
Switching traps have a density of states in the bandgap

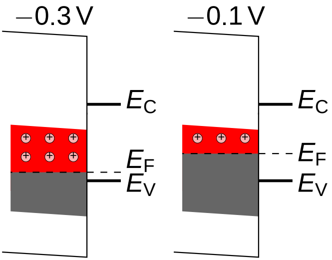
$\Rightarrow$ React to changes in V_{read}

Trapped charges couldn't be bothered

Switching traps recover faster under more positive bias

Trapped charges couldn't be bothered





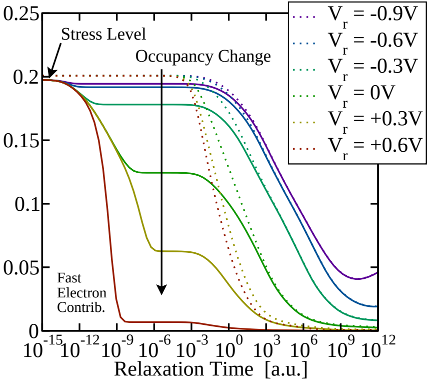
Charge Trapping vs. Defect Generation

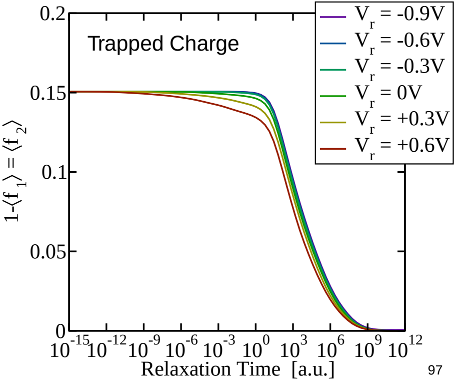
Switching traps have a density of states in the bandgap

- React to changes in V_{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_{read}
- Cause a rigid shift of the $I_D - V_G$ curves

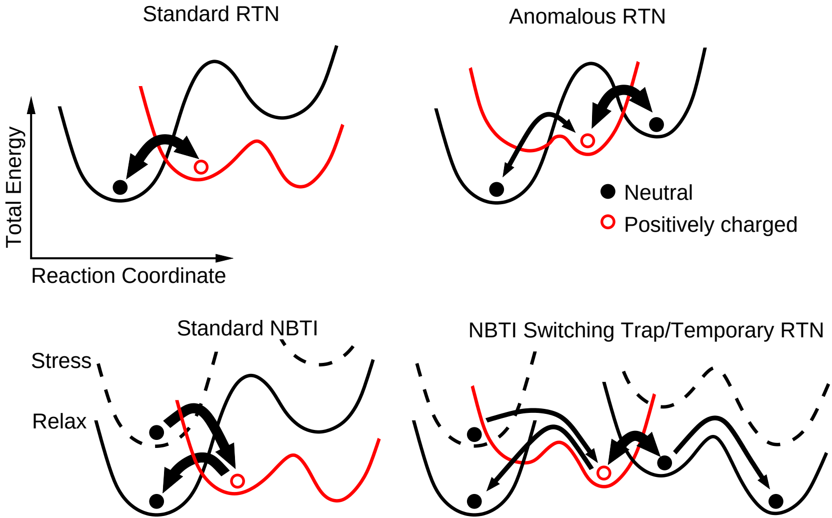




Model Summary

All features can be explained with a general defect model

Different defect potentials in the amorphous oxide



Outline

Motivation

Fundamentals of Stochastic Processes

Experimental Determination of the Capture and Emission Times

Distribution of the Capture and Emission Times

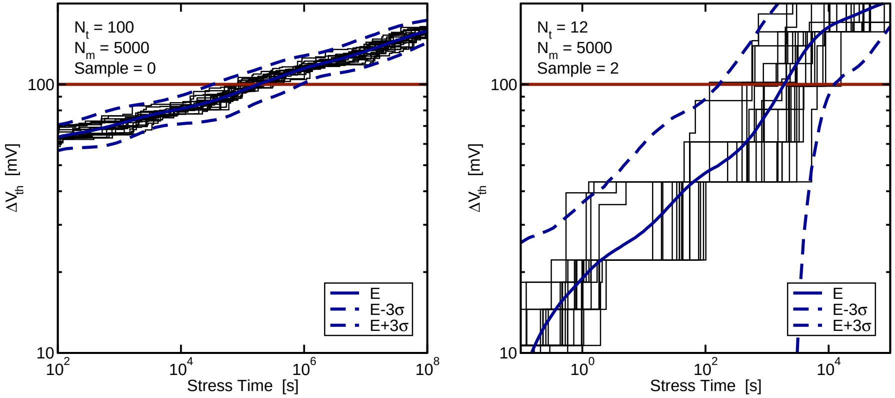
Physical Models for the Capture and Emission Times

Stochastic BTI

Stochastic Lifetimes

Small area devices: lifetime is a stochastic quantity[1]

