Cause, Detection, and Impact of Charge Trapping on Aging

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An electronic version of this presentation containing all animations is available at
http://www.iue.tuwien.ac.at/pdf/ib_2011/VLSI_Grasser_2011.pdf

Idealized Aging Mechanisms

In order to characterize degradation, stress is accelerated

Idealized stress conditions are defined

Time-dependent dielectric breakdown (TDDB)

Very large gate voltages $\Rightarrow$ oxide loses insulating property

Bias temperature instability (BTI)

S/D grounded, elevated temperature

pMOS: $-V_G \Rightarrow$ NBTI

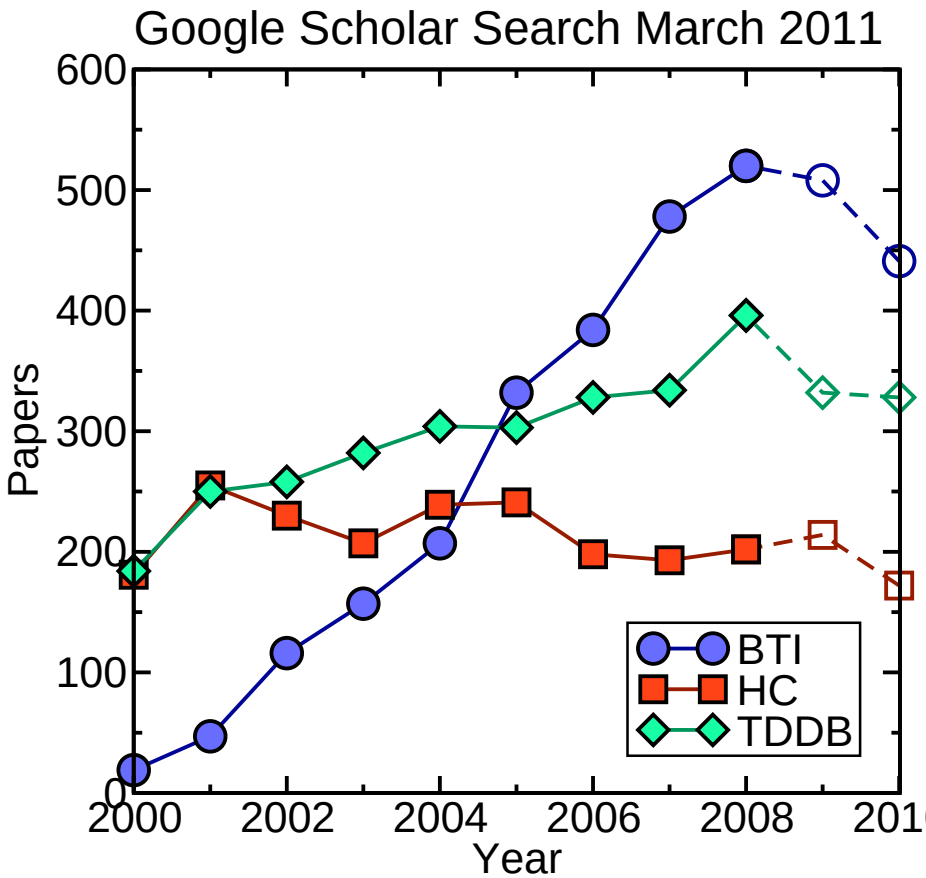
nMOS: $+V_G \Rightarrow$ PBTI (mostly high-κ)

Hot carrier (HC) degradation

Current flow between S/D

Circuit:

All of the above in a mixed form!



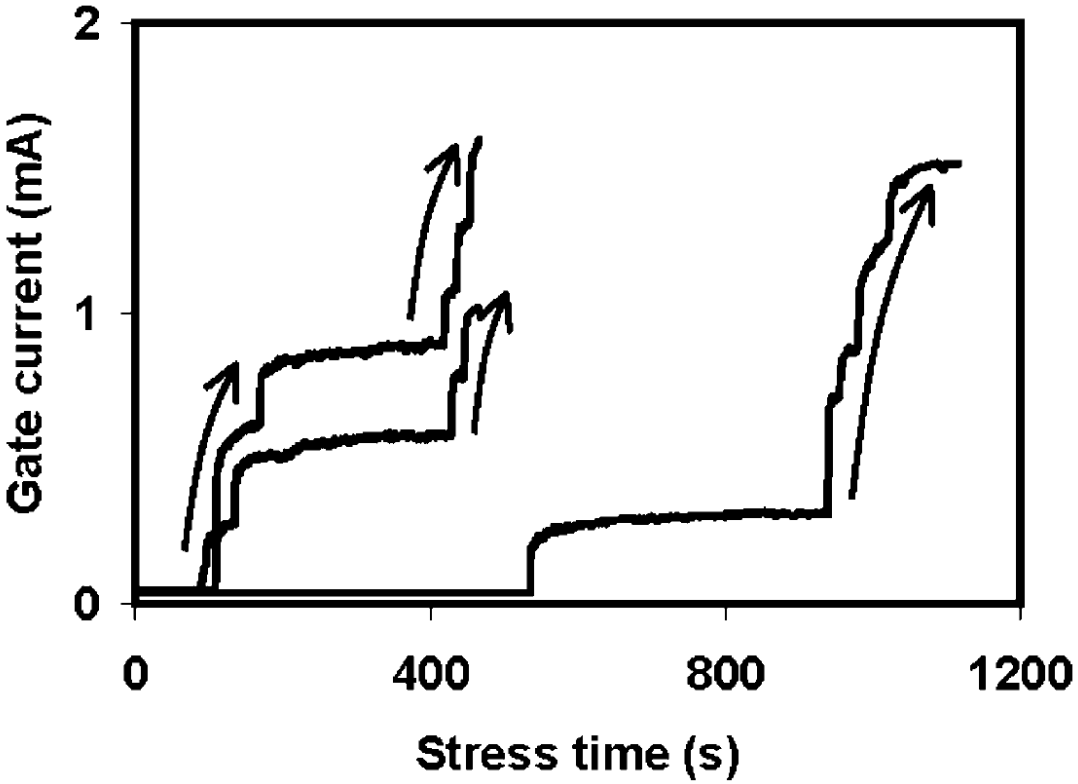
Time Dependent Dielectric Breakdown

Very large voltages applied to the gate

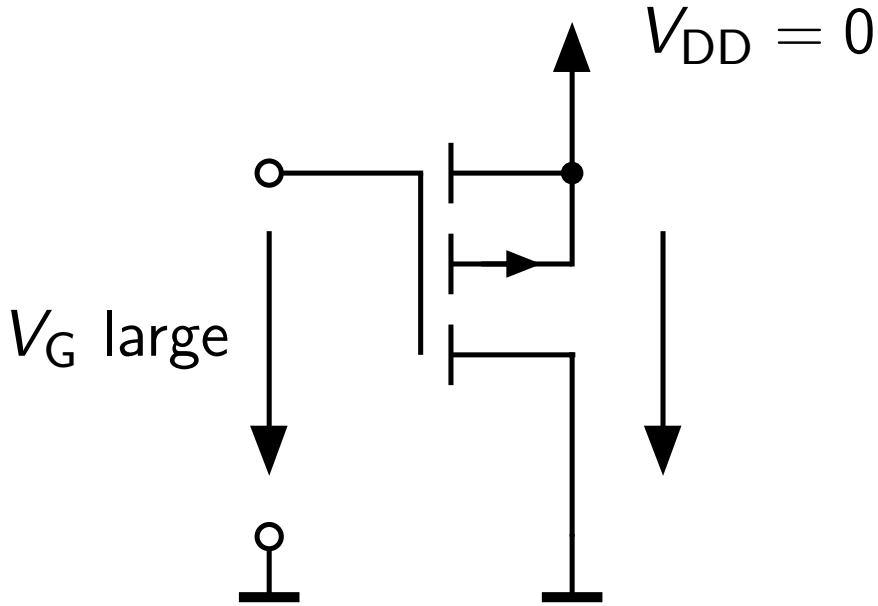
- Larger than about 10 MV/cm
- All other terminals grounded

Cause of degradation: creation of defects (conducting paths in the oxide)

- Oxide loses insulating property
- Soft and hard breakdowns



[Sune *et al.*, T-ED '04]



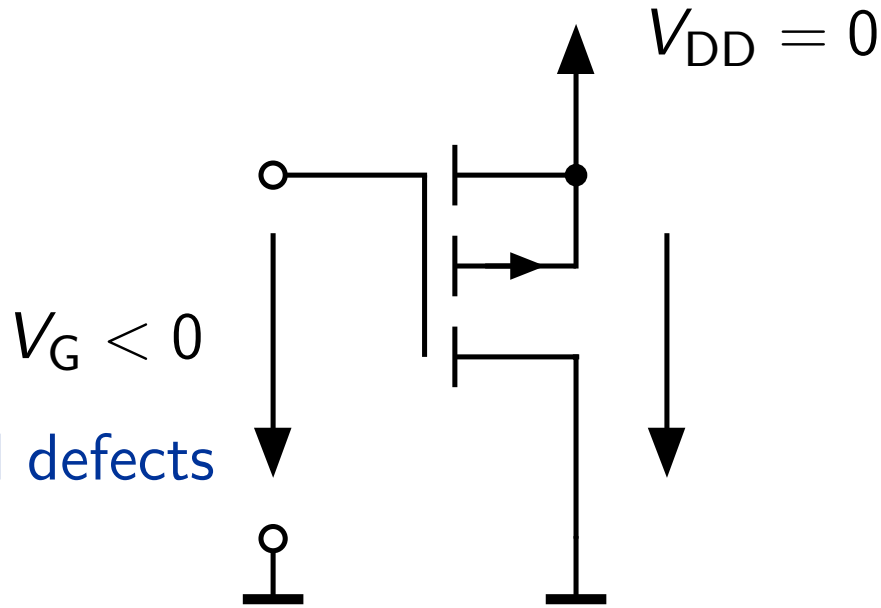
The Negative Bias Temperature Instability

Large negative voltage applied to the gate of a PMOS (NBTI)

- Larger than about 4 MV/cm
- All other terminals grounded

Elevated temperatures (NBTI)

- Typically 125 °C



Cause of degradation: oxide charges and defects

- Drift of V_{th}, g_m, etc.

Degradation occurs in all four configurations

- NMOS/PMOS
- Negative and positive stress voltages
- NBTI in PMOS most important
- In high-k NMOSFETs, PBTI equally important

Note:

- Degradation occurs also at room temperature and voltages slightly larger than V_{th}

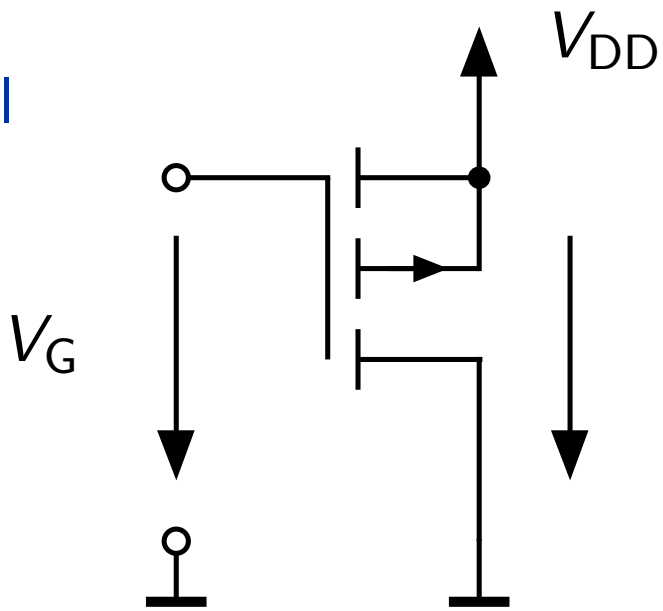
Hot Carrier Degradation

Voltages applied to both gate and drain

Like BTI, but with current flow from S/D

Carriers become 'hot' as they traverse the channel

Excess energy can create defects at drain side



Cause of degradation: oxide charges and defects

Drift of V_{th}, g_m, etc.

Very similar to BTI, except:

Inhomogeneous degradation at the drain side

Degradation does not recover that well

Degradation typ. becomes weaker with increasing T

NBTI vs. HC Degradation

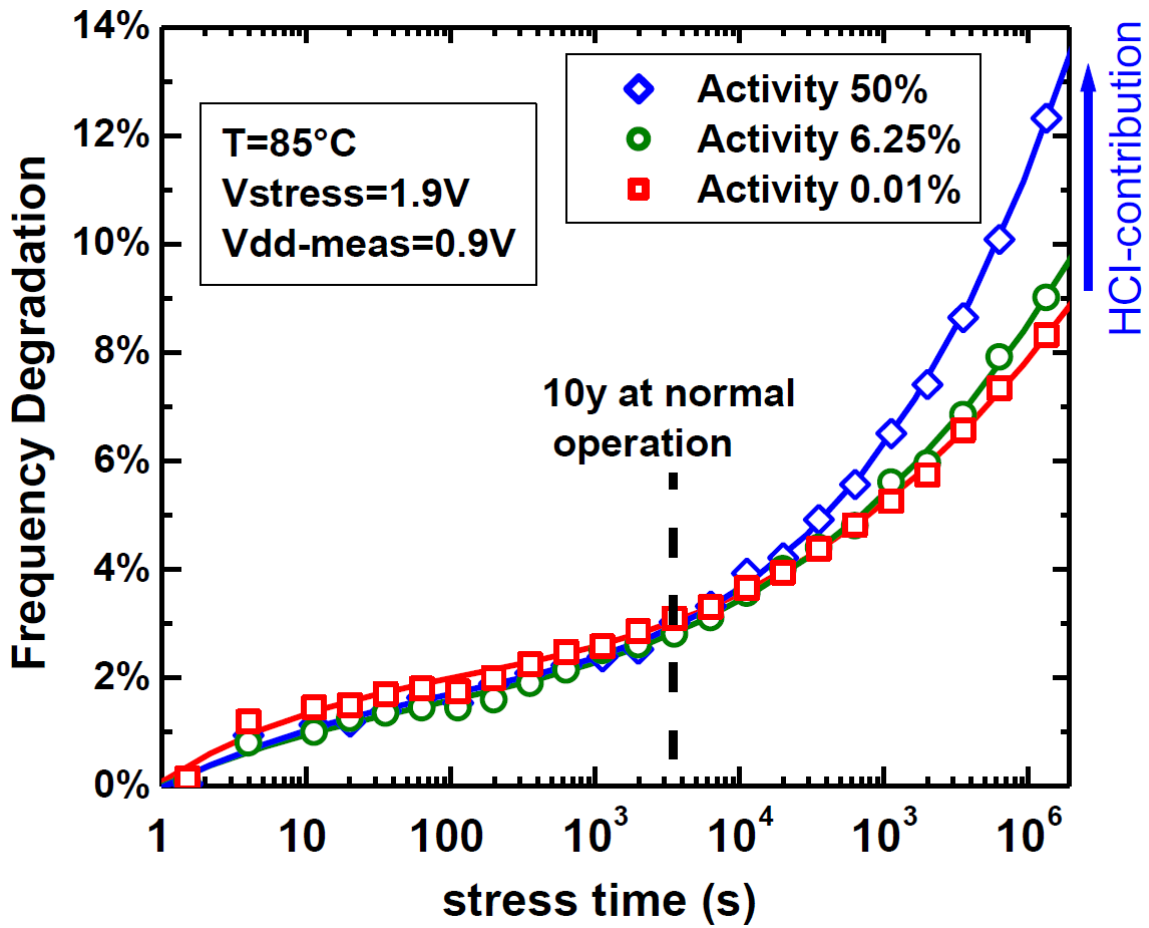
In a circuit NBTI and HC degradation can occur simultaneously

Separation using modified ring-oscillators[1]

- Feedback interruptable by control circuitry
- Allows separation of BTI and HCI
- Activity 50%: BTI + HCI
- Activity 0.01%: Almost static BTI

At normal operating conditions

- Degradation NBTI dominated
- At least for combinatorial logic



[1] Hofmann *et al.*, VLSI Symp. '10

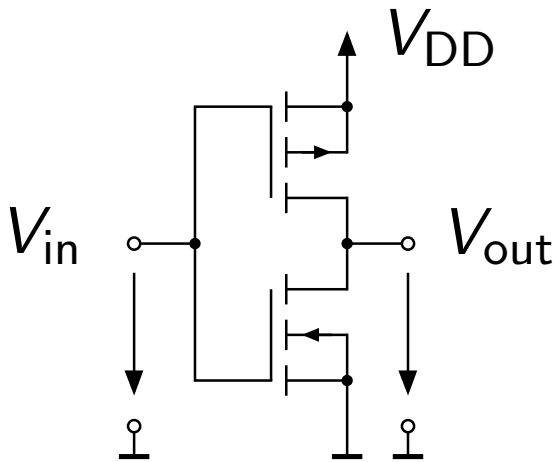
The Negative Bias Temperature Instability

When does the NBTI scenario occur?

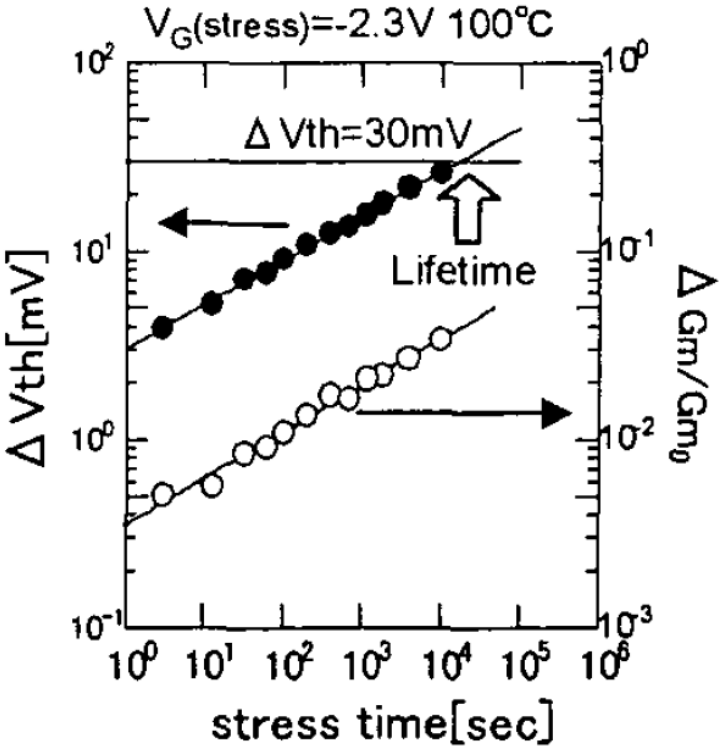
NBTI: $V_G \ll 0\,\mathrm{V}$, $V_S = V_D = 0\,\mathrm{V}$

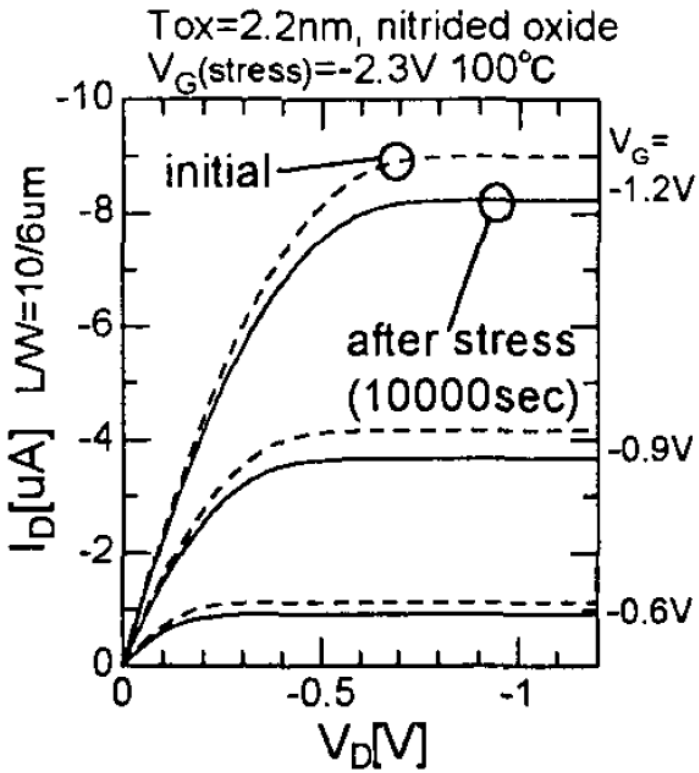
Example: inverter with $V_{in} = 0\,\mathrm{V}$

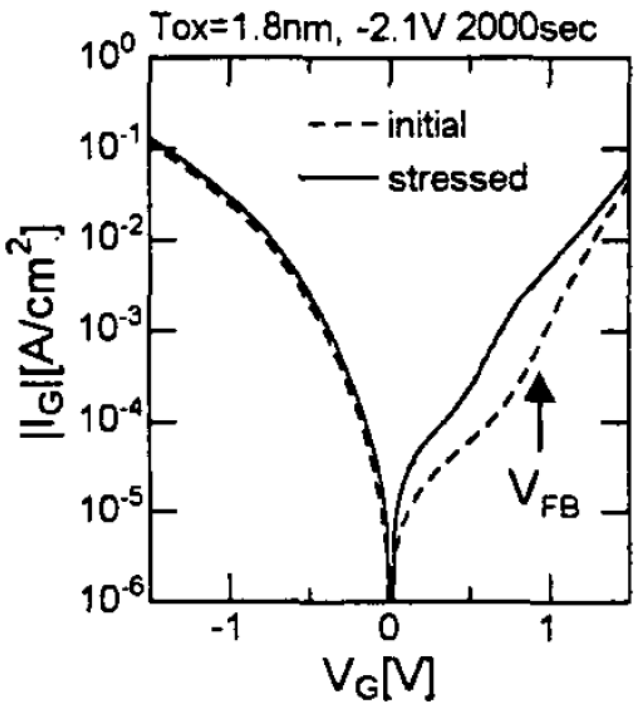
Similar scenarios in ring-oscillators, SRAM cells, etc.



What happens to the pMOS transistor?







Kimizuka *et al.*, VLSI Symp. '00

Conventional NBTI Model

Most popularized model for NBTI

Reaction-diffusion theory

Stress

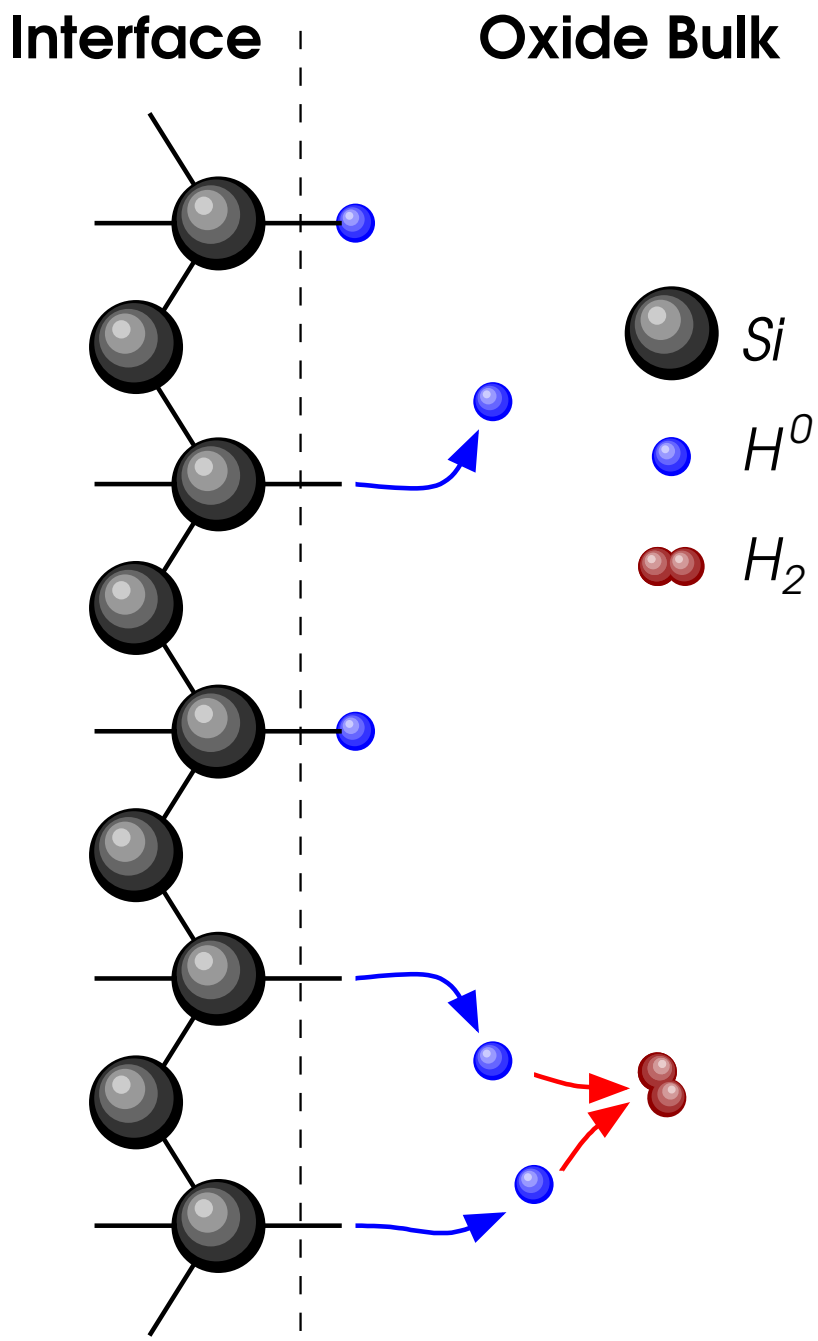
Si–H breaks

Creation of Si–$^{\bullet}$

H diffuses away

2 H form H_2

H_2 diffusion controls kinetics



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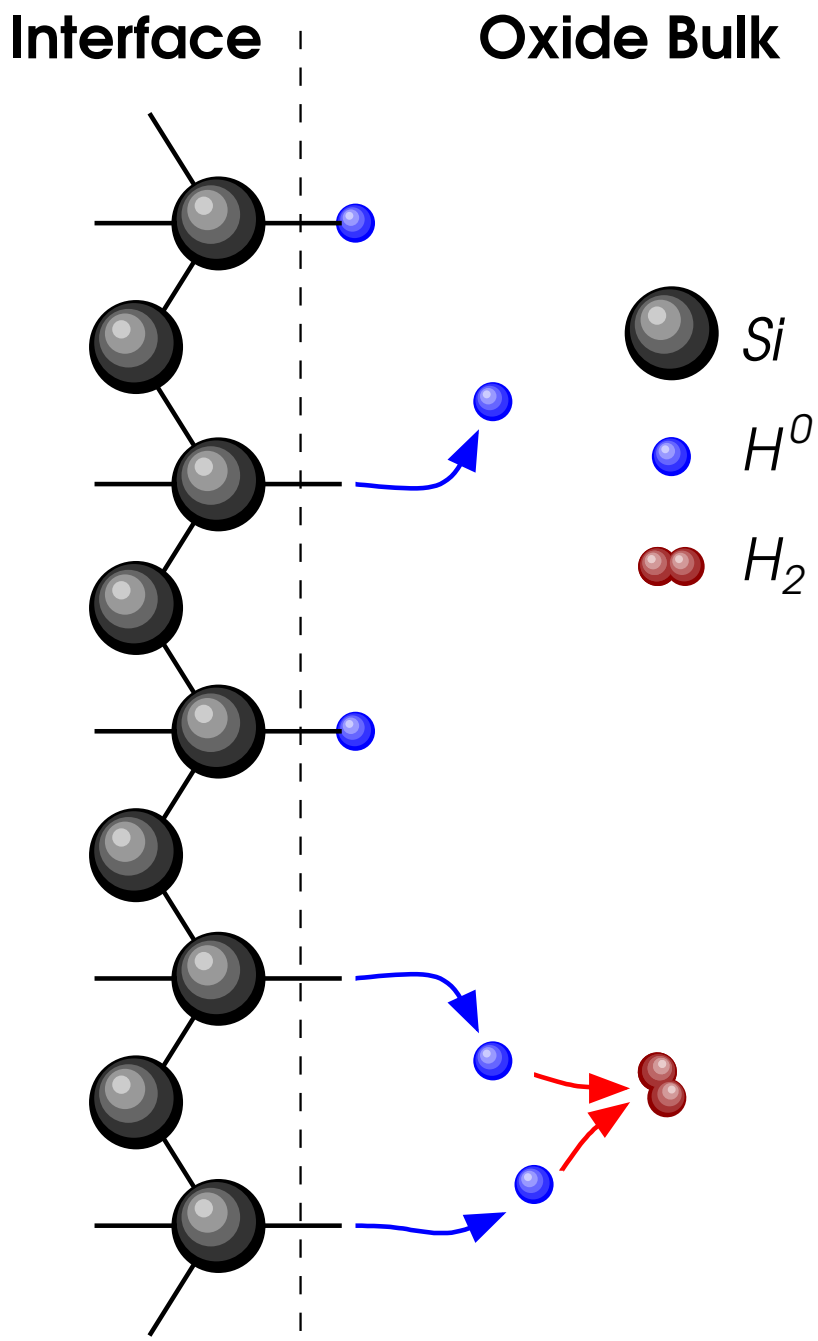
Recovery