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



[1] Rauch, TDMR ’07; Kaczer *et al.*, IRPS ’10; Grasser *et al.*, IEDM ’10

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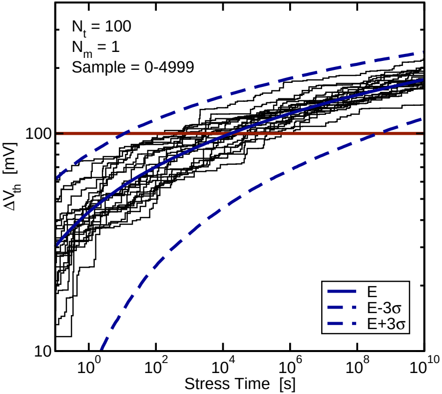
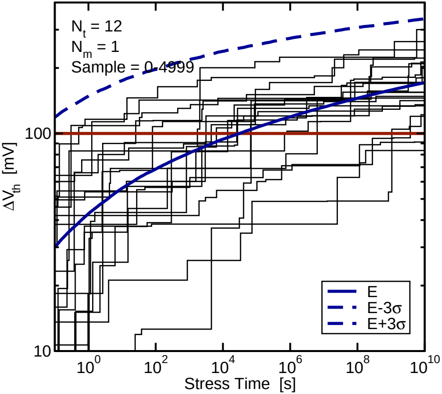


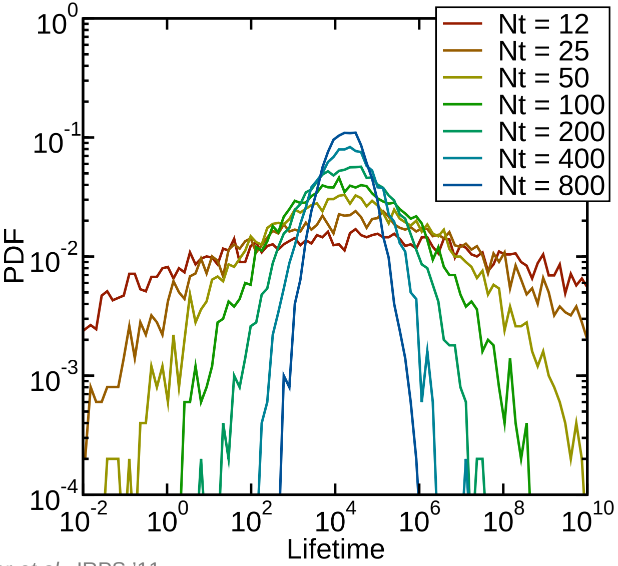


[1] Kaczer *et al.*, IRPS ’10; Grasser *et al.*, IEDM ’10

Stochastic Lifetimes

Distribution of lifetime[1]

Variance increases with decreasing number of defects

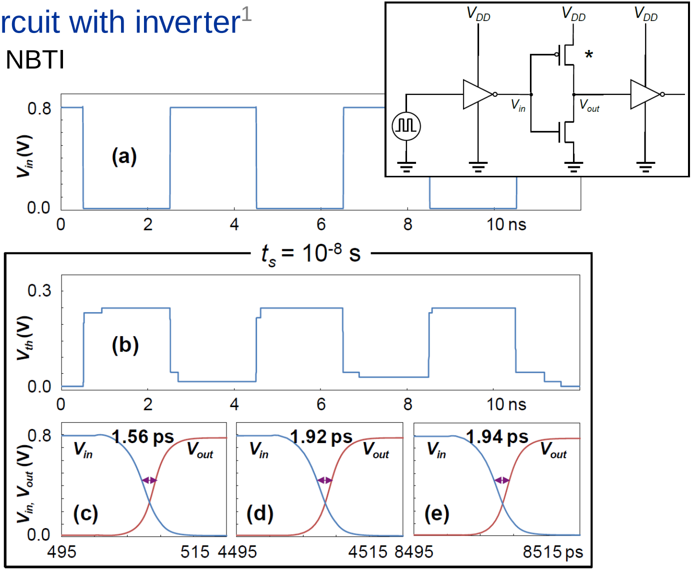


[1] Kaczer *et al.*, IRPS '11

Stochastic Impact on Circuit

Example circuit with inverter[1]

Jitter vs. NBTI



[1] Kaczer *et al.*, IRPS '11

Stochastic Impact on Circuit

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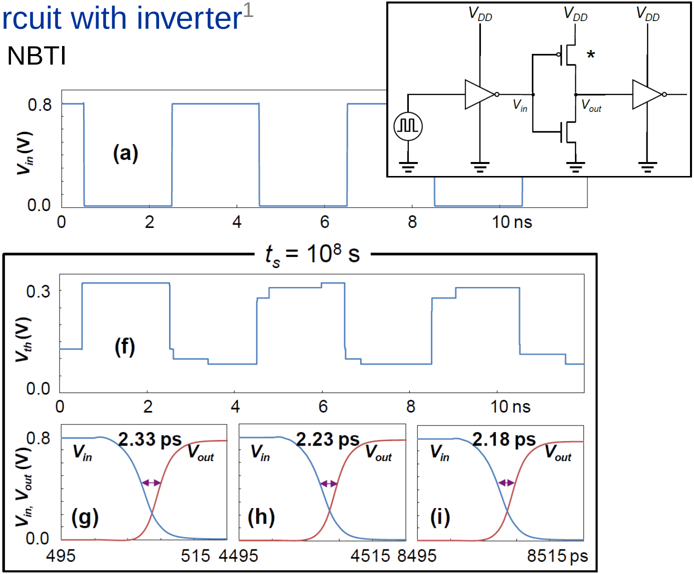

[1] Kaczer *et al.*, IRPS '11

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