H_2 repassivates Si–•

H_2 back-diffusion controls kinetics



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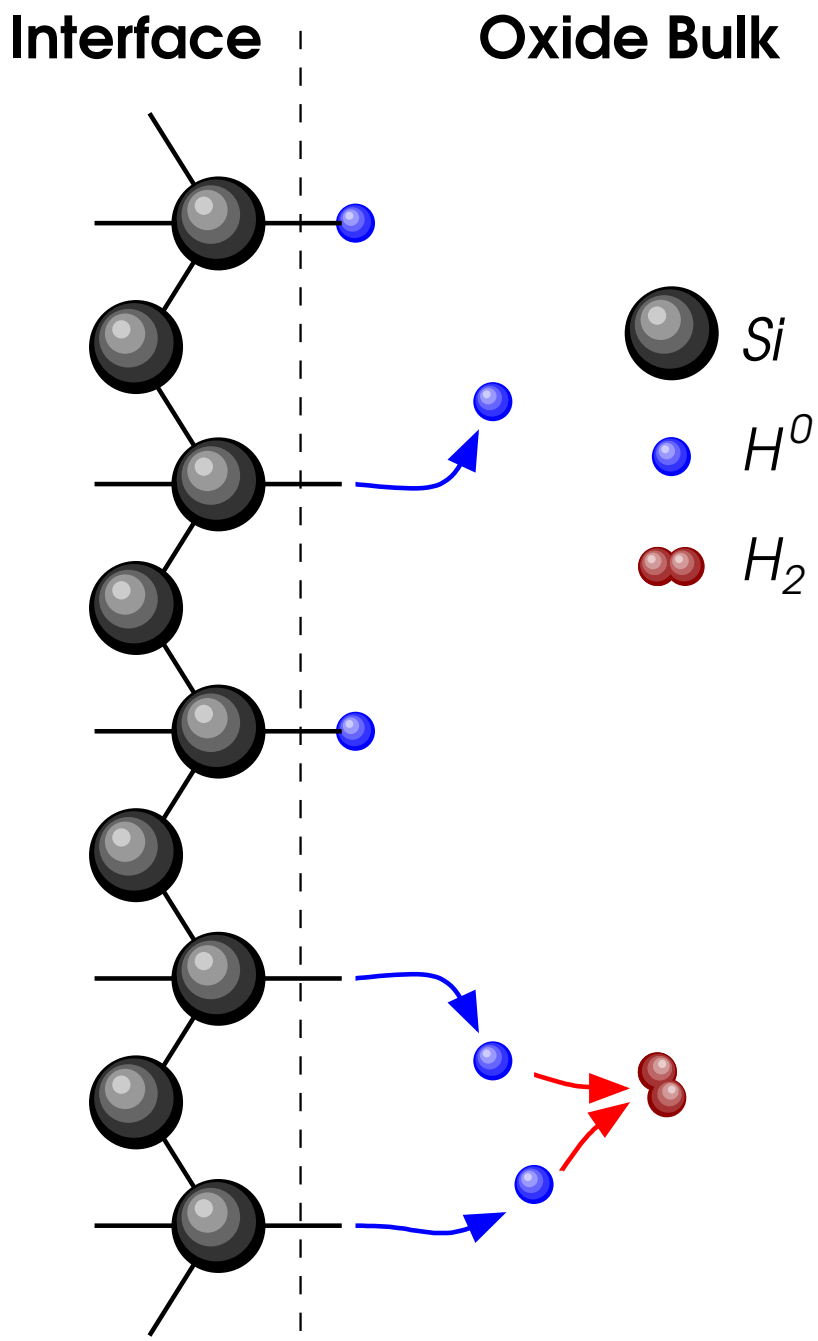
Hole trapping

Obscures data up to 1 s

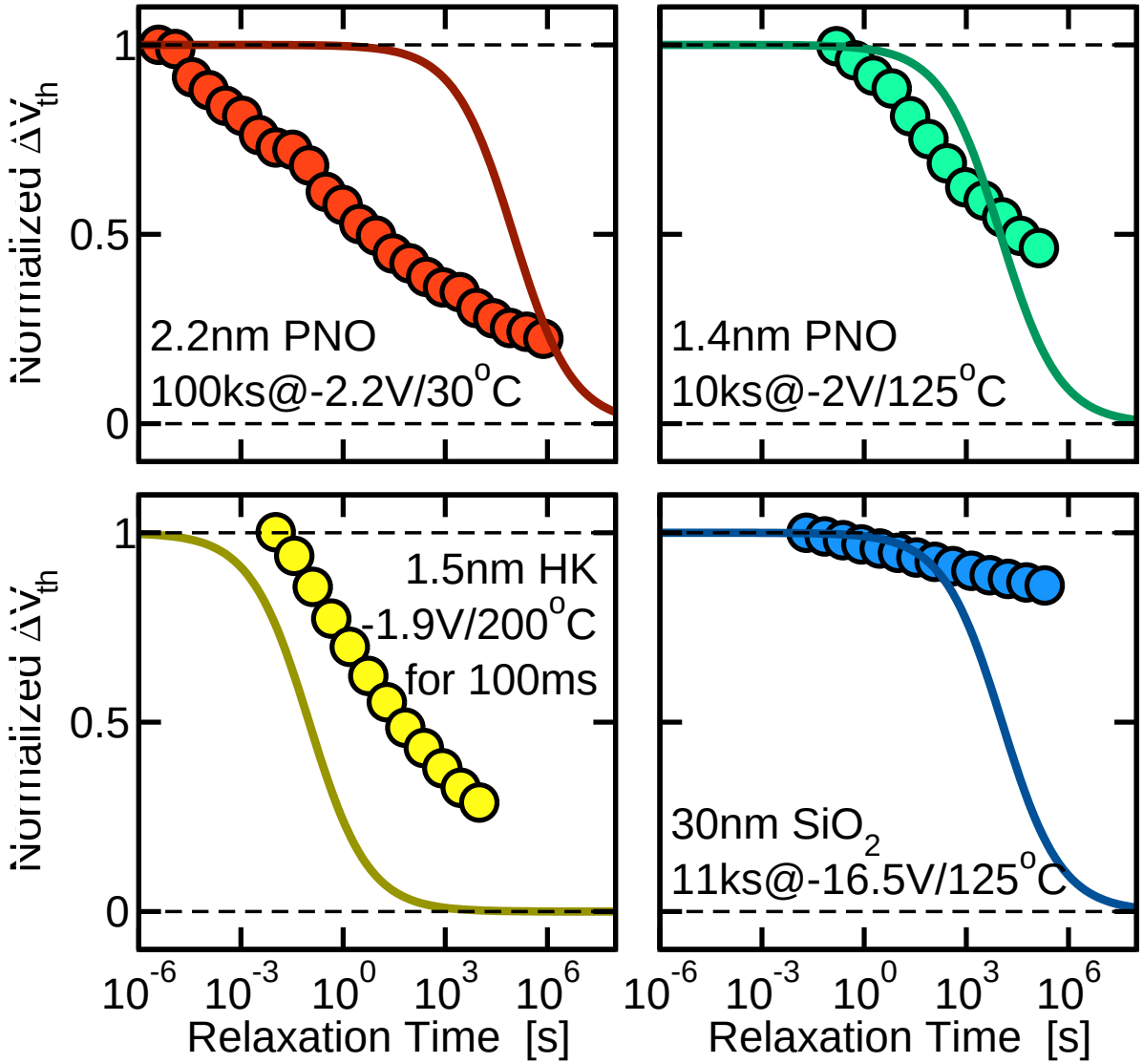
Has to be 'subtracted'



Conventional NBTI Model

Reaction-diffusion (RD) theory

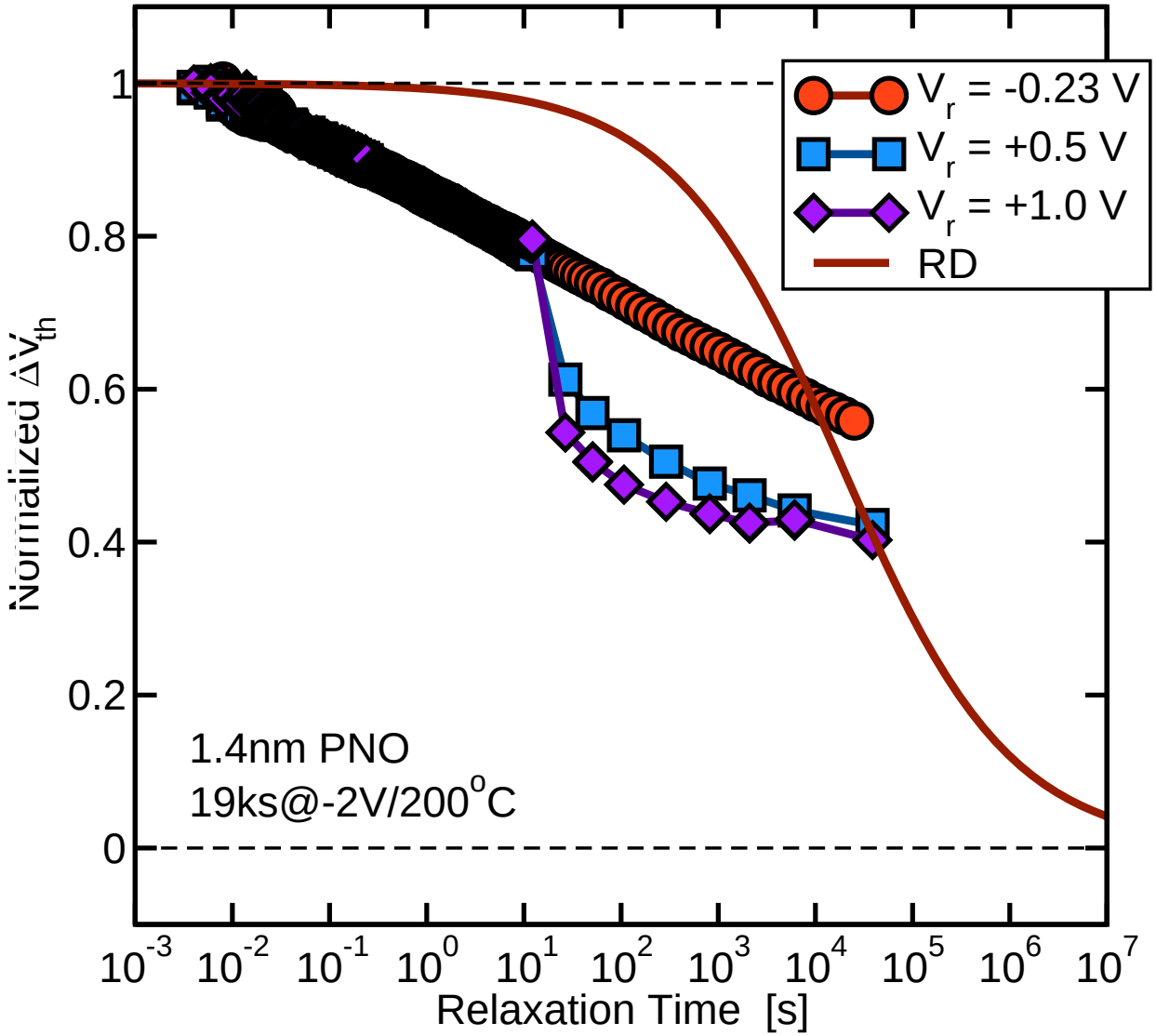
Problem #1: cannot reproduce recovery



Conventional NBTI Model

Reaction-diffusion (RD) theory

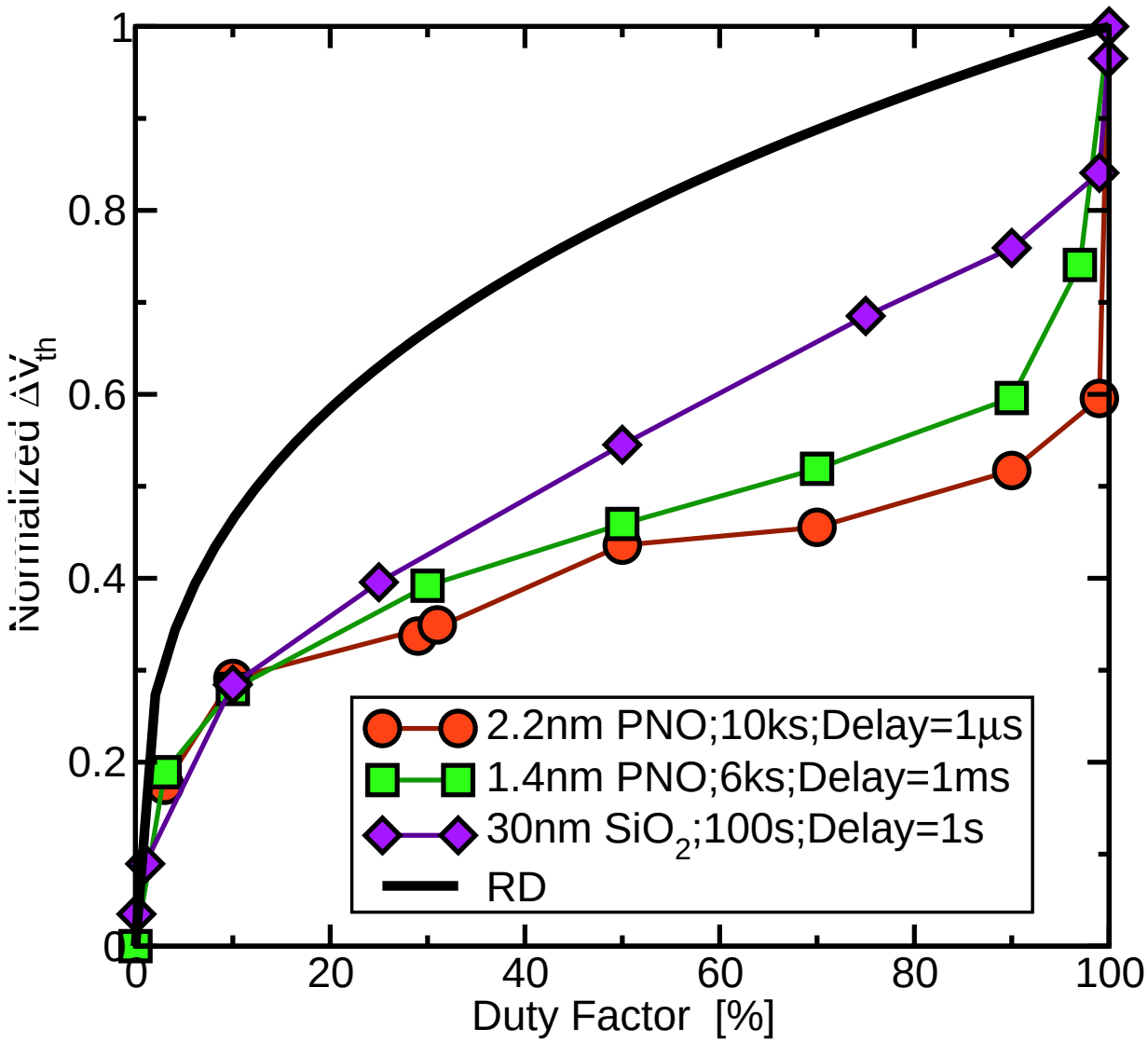
Problem #2: long-time recovery is due to back-diffusion of neutral H_2



Conventional NBTI Model

Reaction-diffusion (RD) theory

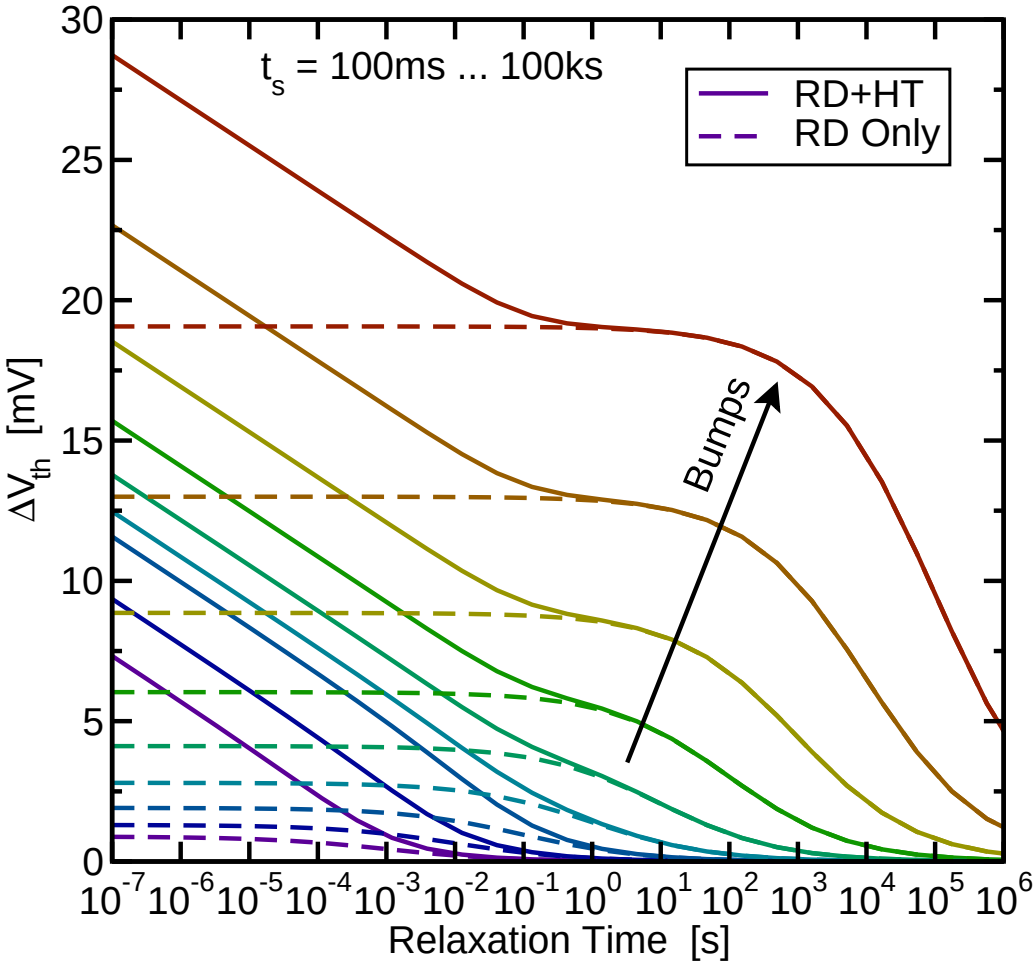
Problem #3: Duty-factor (DF) dependence nearly constant for DF $\rightarrow$ 100%

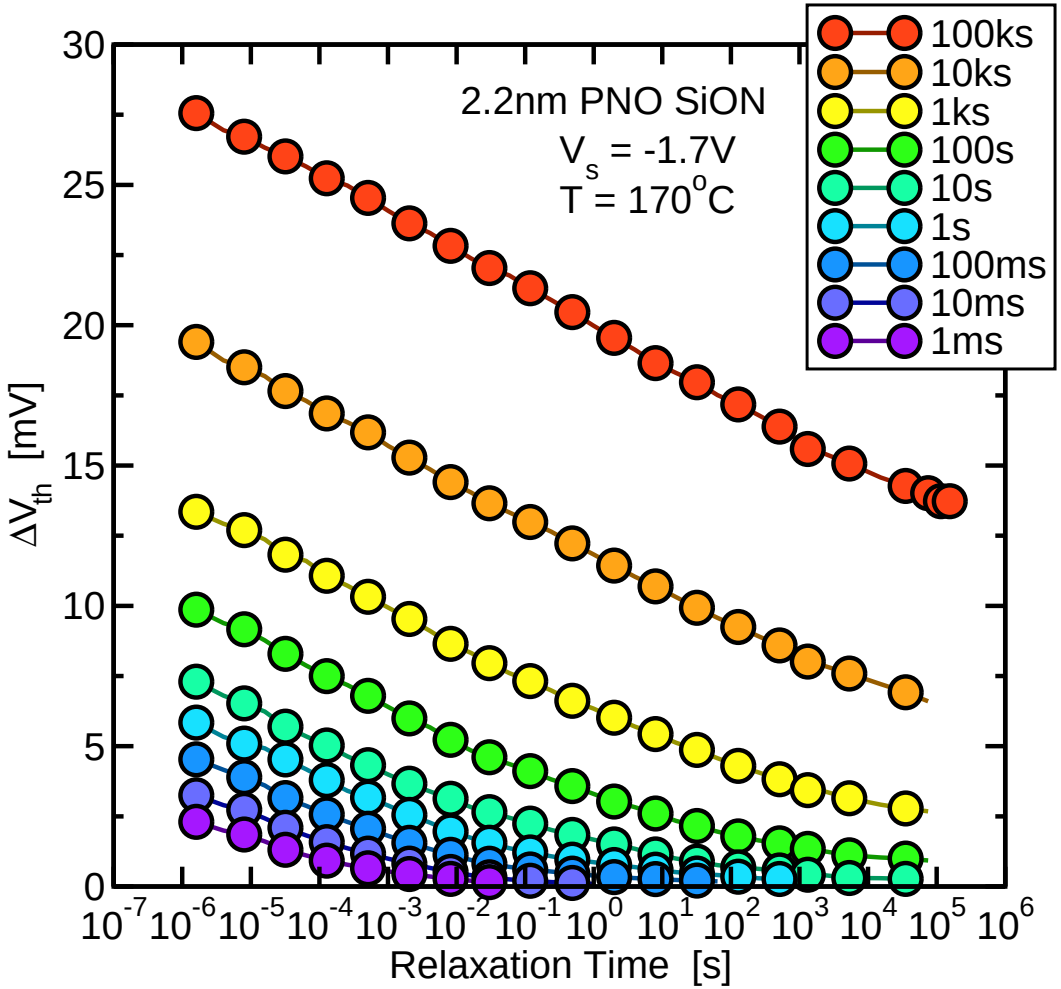


Conventional NBTI Model

Reaction-diffusion (RD) theory

Problem #4: elastic hole trapping (HT) cannot fix recovery





Overview

Introduction

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

New measurement technique

The time dependent defect spectroscopy

Anomalous defect behavior

Present in all defects

Stochastic model

Additional metastable states, multiphonon theory

Implications

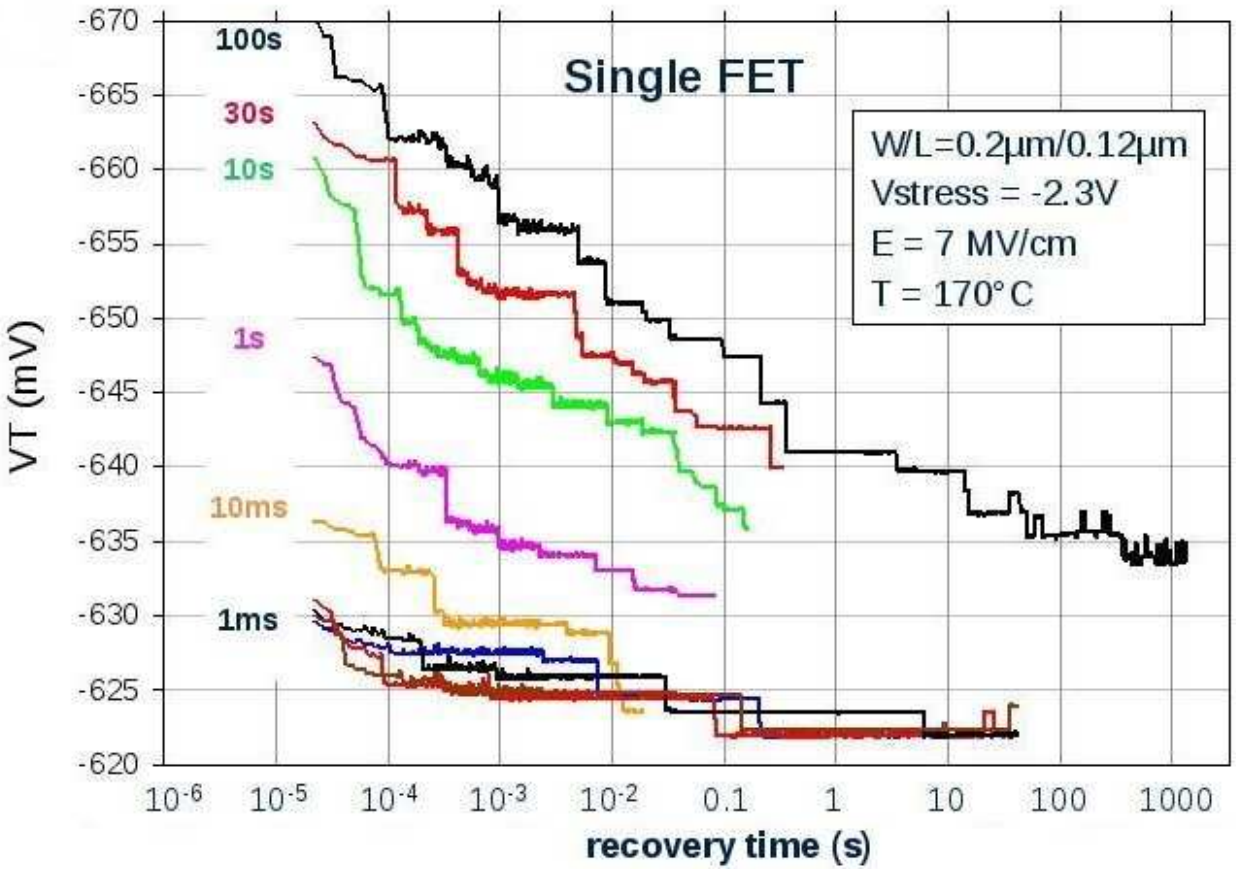
Lifetime of nanoscale MOSFETs

Conclusions

What is Really Going On?

Study of NBTI recovery on small-area devices [1] [2] [3] [4] [5]

Stochastic and discrete charge emission events, no diffusion



[1] Reisinger *et al.*, IIRW '09 [2] Grasser *et al.*, IEDM '09 [3] Kaczer *et al.*, IRPS '10 [4] Grasser *et al.*, IRPS '10
[5] Reisinger *et al.*, IRPS '10

Recoverable NBTI due to the same Defects as RTN

Quasi-equilibrium:

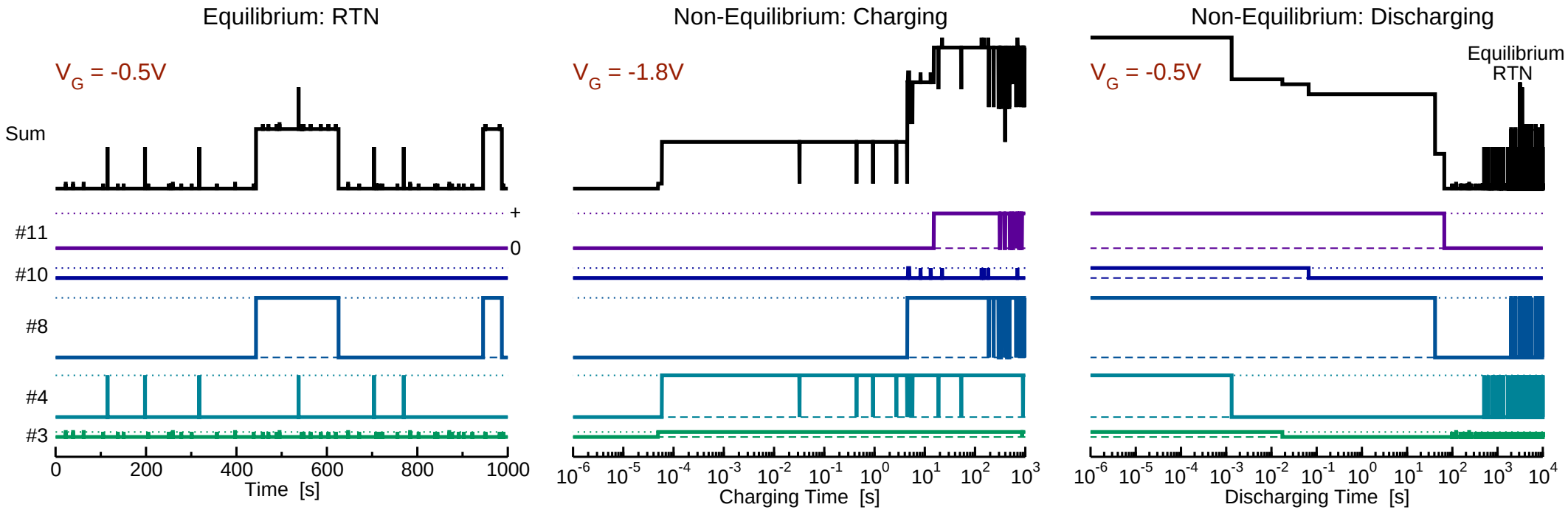
Some defects neutral, others positive, a few produce random telegraph noise (RTN)

Stress:

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

Recovery:

Slow transition (broad distribution of timescales) to initial quasi-equilibrium



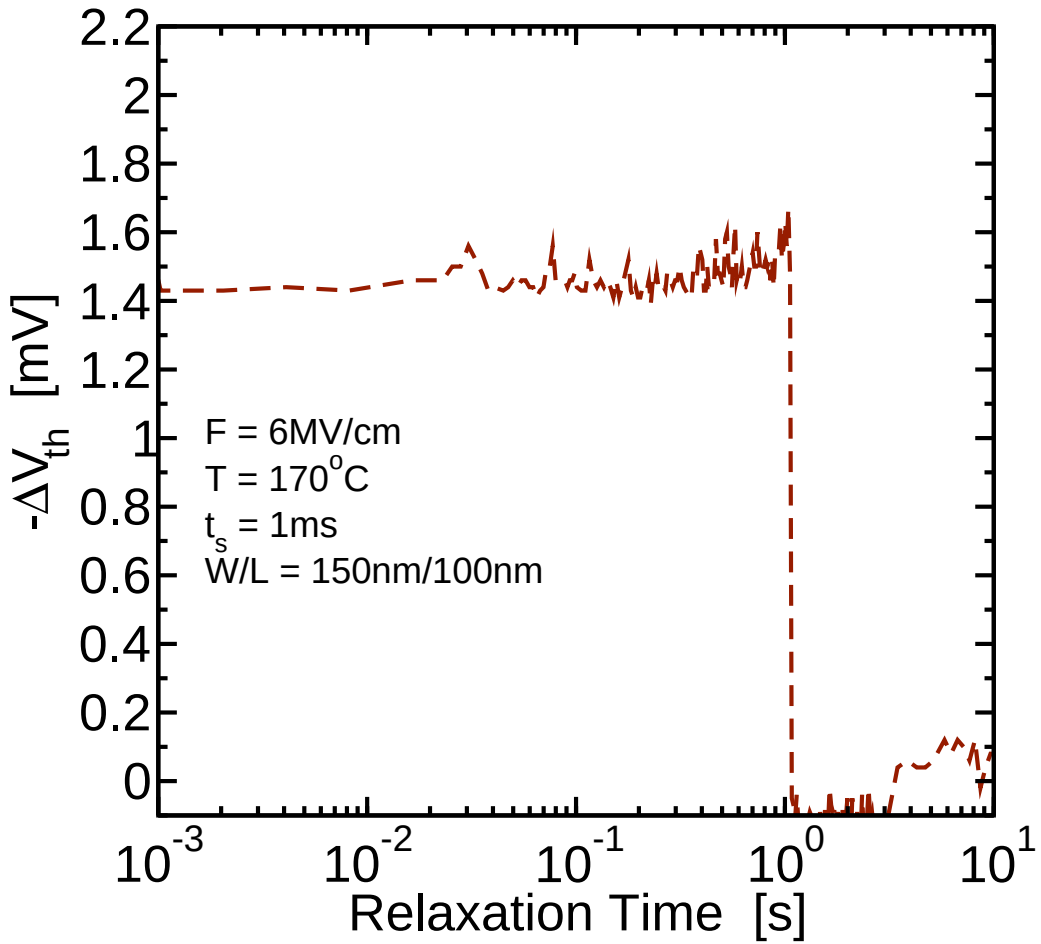
Experimental Results

Short stress may activate only a single defect

Defect initially only charged with 30%, $1 - \exp(-t_s/\tau_c) = 0.3 \;\Rightarrow\; \tau_c \gtrsim 3\,\text{ms}$

Defect discharges around $\tau_e = 4\,\text{s}$

Averaging results in the expected $\exp(-t/\tau)$ behavior



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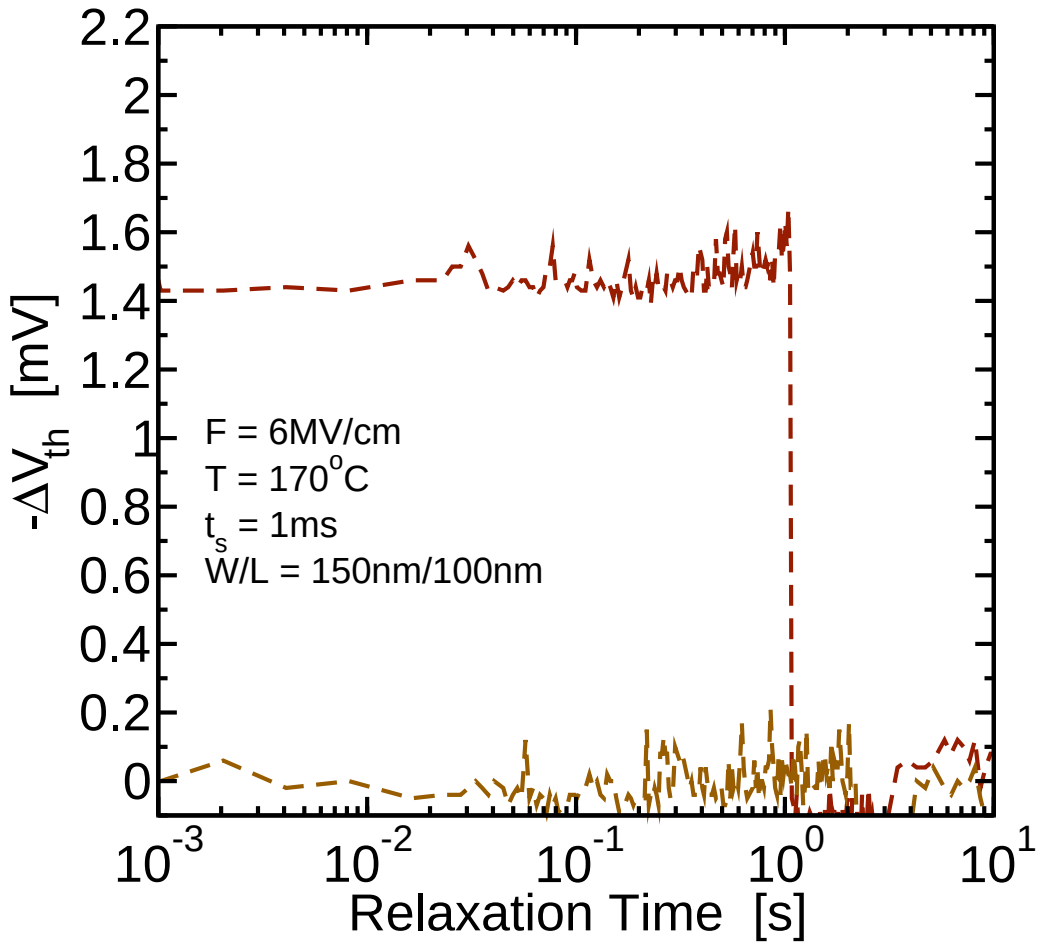

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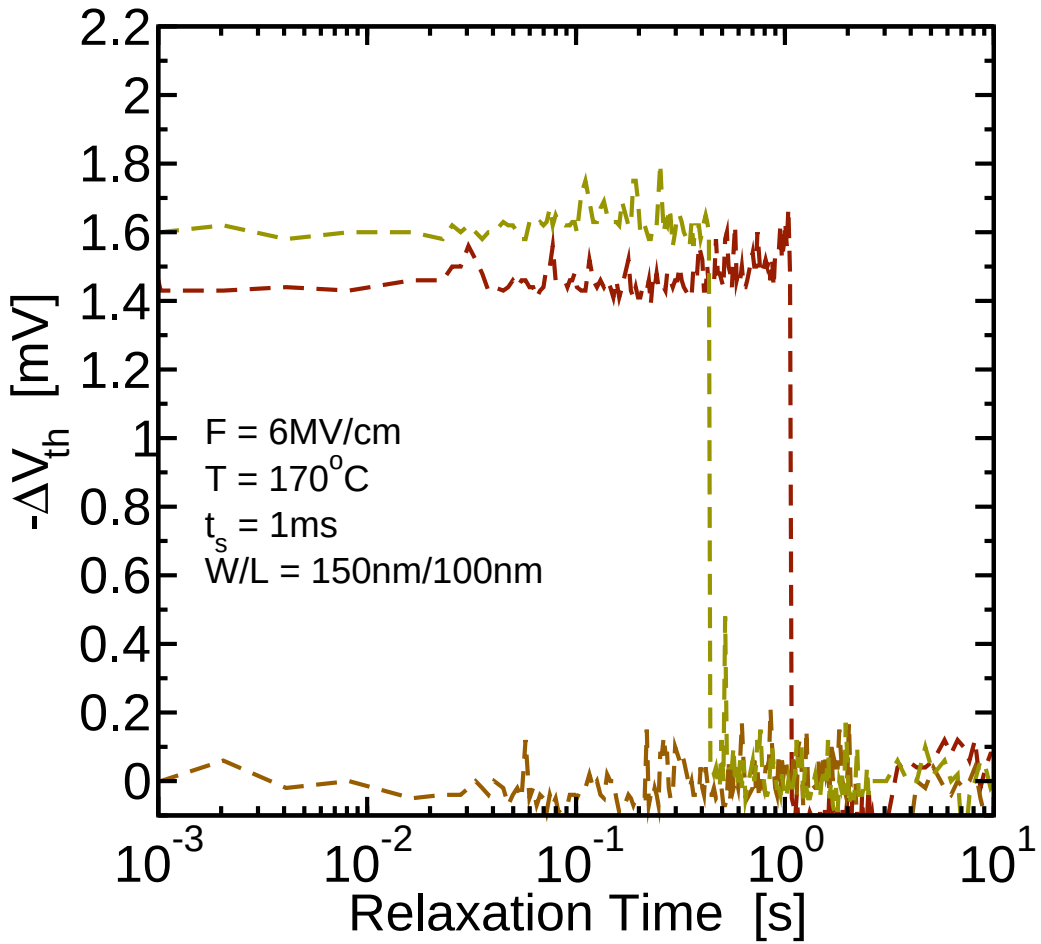

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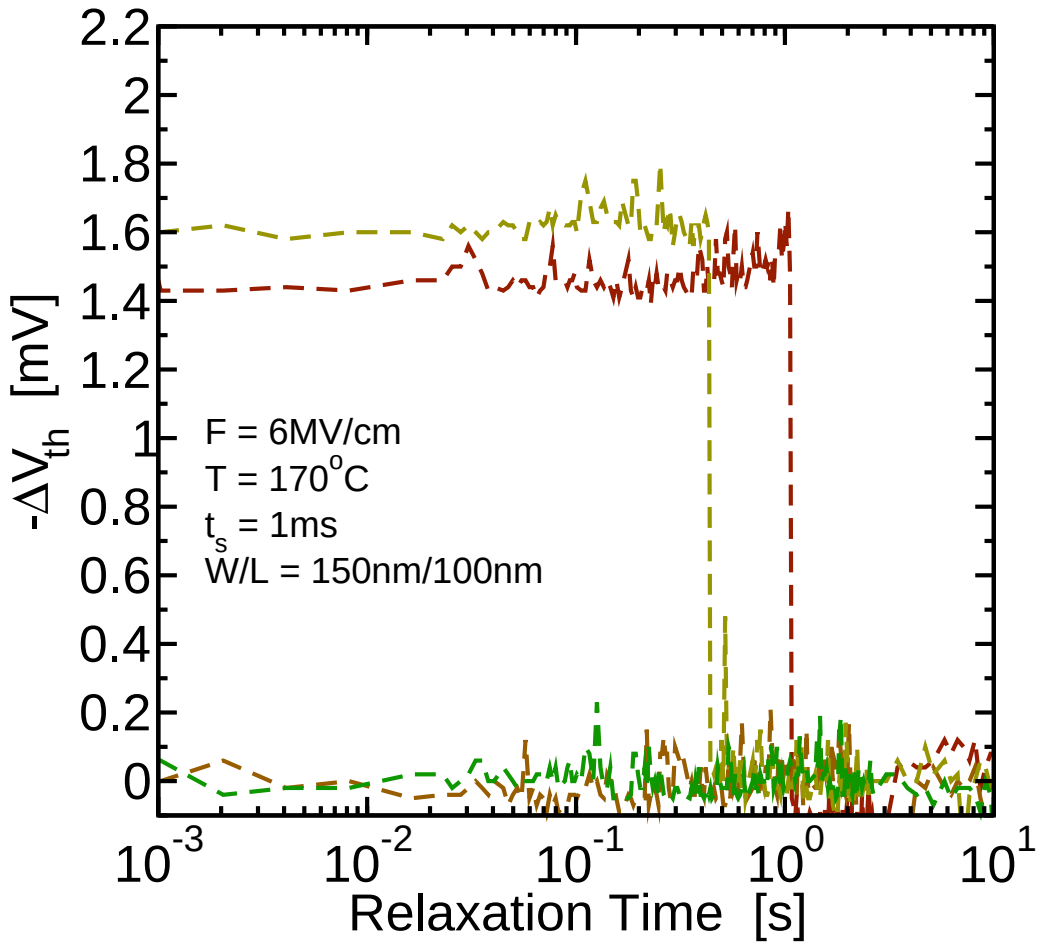

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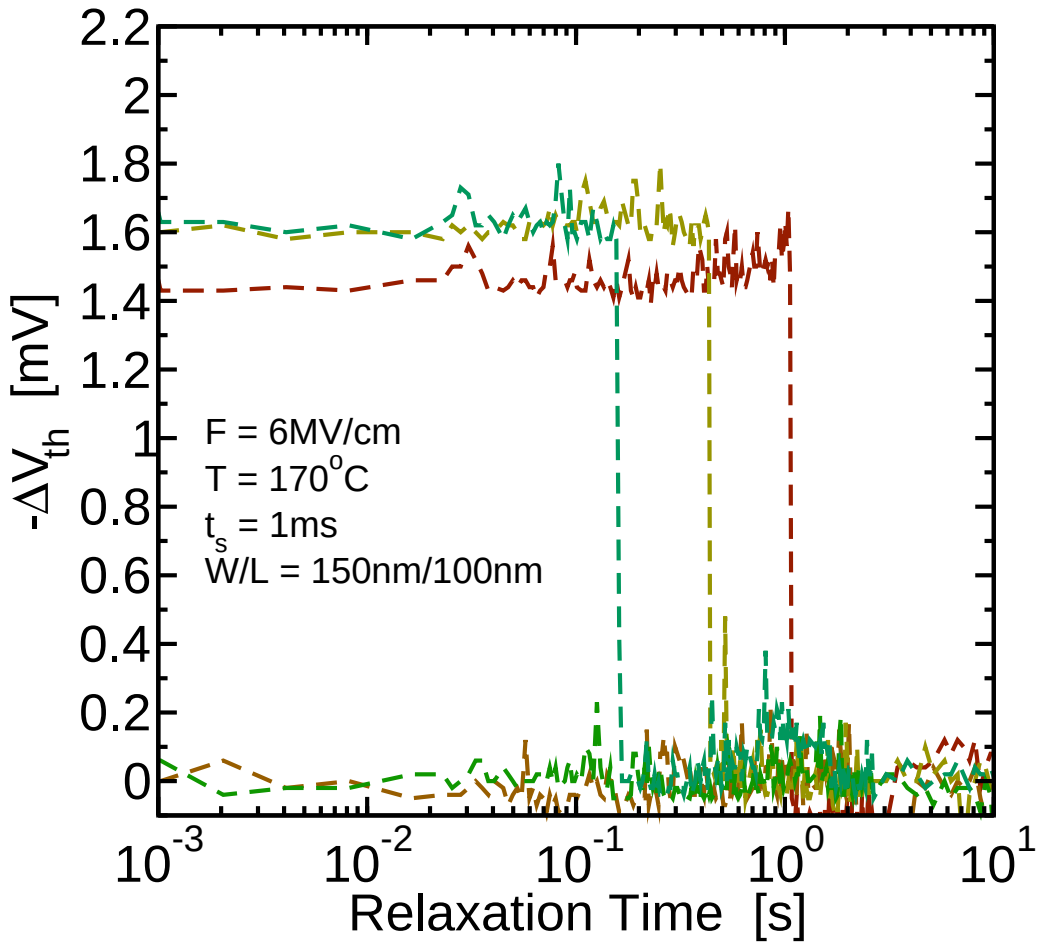

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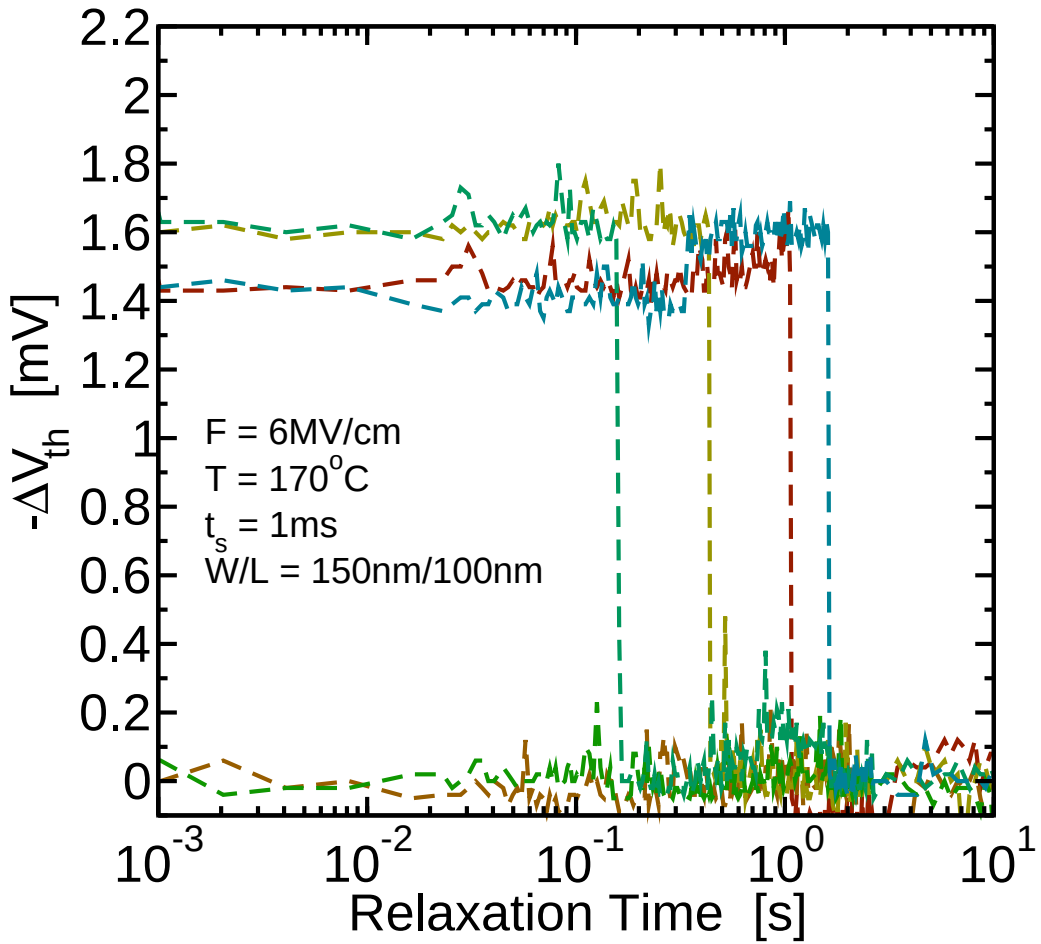

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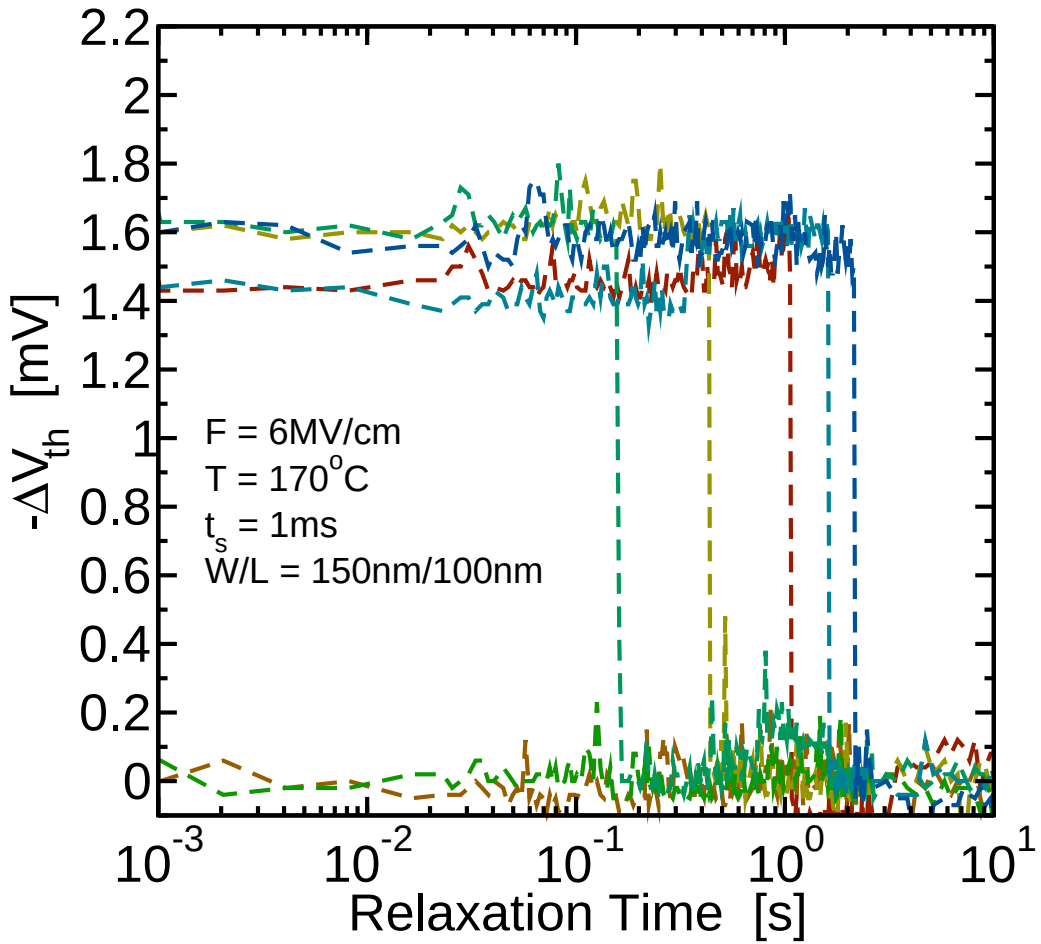

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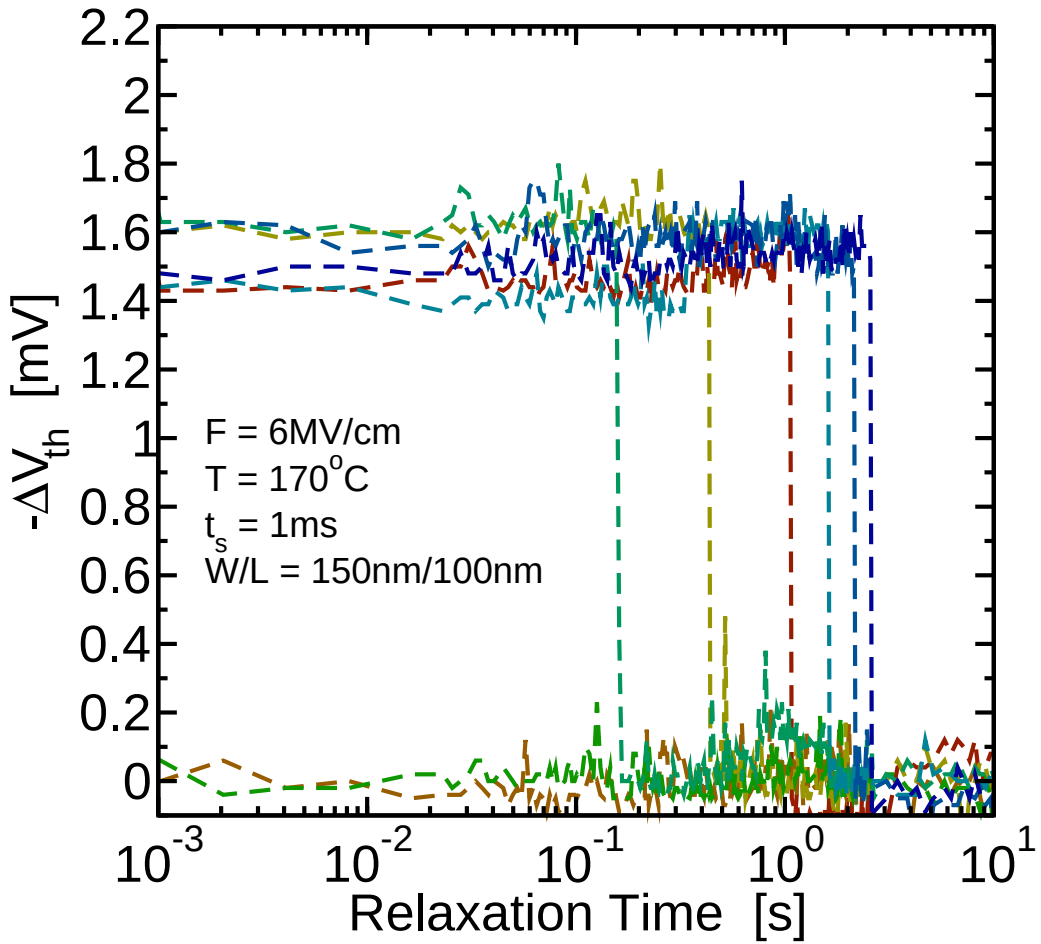

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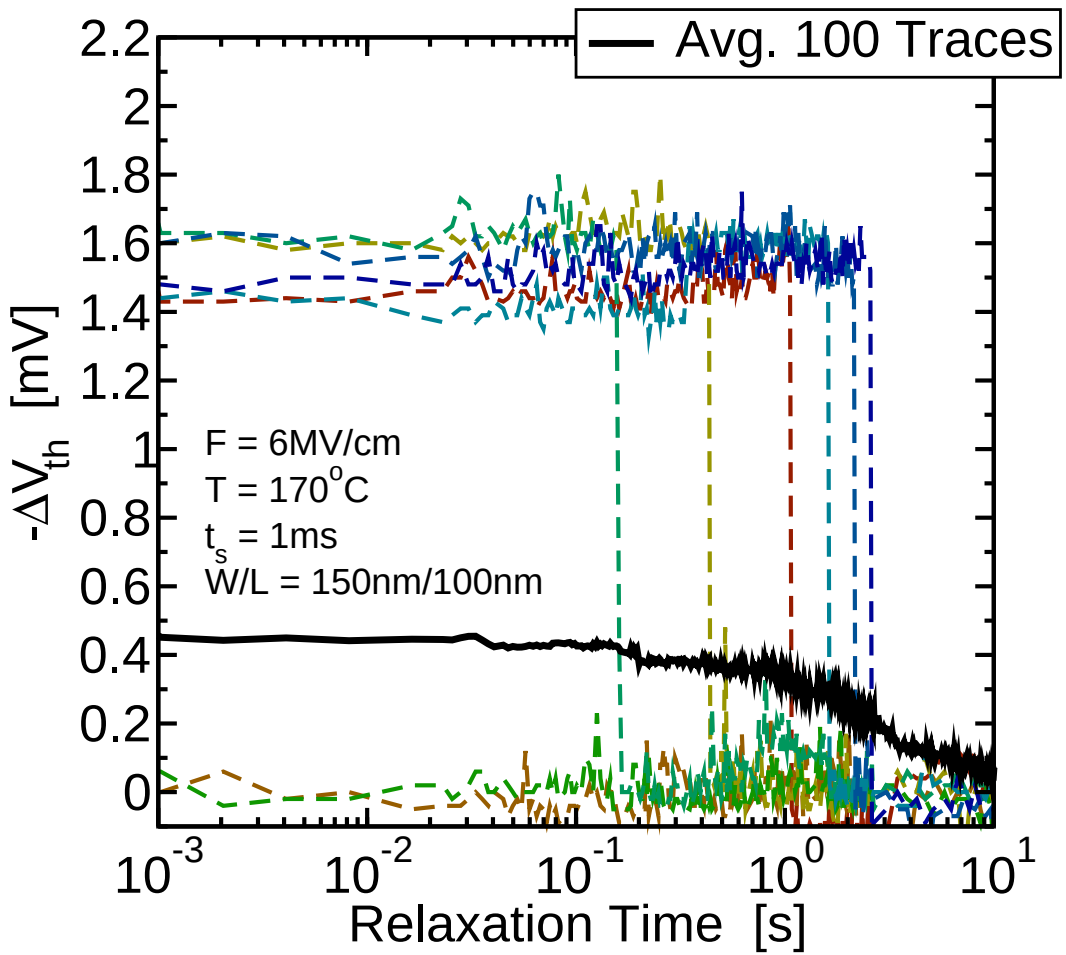

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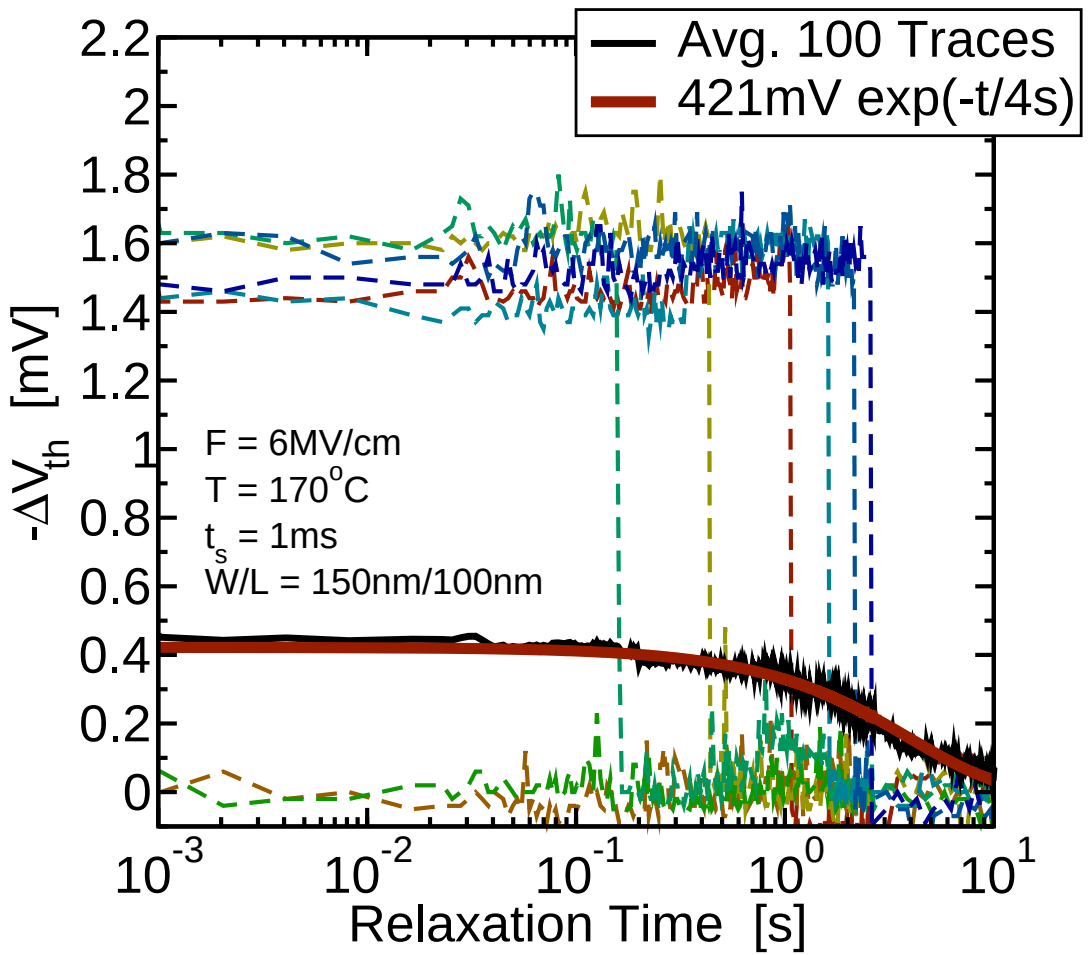
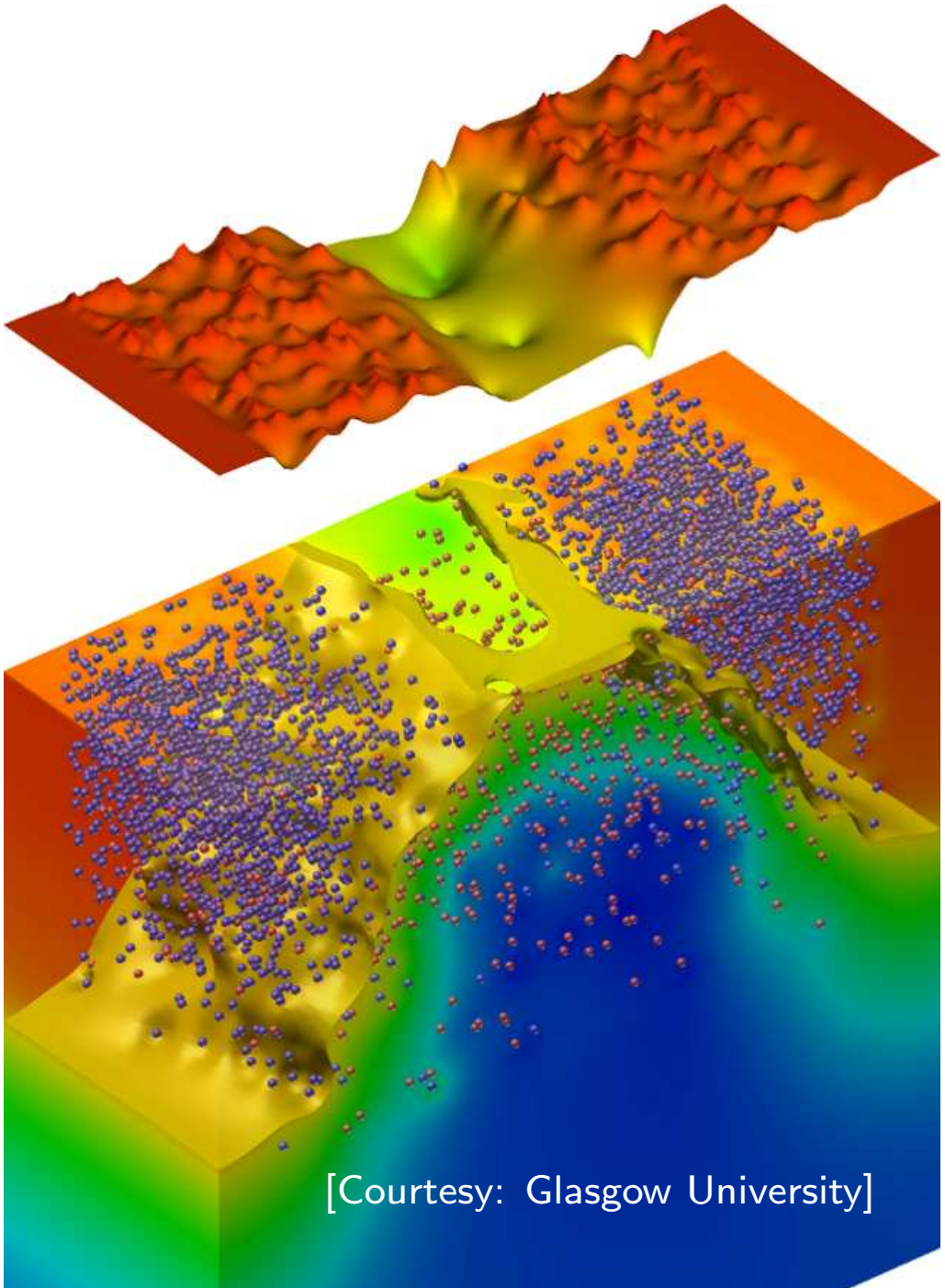


Each Defect has Unique Fingerprint



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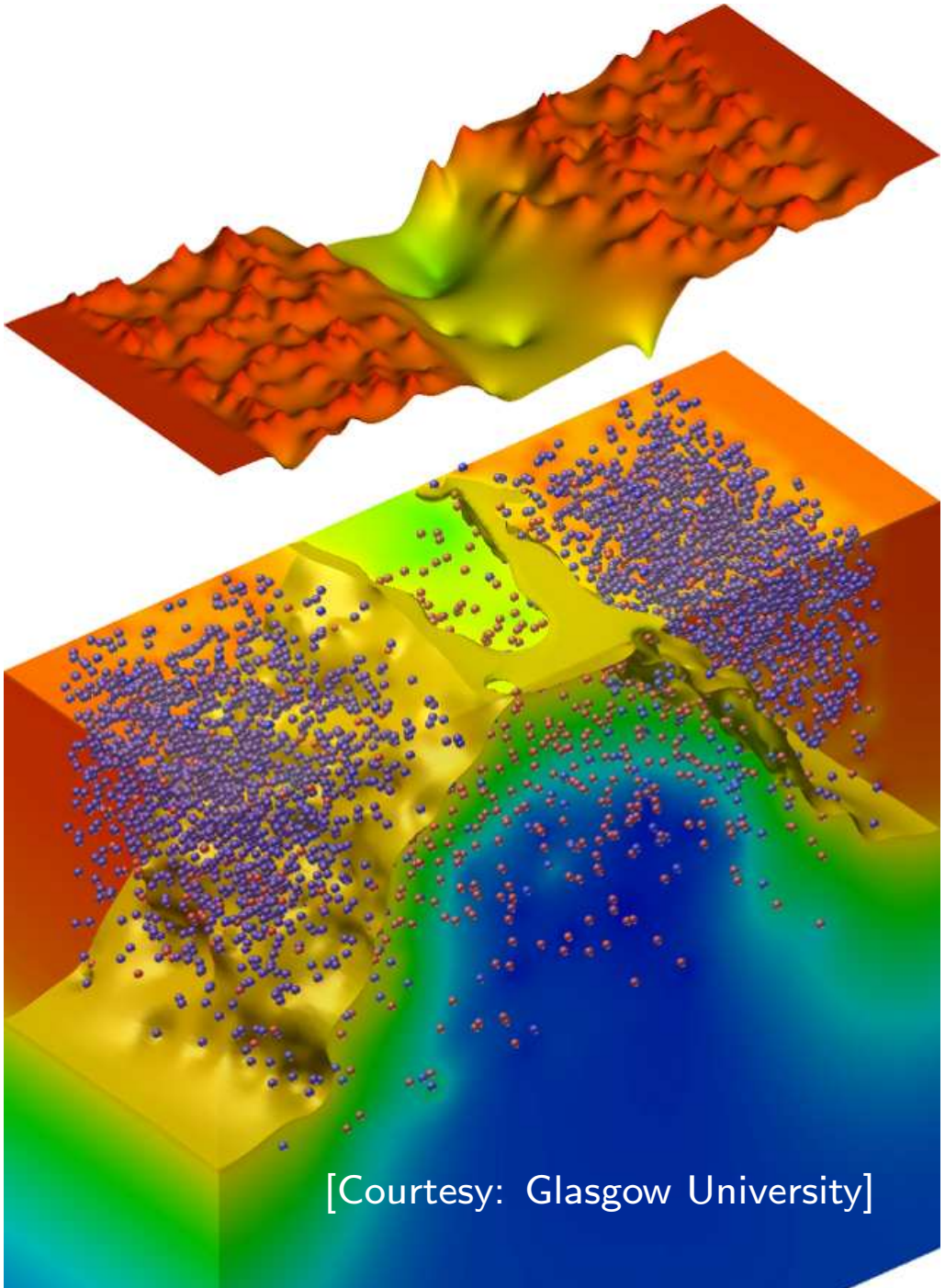
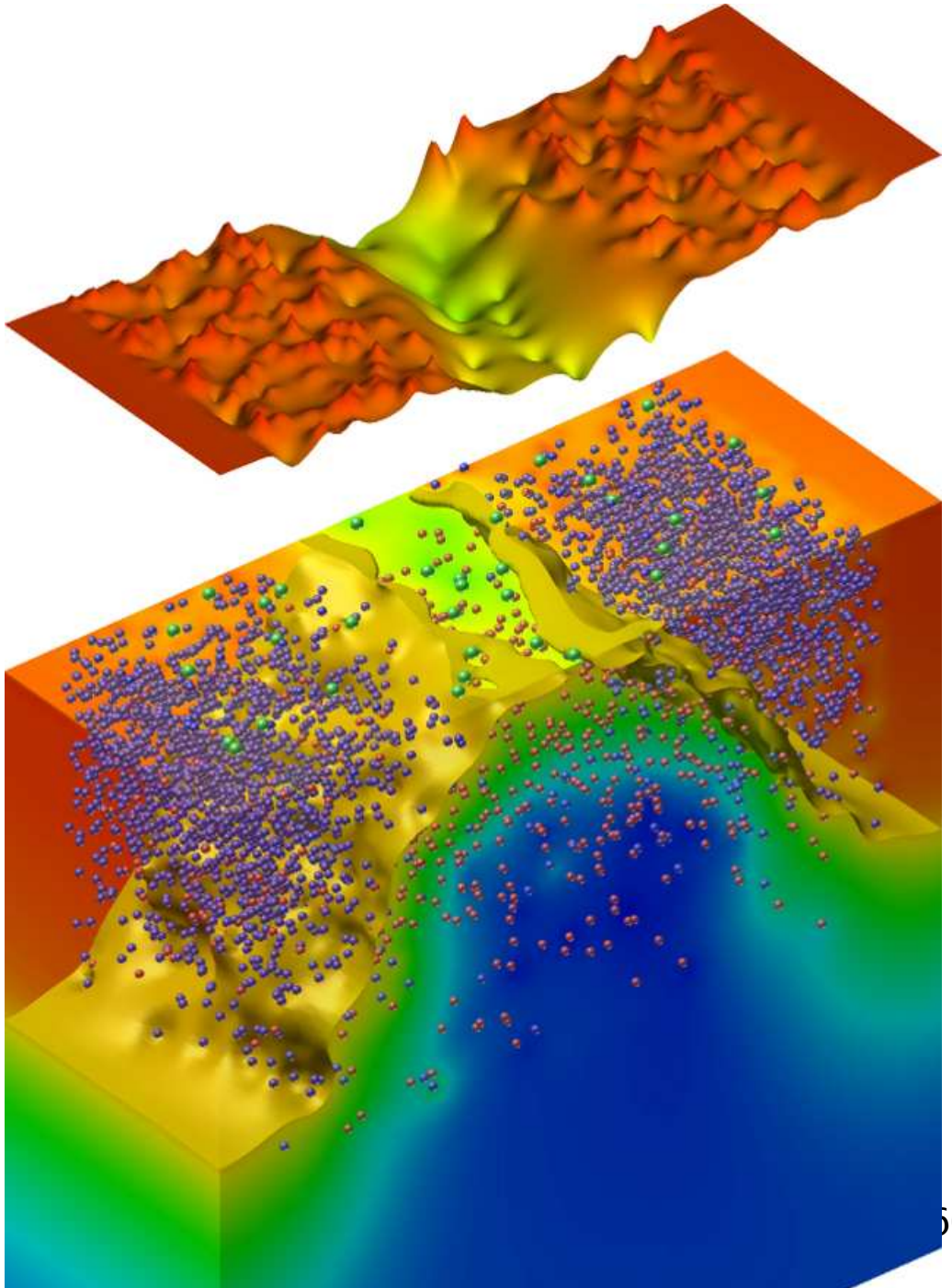
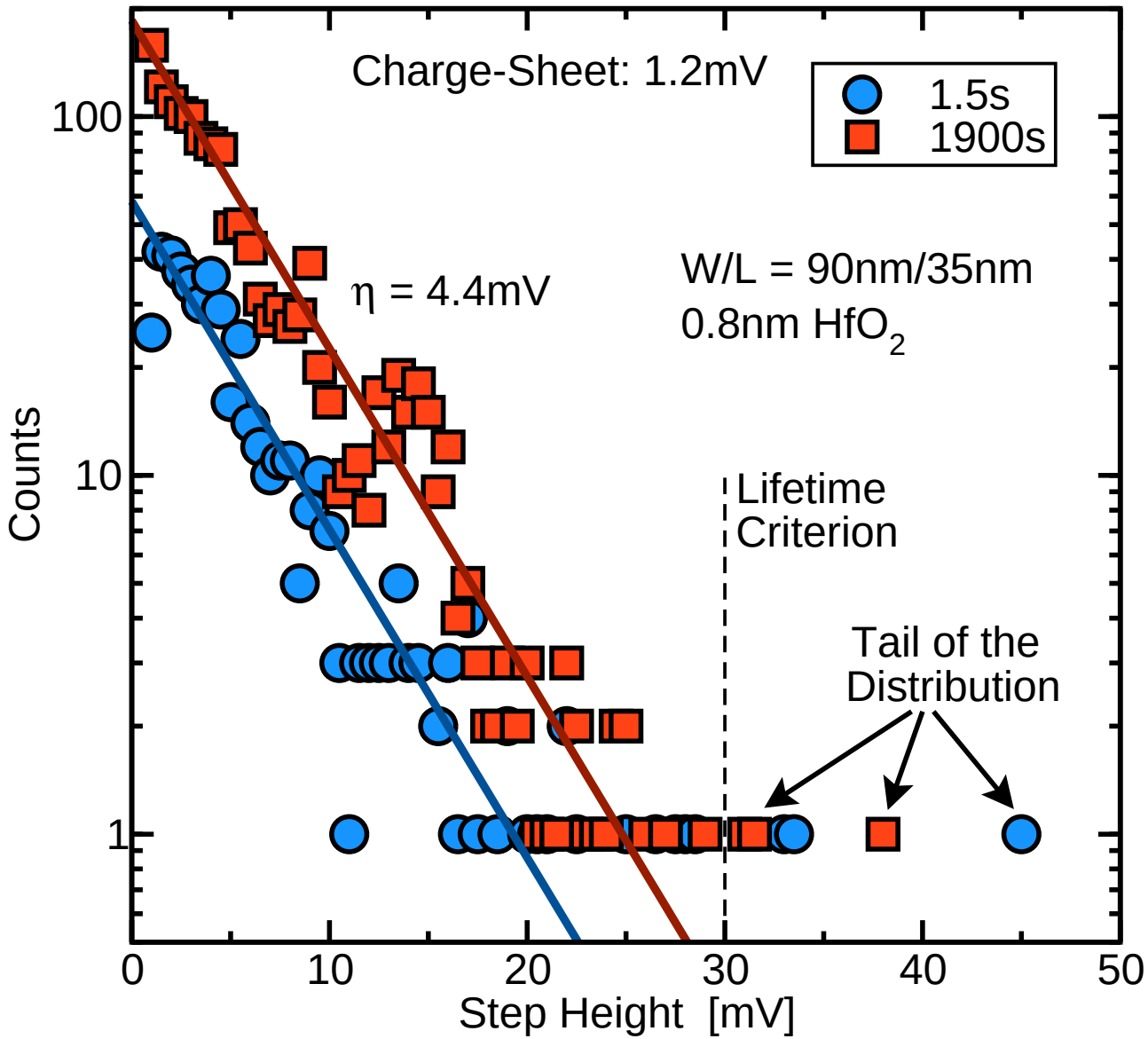




Distribution of Step-Heights

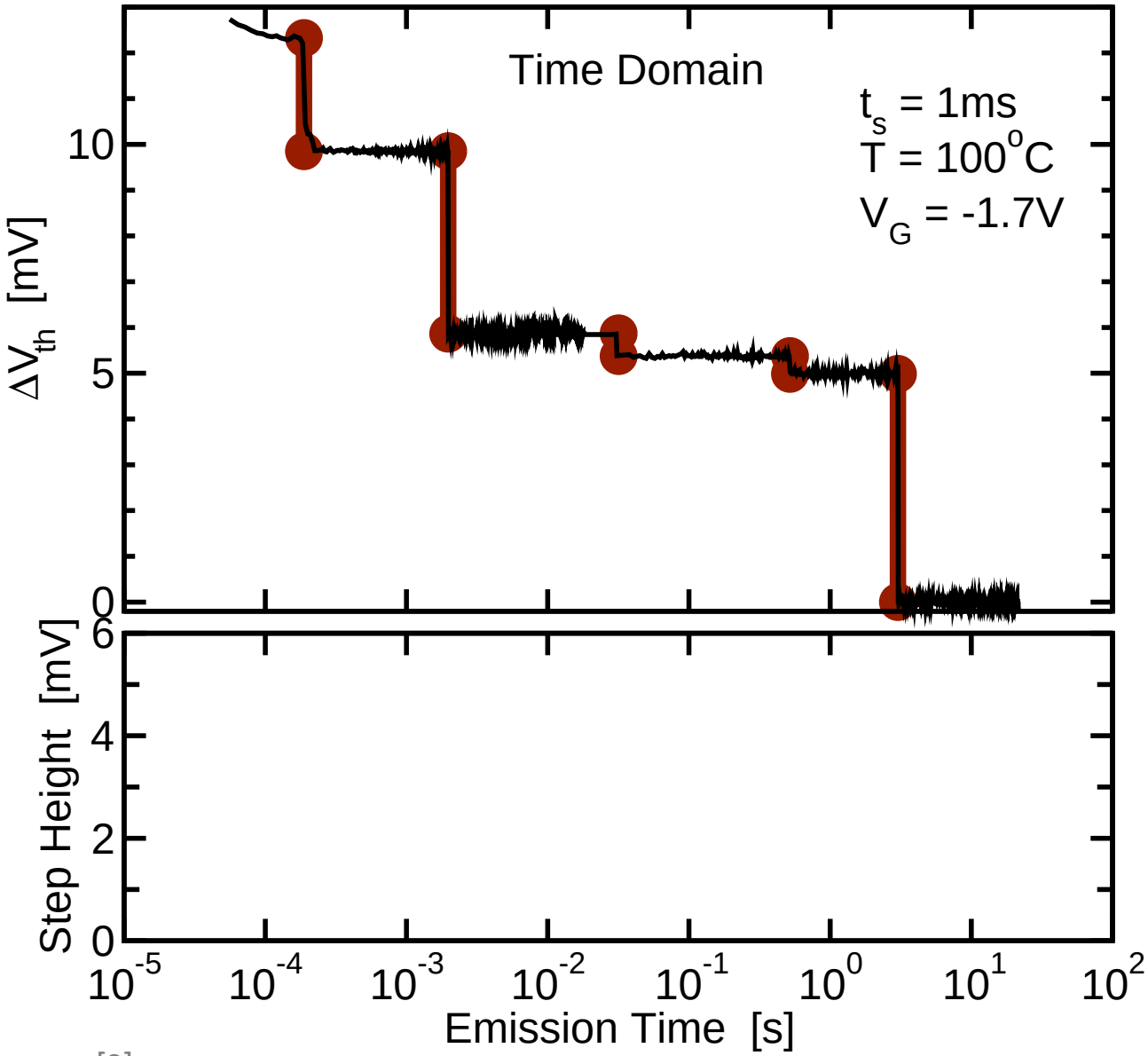
Like RTN, NBTI step-heights are exponentially distributed[1]



[1] Kaczer, IRPS '10

The Time Dependent Defect Spectroscopy (TDDS)

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



[1] Grasser *et al.*, IRPS '10 [2] Grasser *et al.*, PRB '10

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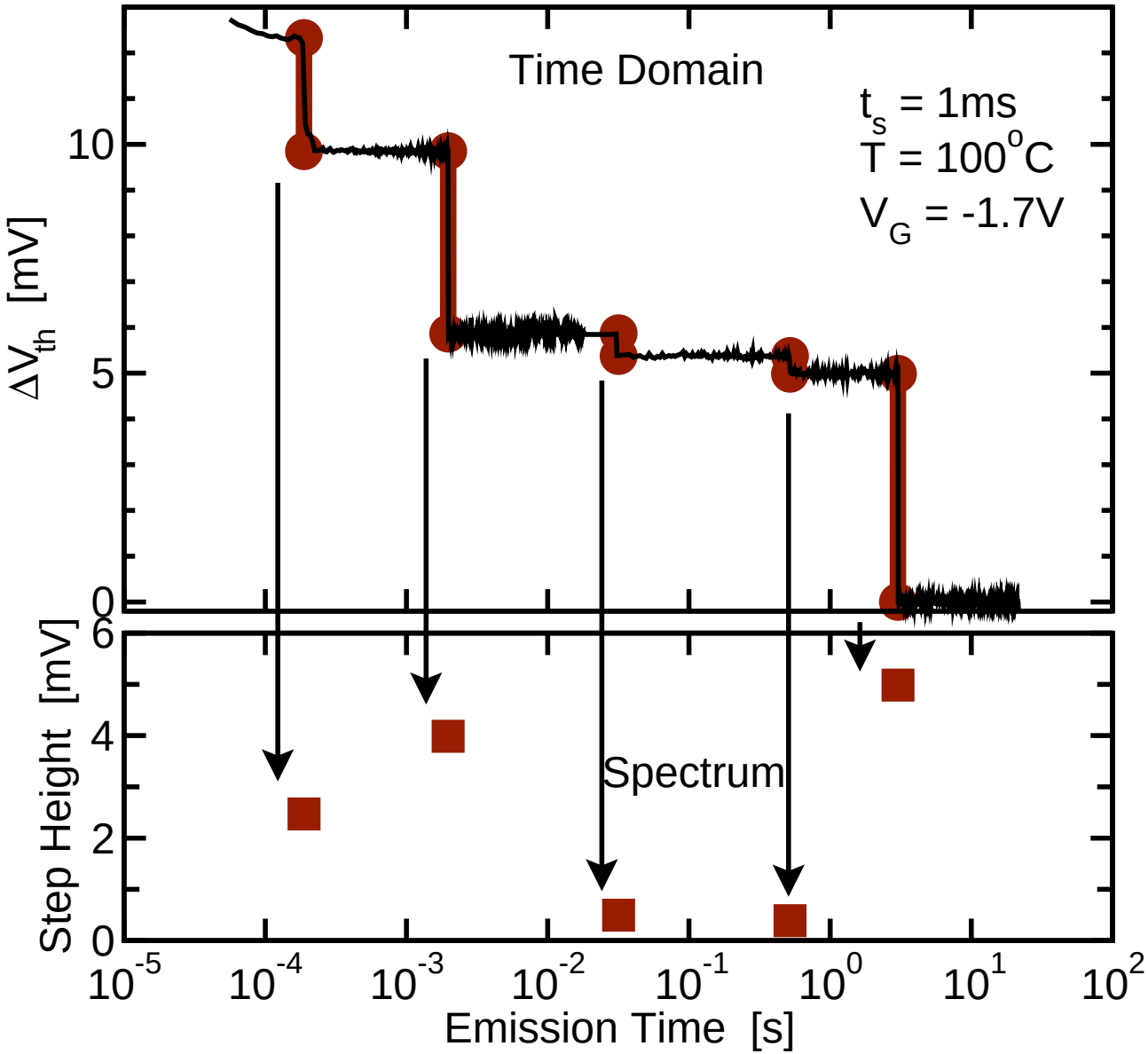

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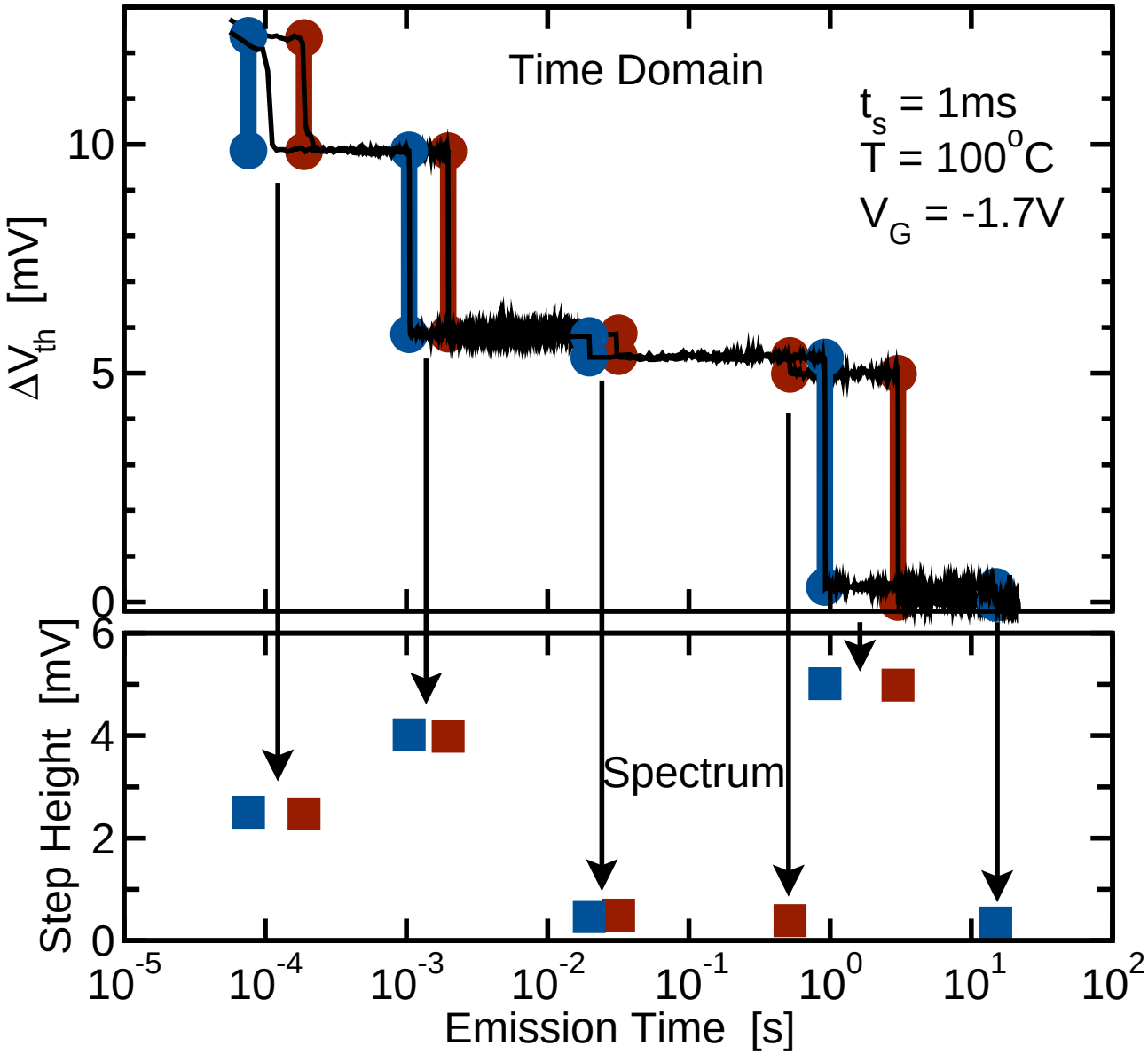

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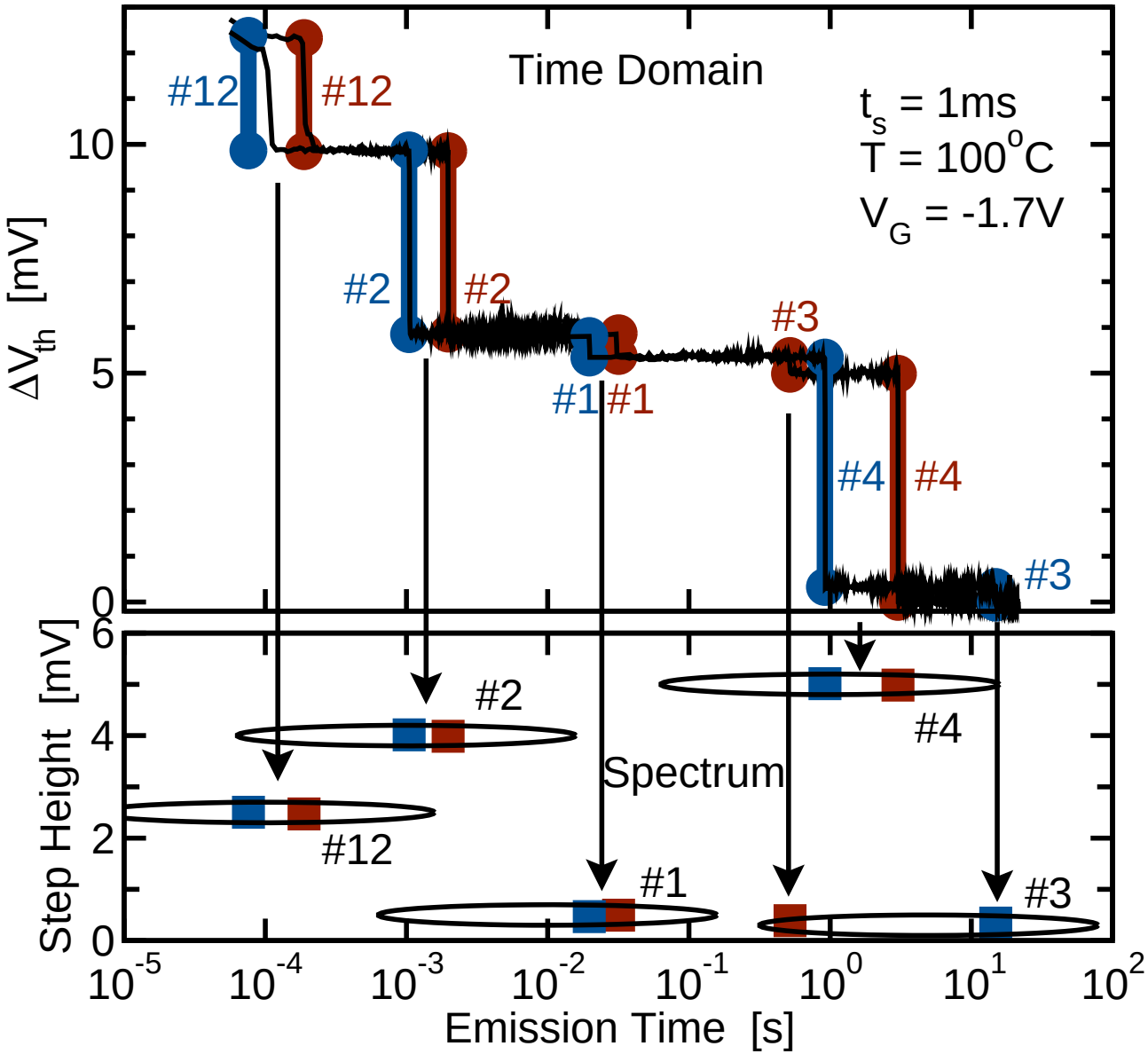
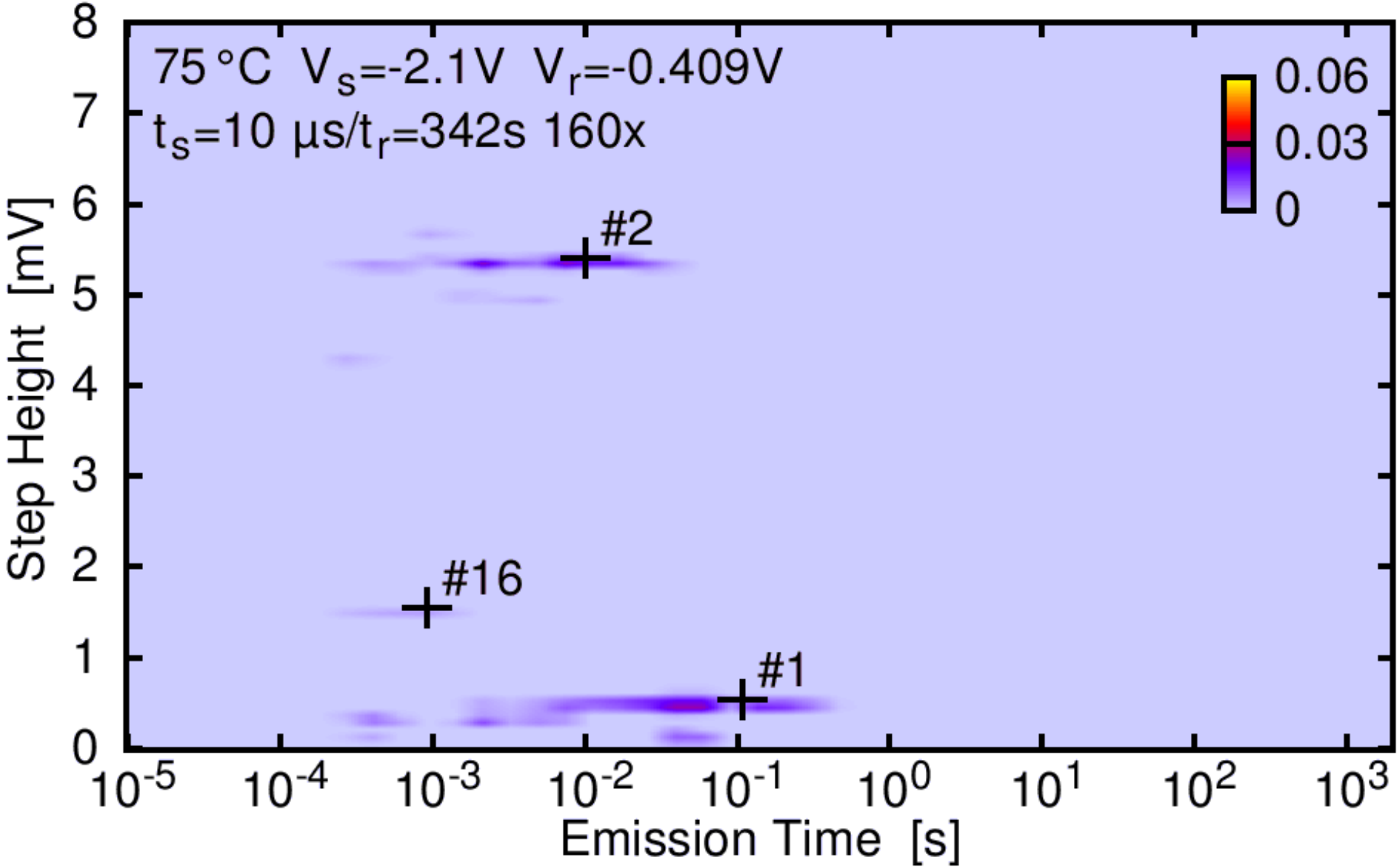


The Time Dependent Defect Spectroscopy

Function of stress time t_s



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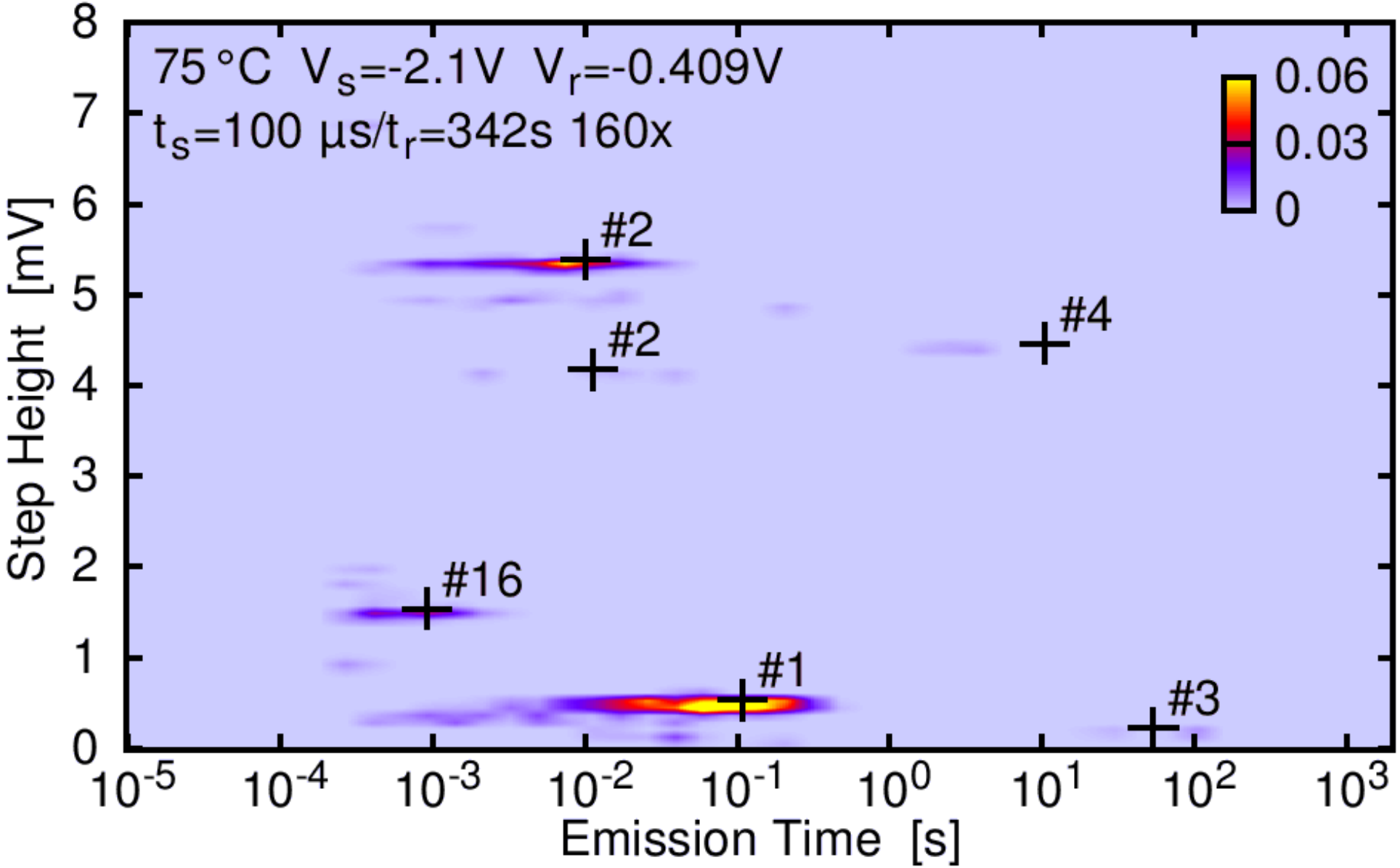

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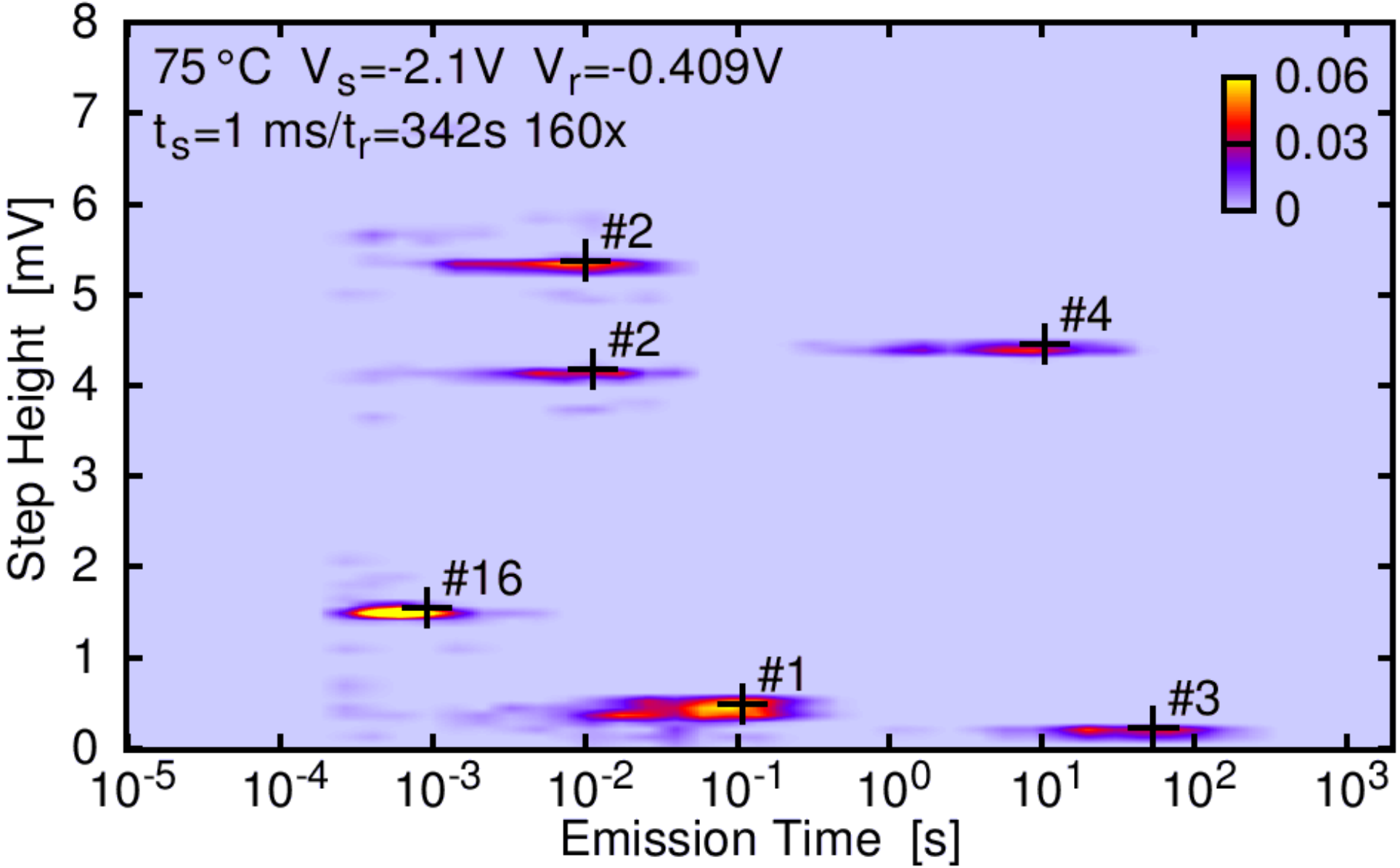

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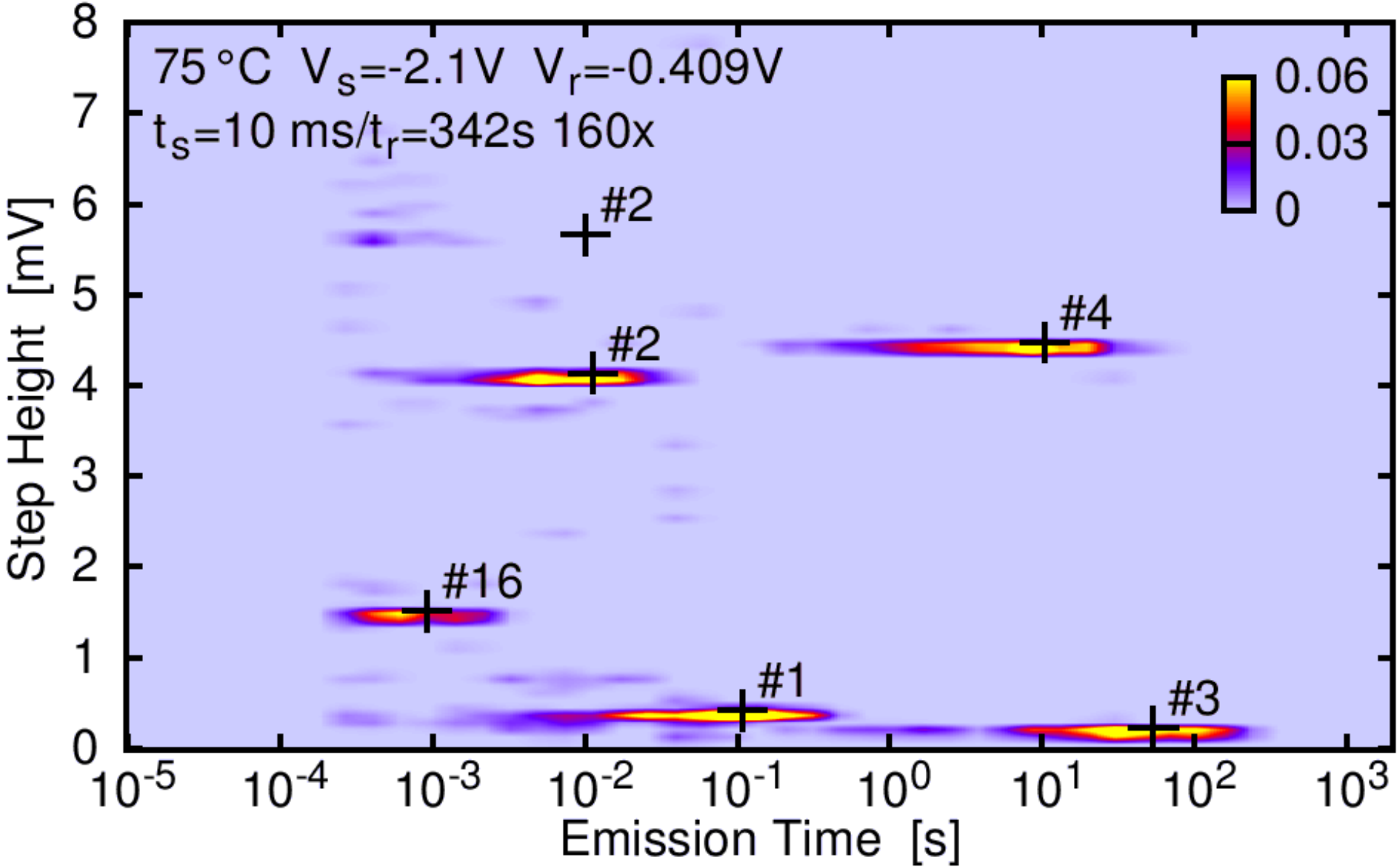
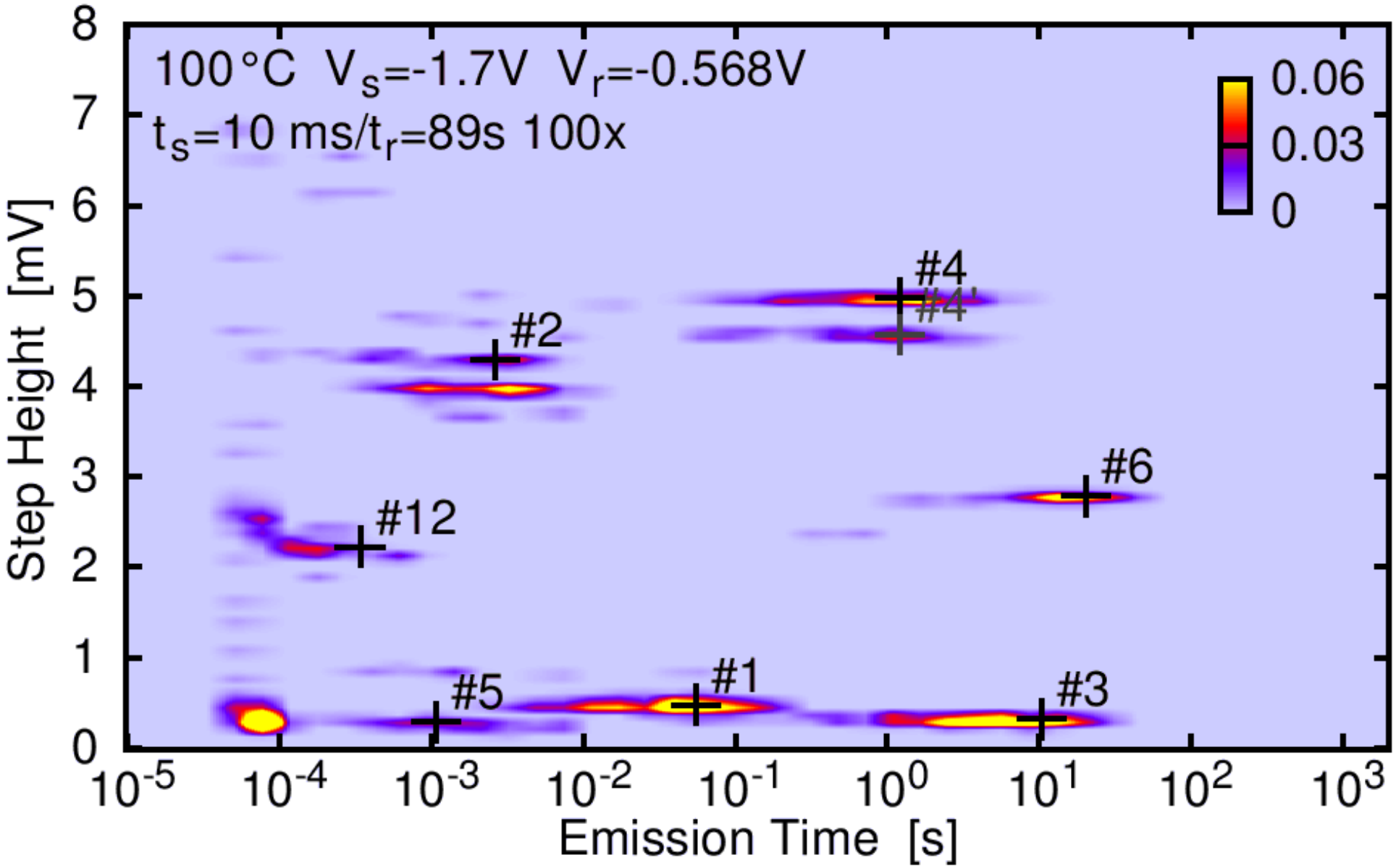


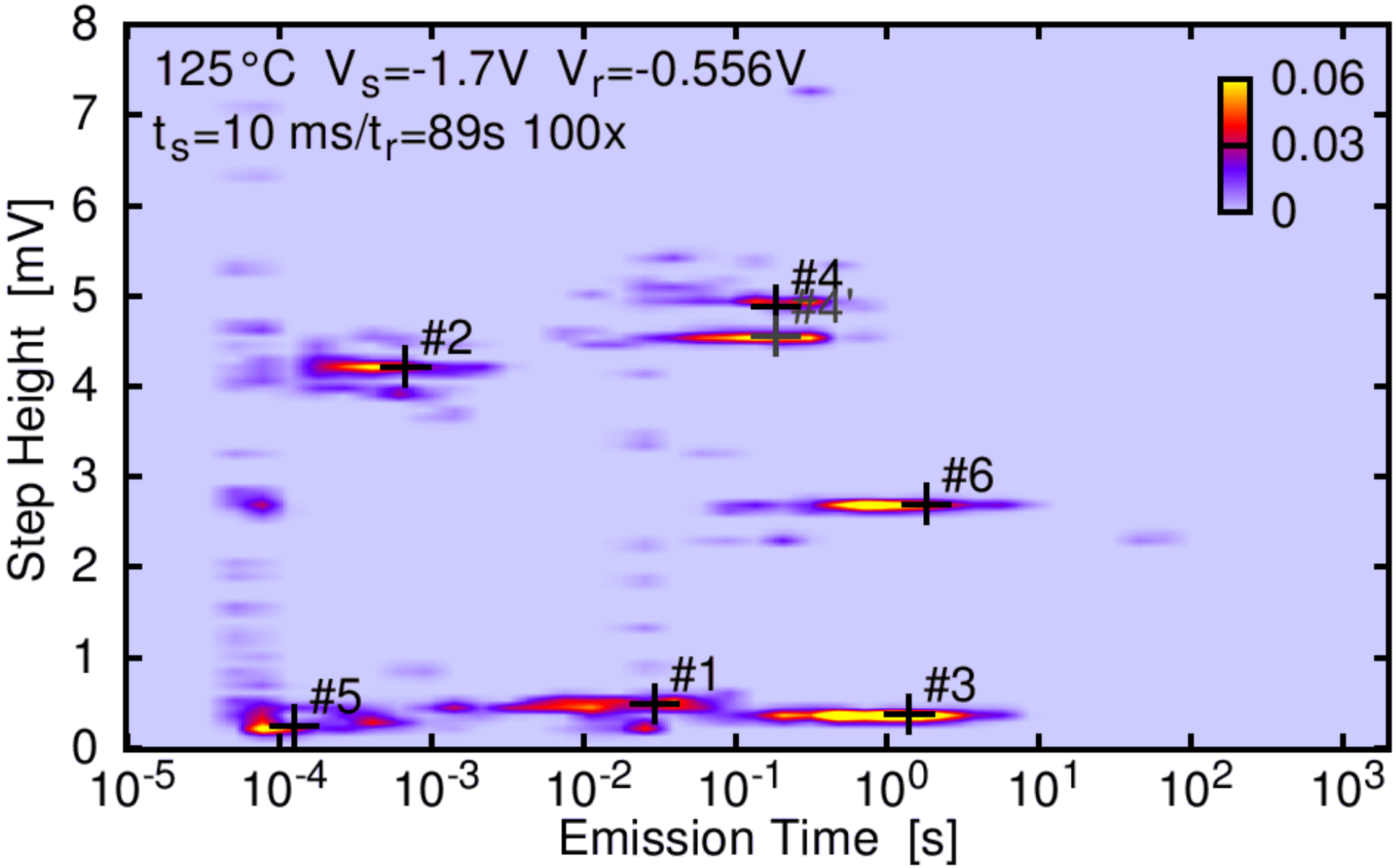
The Time Dependent Defect Spectroscopy

Function of temperature



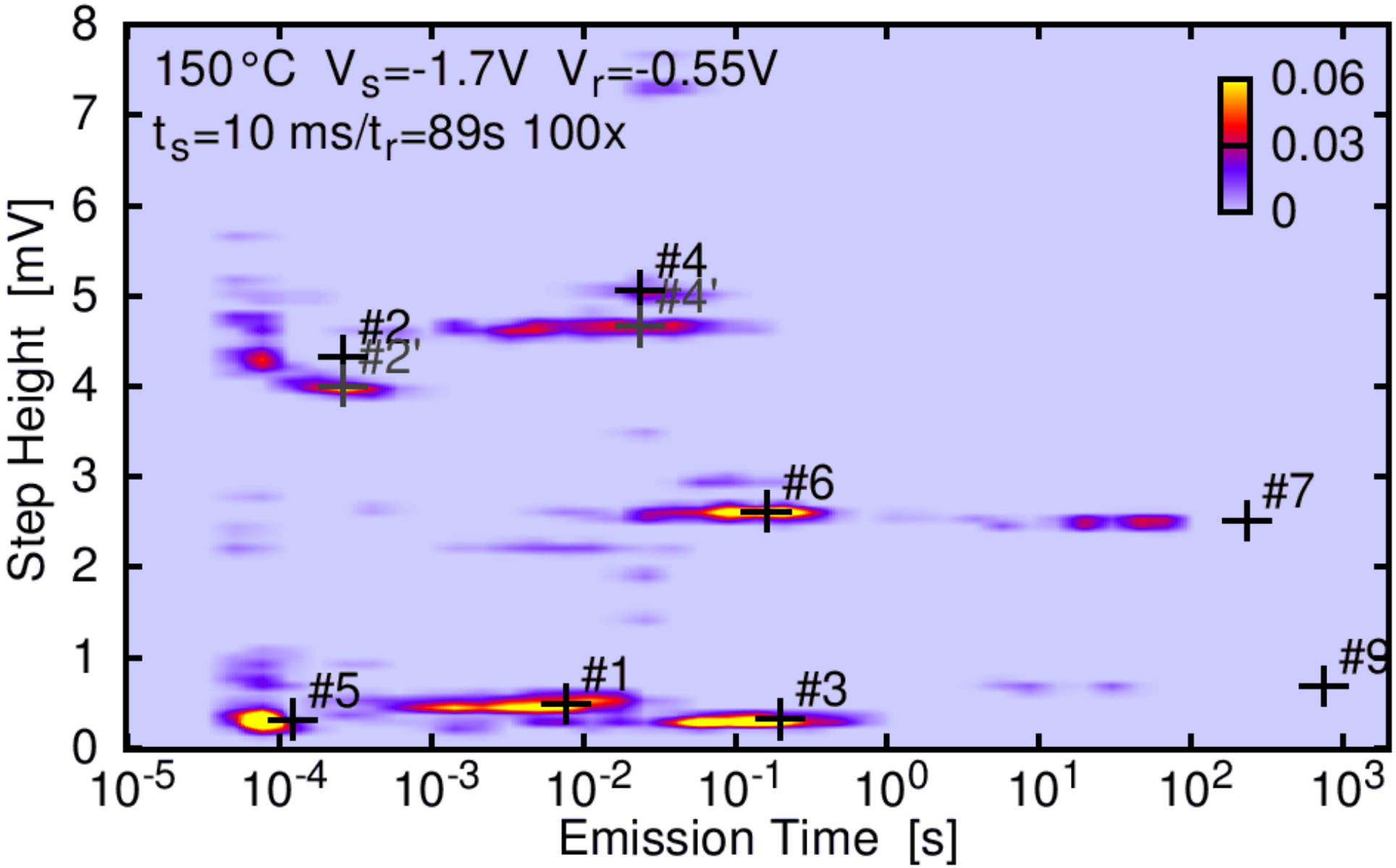
The Time Dependent Defect Spectroscopy

Function of temperature



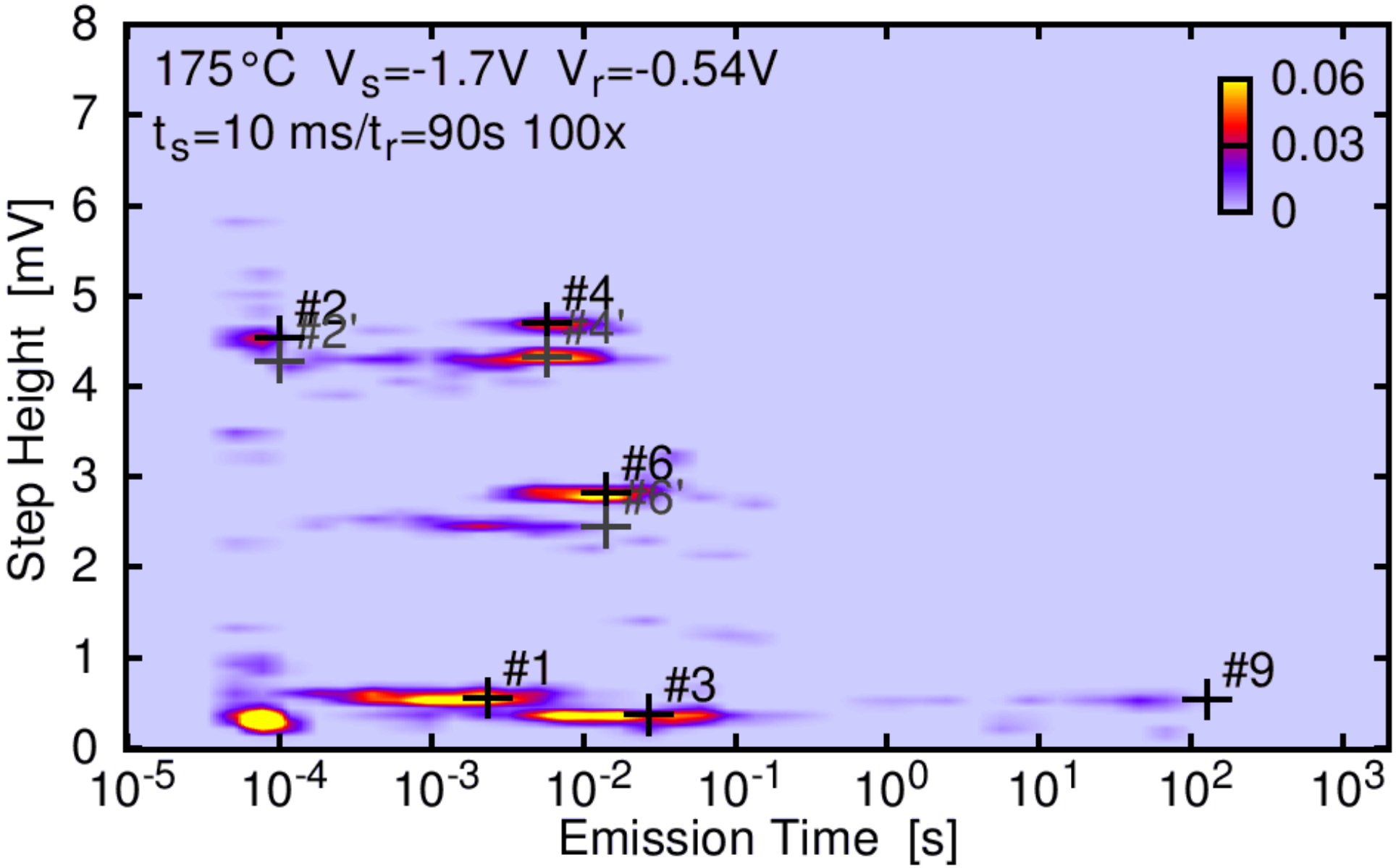
The Time Dependent Defect Spectroscopy

Function of temperature



The Time Dependent Defect Spectroscopy

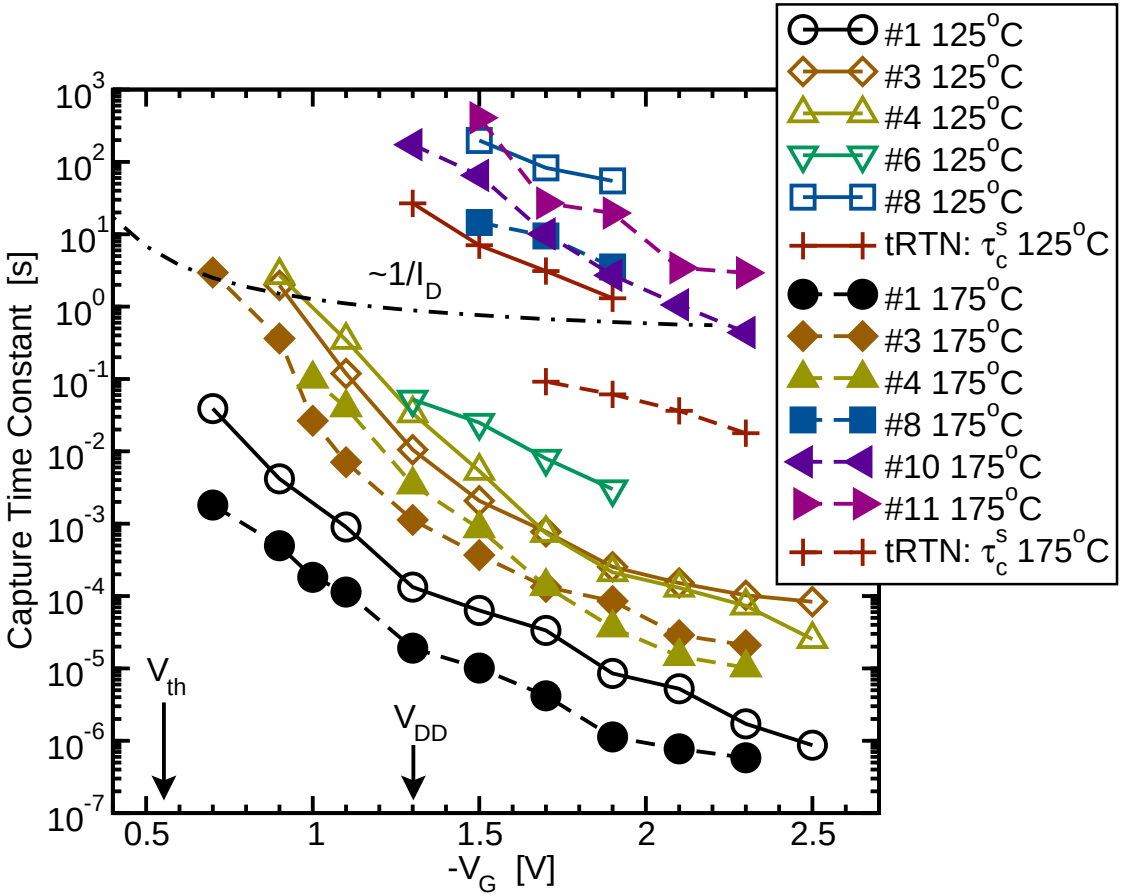
Function of temperature

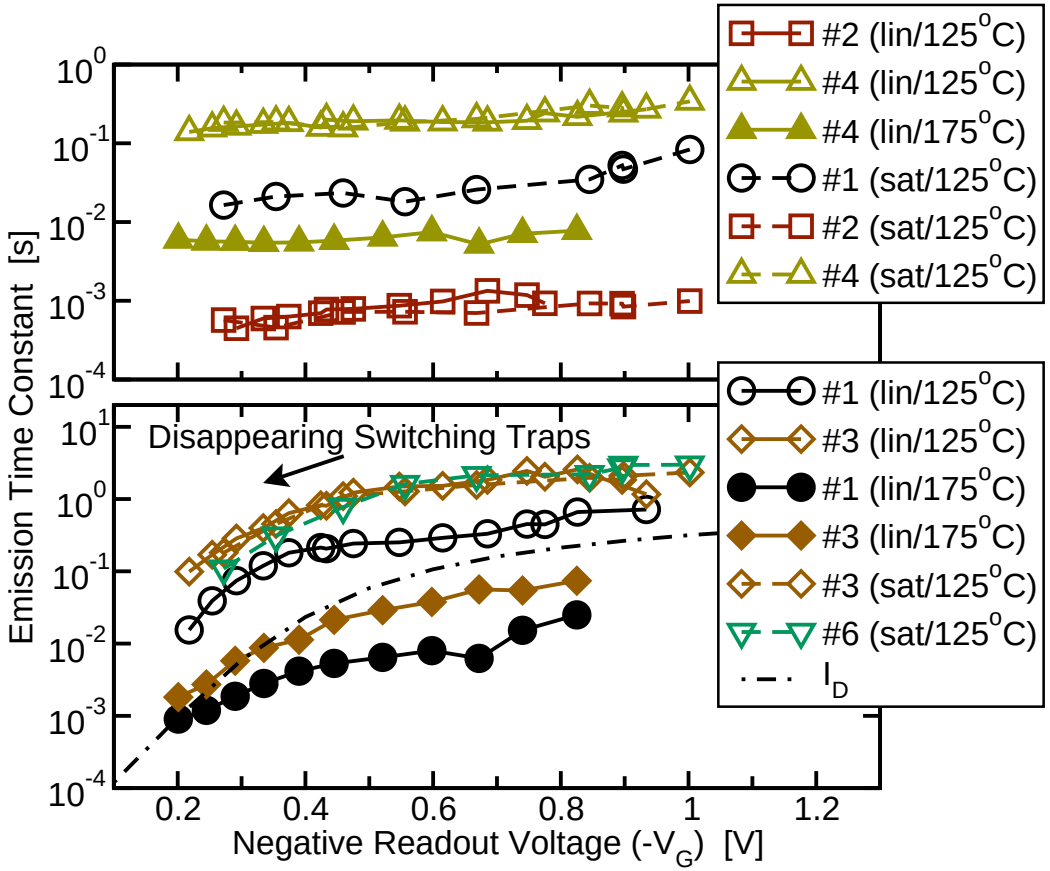


The Time Dependent Defect Spectroscopy

Different non-linear field dependence of the capture time constants

Different bias dependence of emission time constant: two defect types?



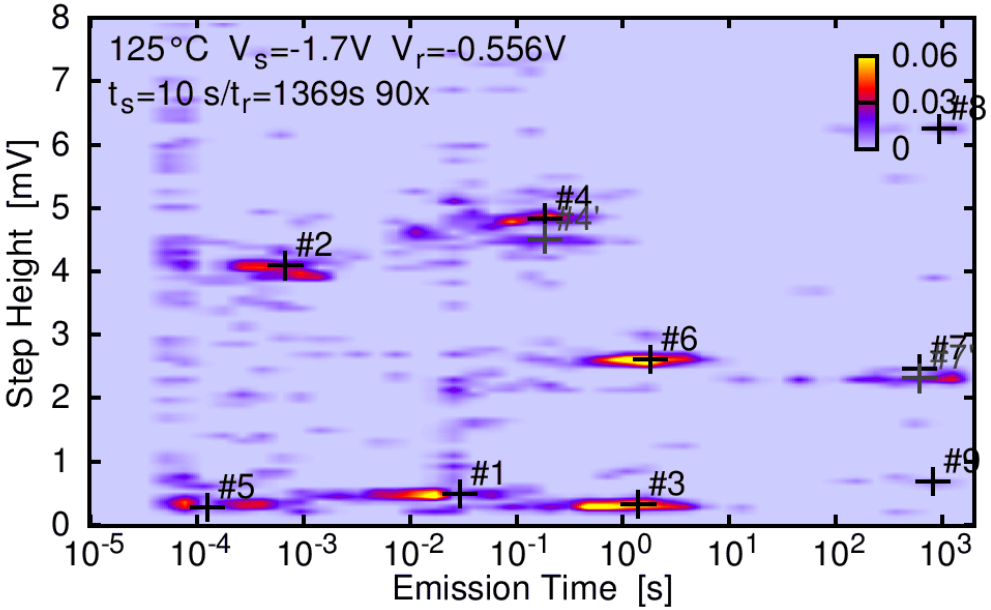


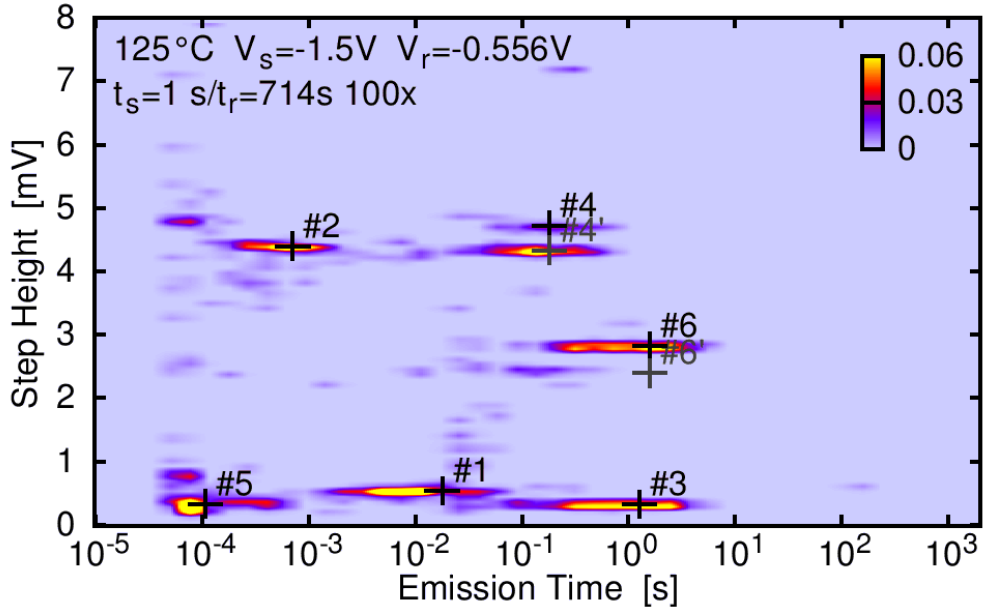
Compare SRH-like model: $\tau_c = \tau_0\, e^{\beta \Delta E_B} \frac{N_v}{p}$

$\tau_e = \tau_0\, e^{\beta \Delta E_B}\, e^{\beta \Delta E_T}\, e^{xF/V_T}$

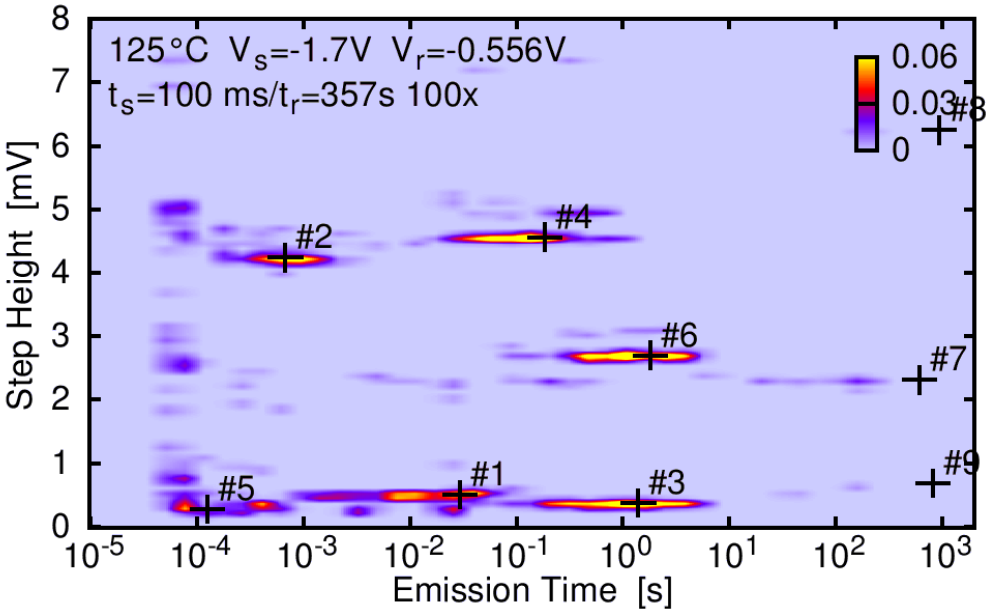
Anomalous Defect Behavior

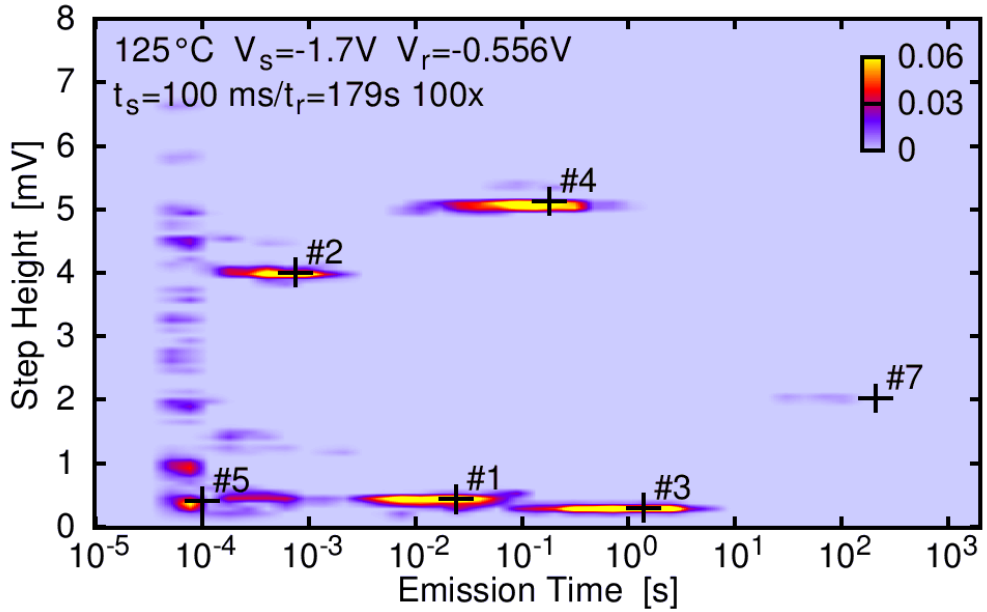
Defects disappear temporarily from the map (#7)





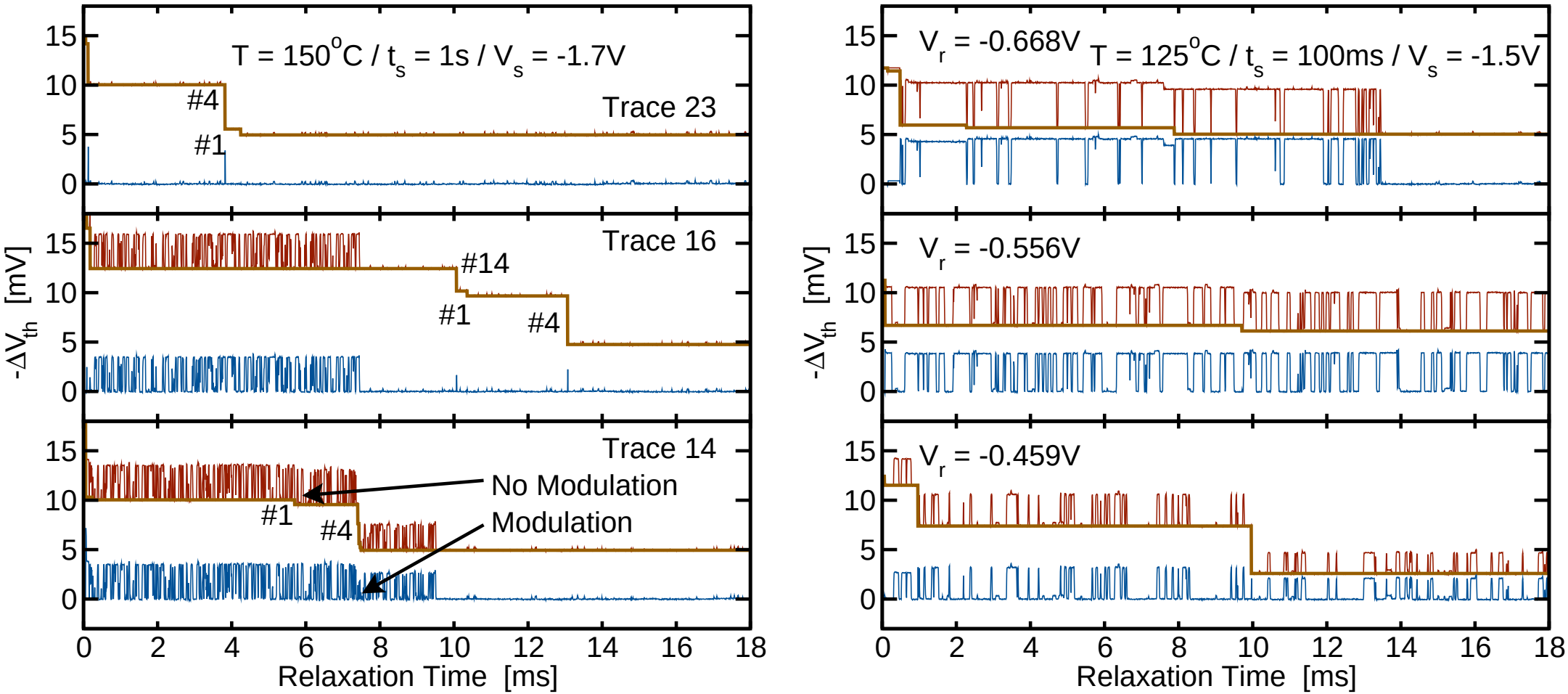
Long term stability: defect #6 missing for a few months now





Anomalous Defect Behavior

Temporary random telegraph noise (tRTN)



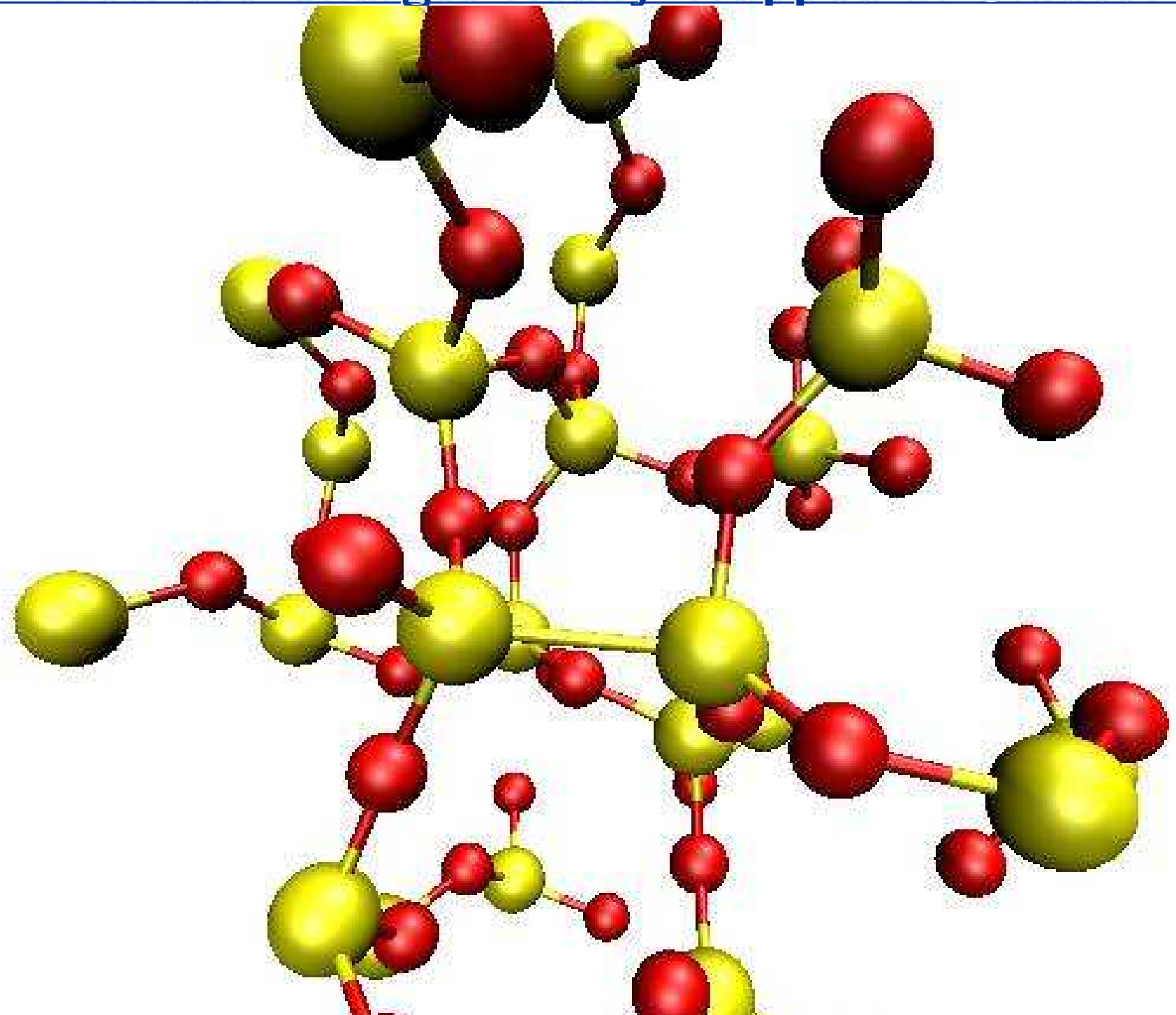
How Can We Model All That?

Charging of Oxide Defects

Conventional model

Elastic tunneling, results in a 'tunneling front' (1 nm in 10 ms)

How are Charges Really Trapped in Oxides?

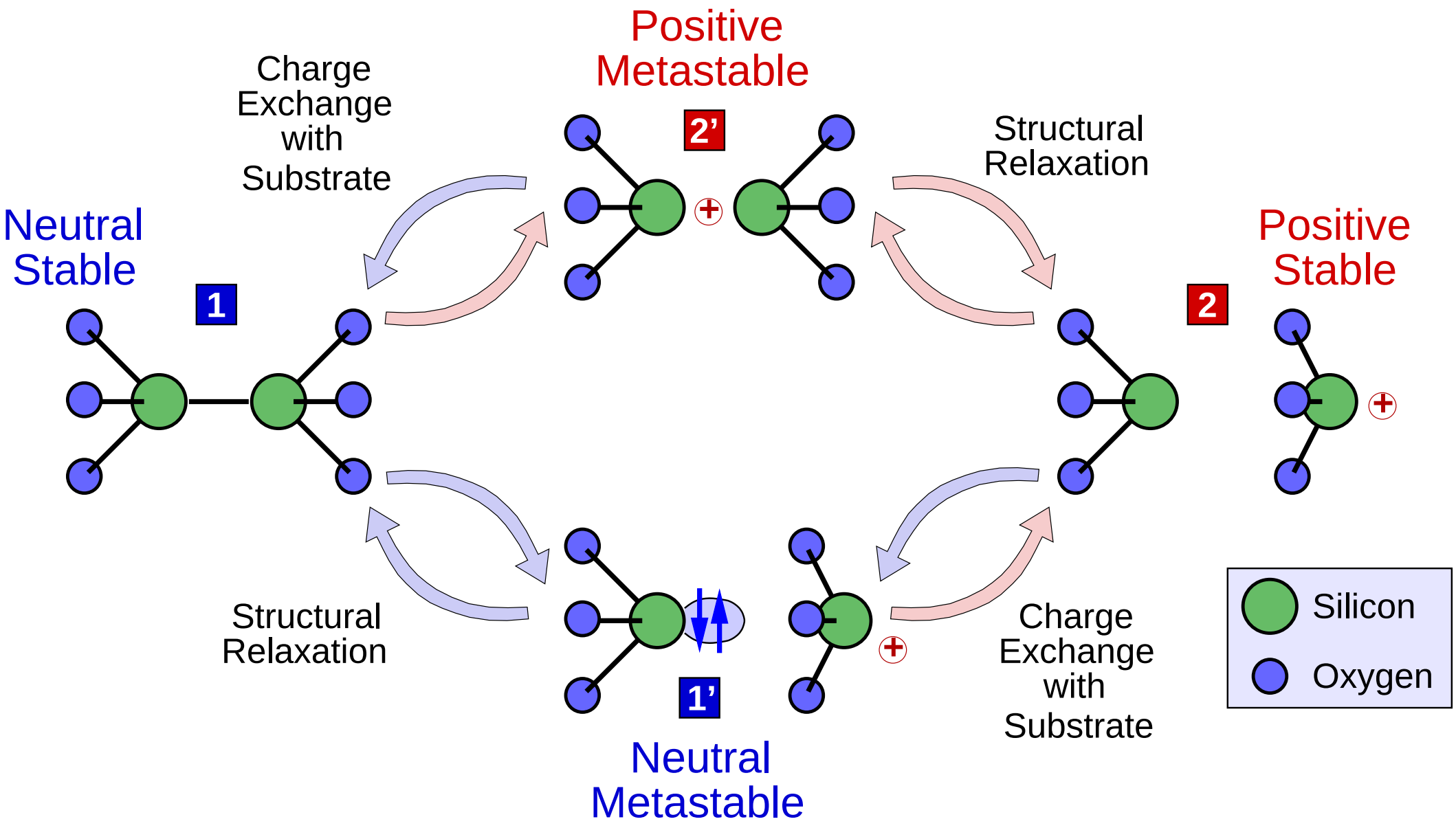


100 Femtoseconds in the Life of an E' center

Charging of an E' center

Puckering of an E' center

Detailed Defect Model Required

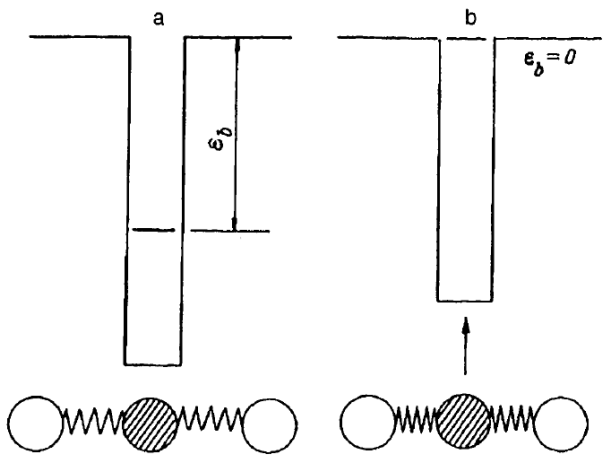


Nonradiative Multiphonon Theory

Developed for F-centers and defects in III-V semiconductors[1] [2]

O in GaP, Fe and Cr in GaAs, etc.

Thermal vibrations modulate E_T



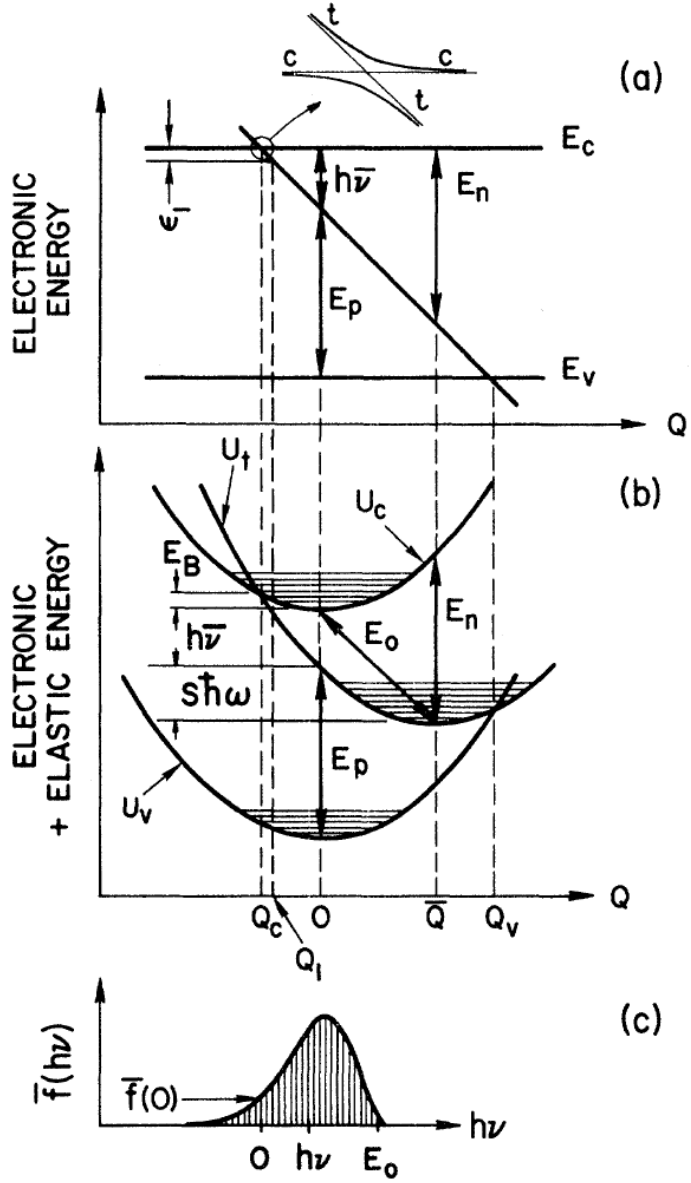
Total energy: vibrational plus electronic

Adiabatic approximation

Linear coupling: changes defect level

Quadratic coupling: changes in vibrational frequency

Explains optical energies



[1] Huang and Rhys, Proc.Roy.Soc.A 50 [2] Henry and Lang, PRB 77

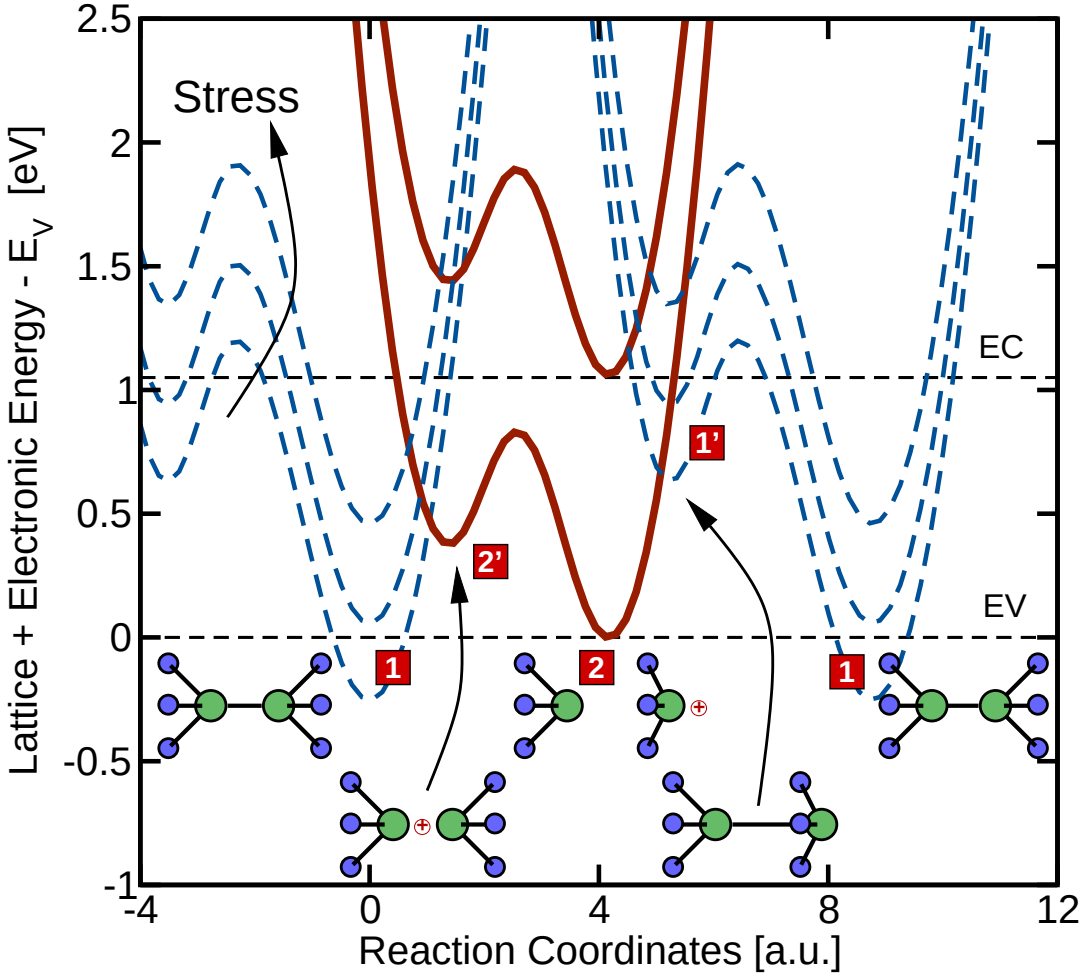
Model

Different adiabatic potentials for the neutral and positive defect

Metastable states 2' and 1' are secondary minima

Thermal transitions to ground states 1 and 2

Stochastic Markov-model for defect kinetics based on multiphonon theory



Charging of Oxide Defects

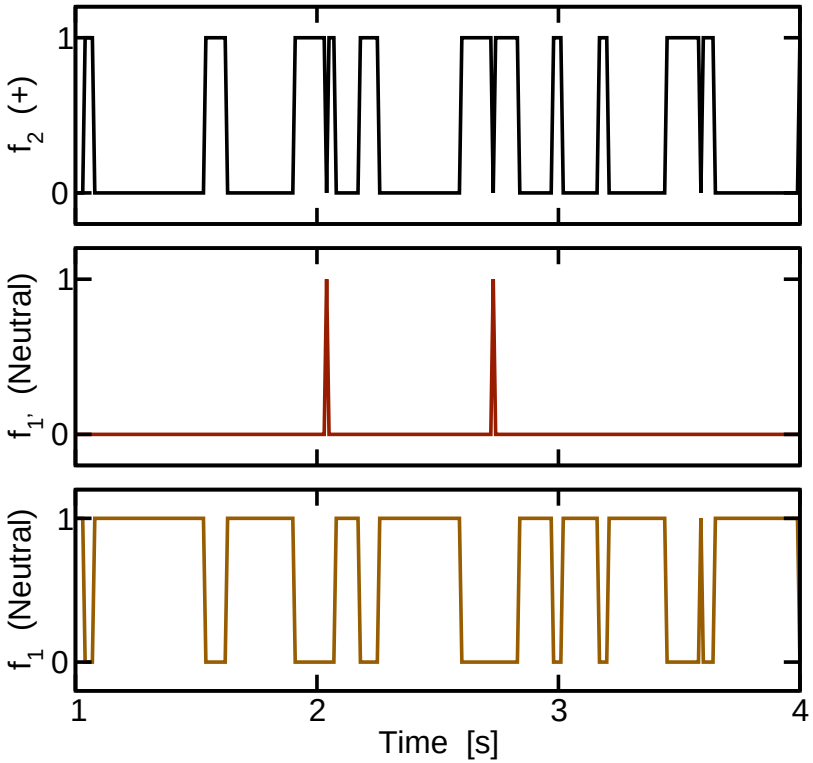
Nonradiative multiphonon model

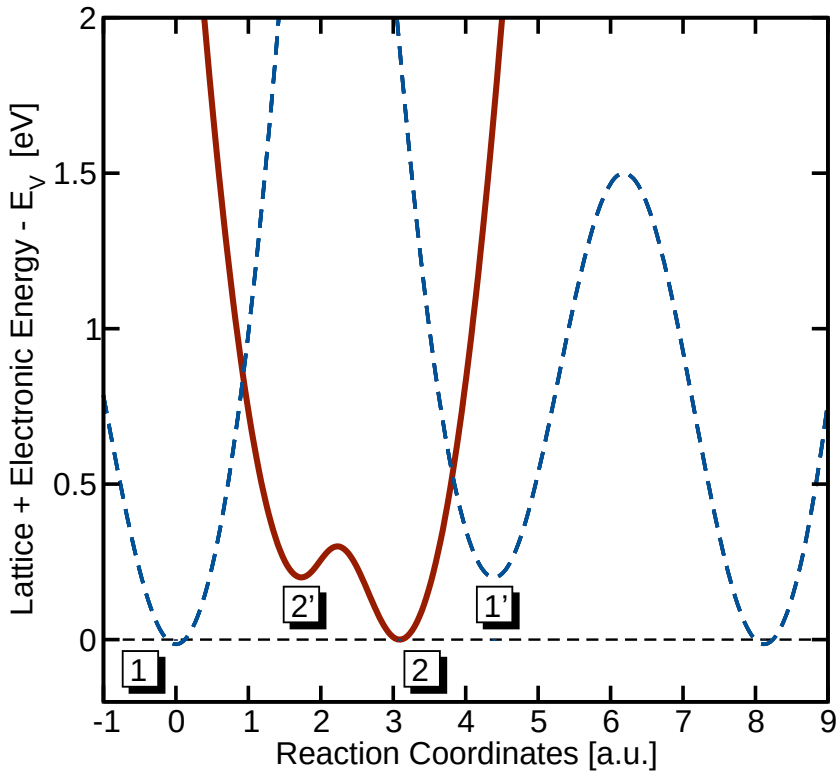
Inelastic tunneling, no 'tunneling front'

Qualitative Model Evaluation

Normal random telegraph noise (RTN)

Very similar energetical position of the minimas 1 and 2



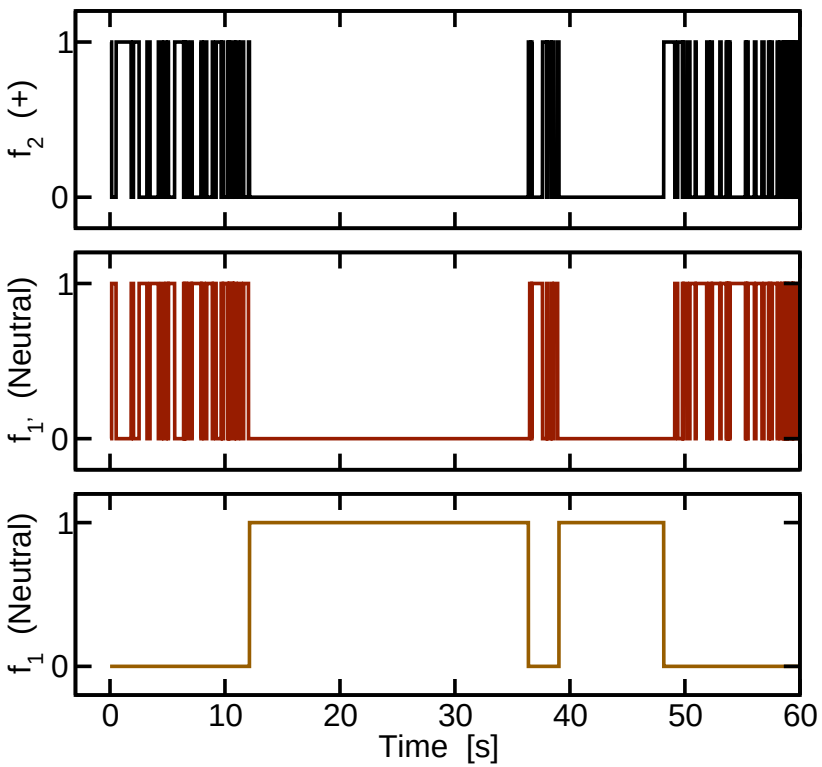


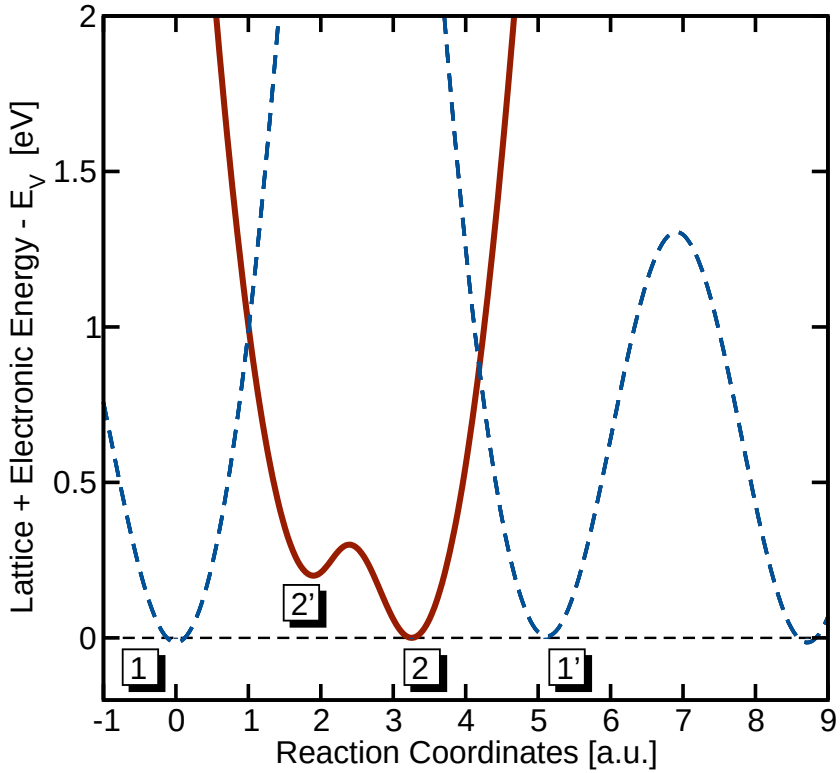
Kirton and Uren, Adv. Phys. '89

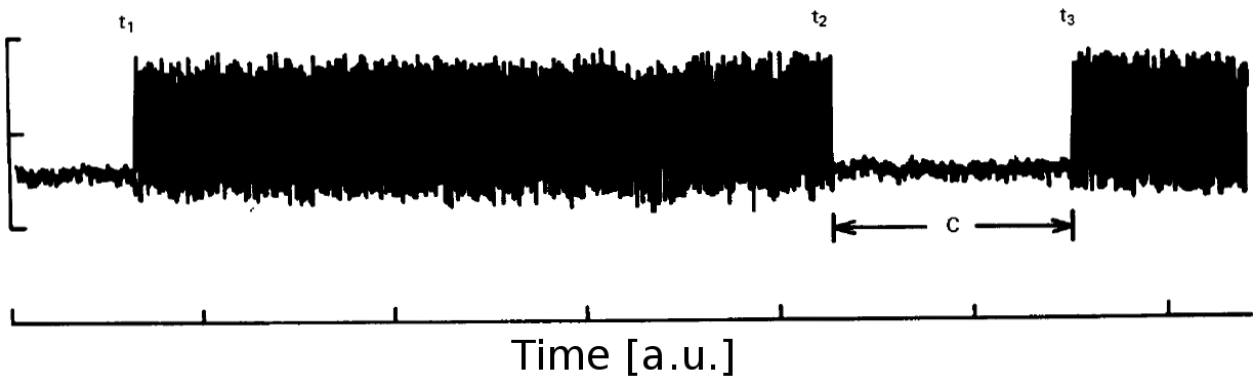
Qualitative Model Evaluation

Anomalous RTN

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





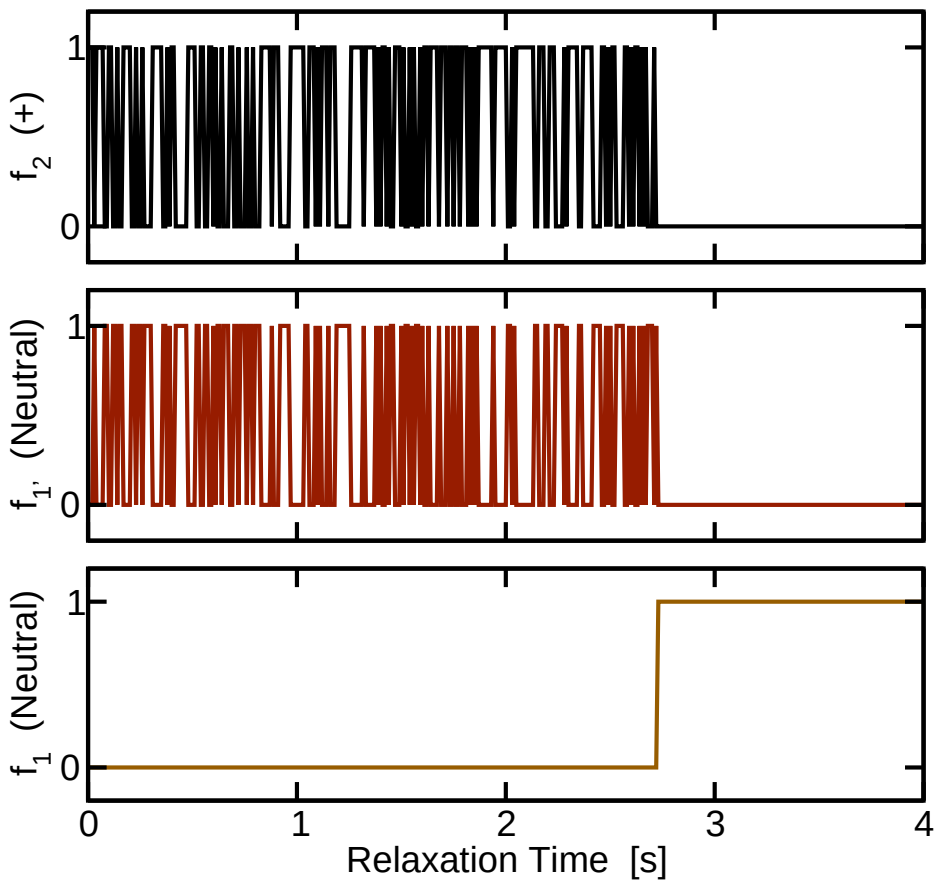


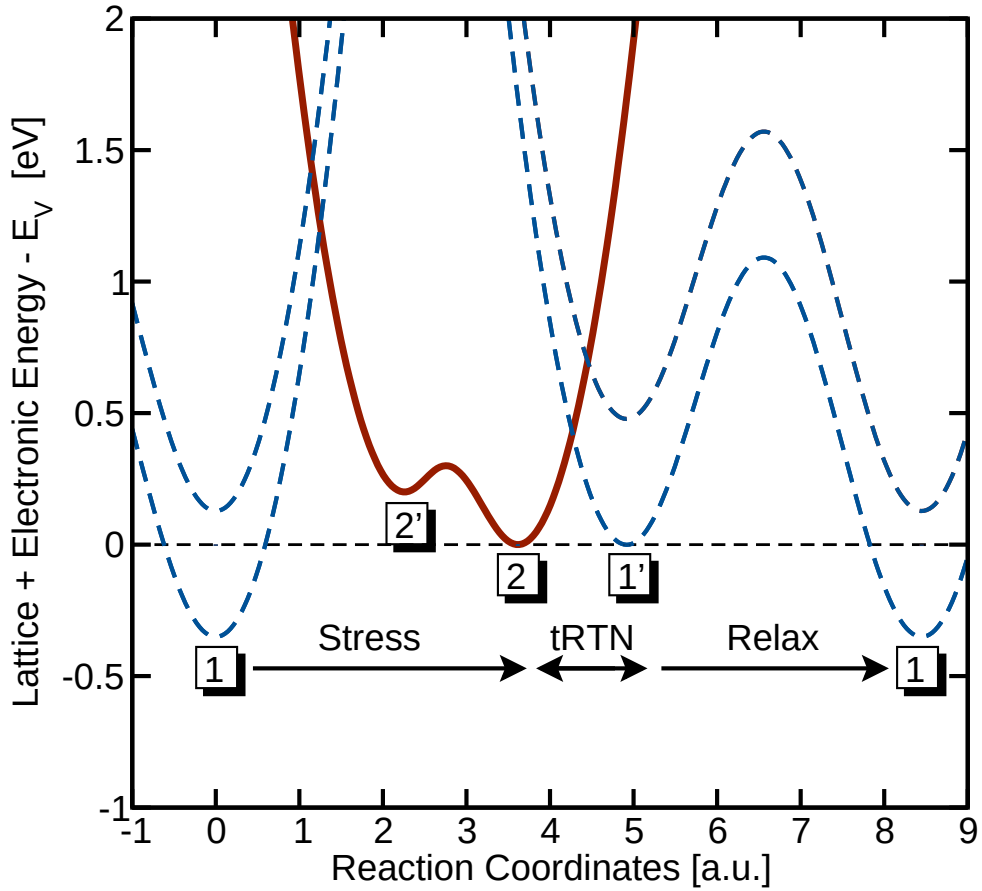
Uren *et al.*, PRB '88

Qualitative Model Evaluation

Temporary random telegraph noise (tRTN)

Very similar energetical position of the minima 2 and 1'





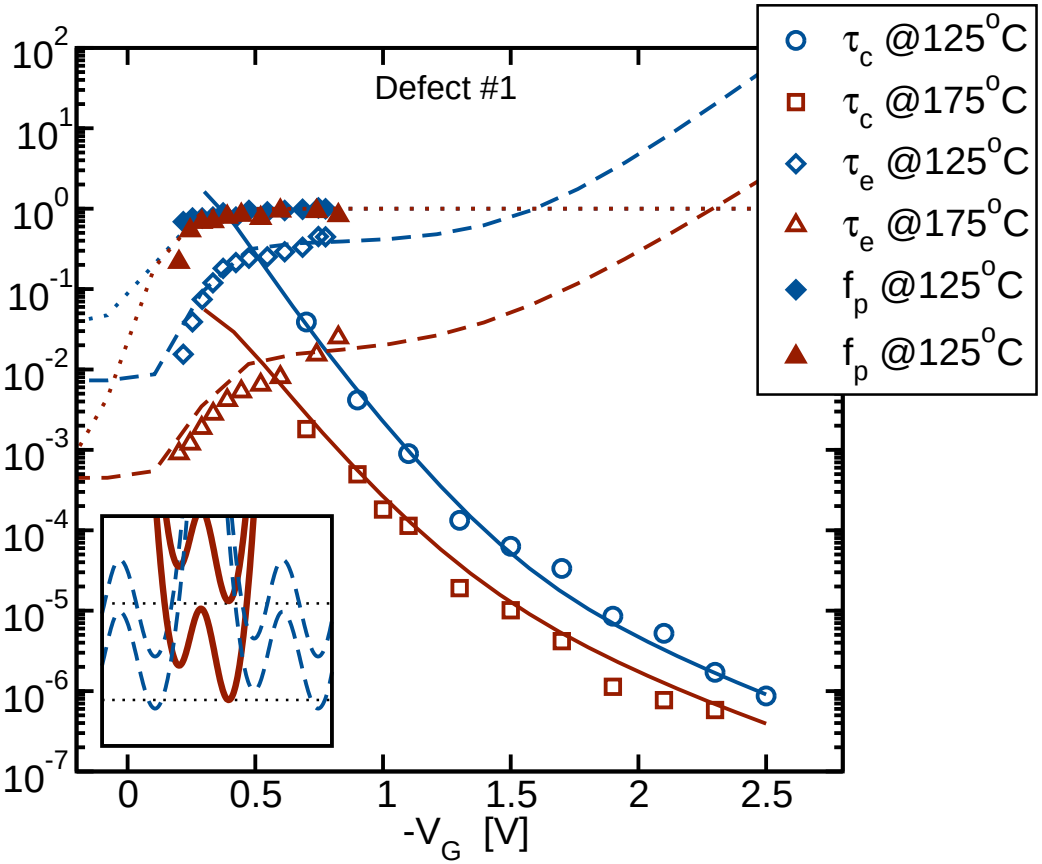
Quantitative Model Evaluation

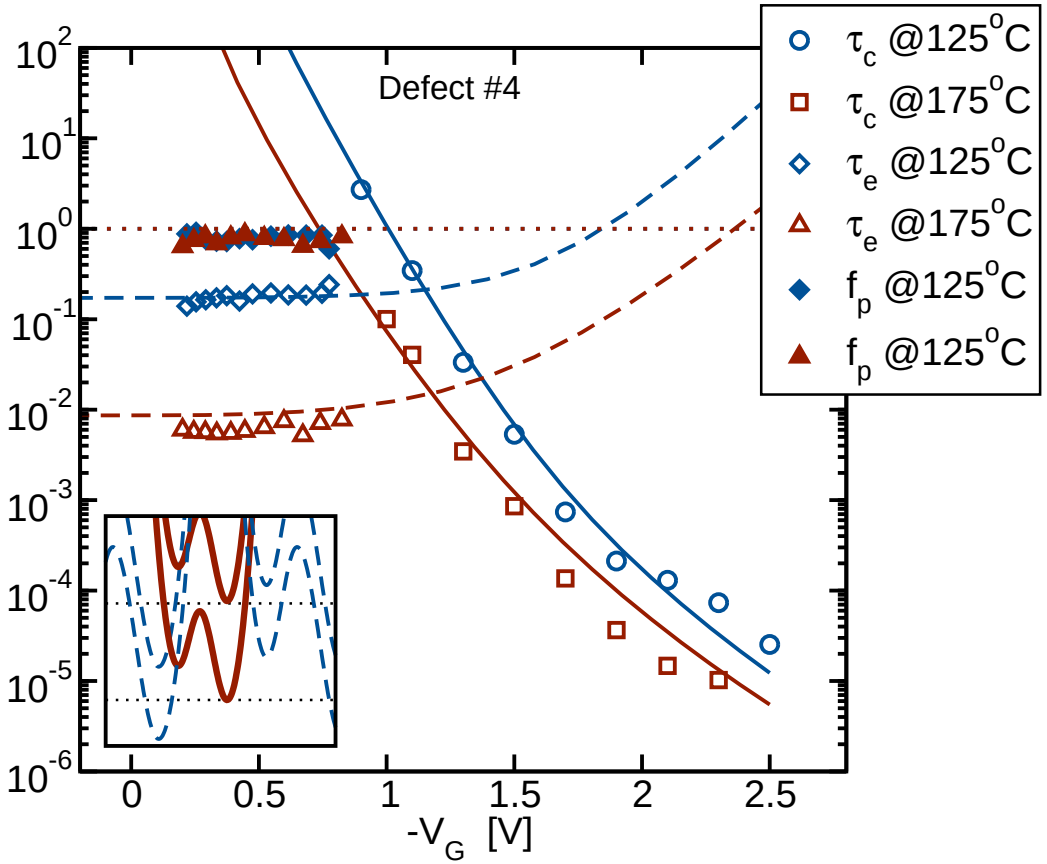
Excellent agreement for both capture and emission time constants

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

Does the defect act like a switching trap?

- Depends on the defect configuration

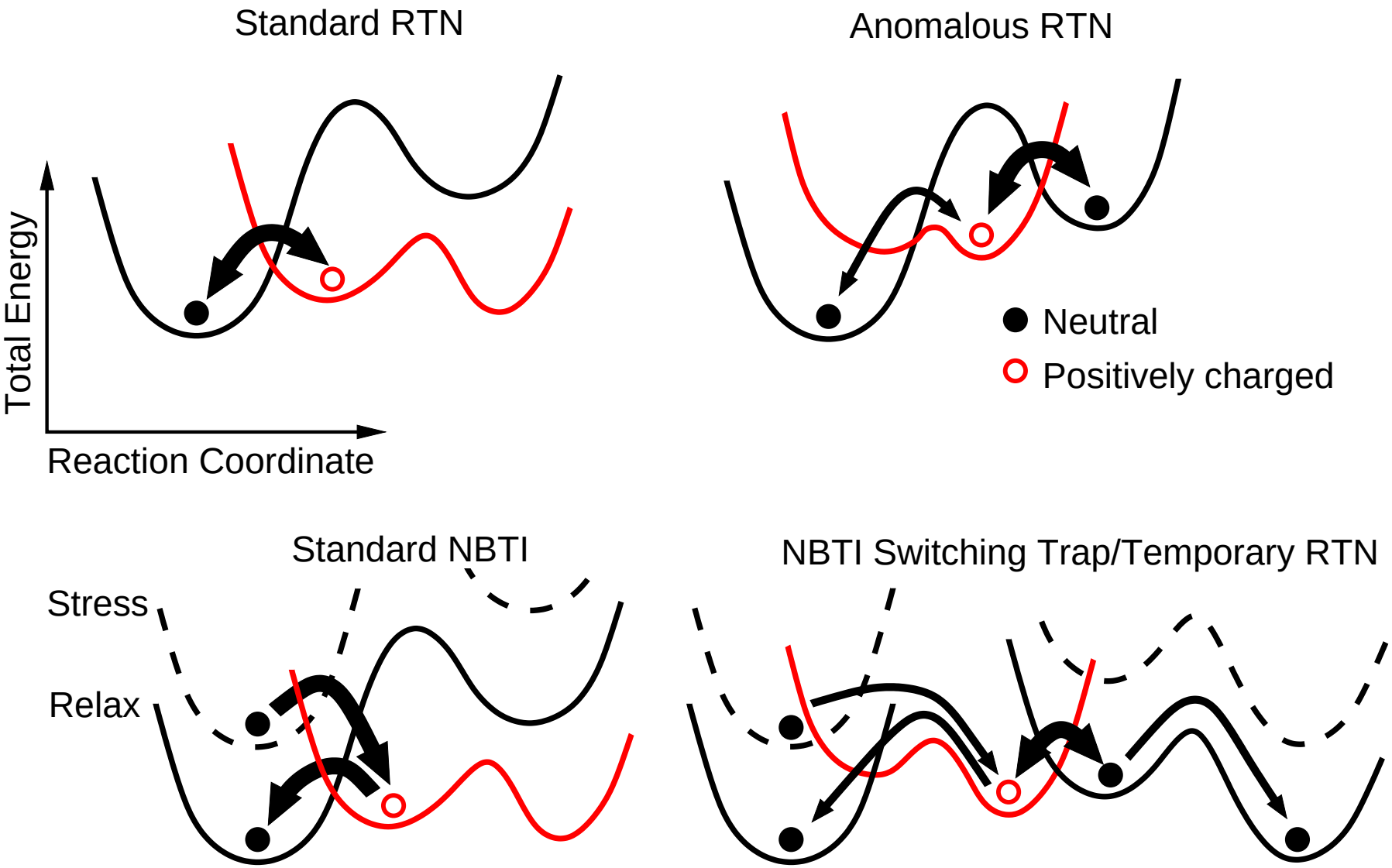




Model Summary

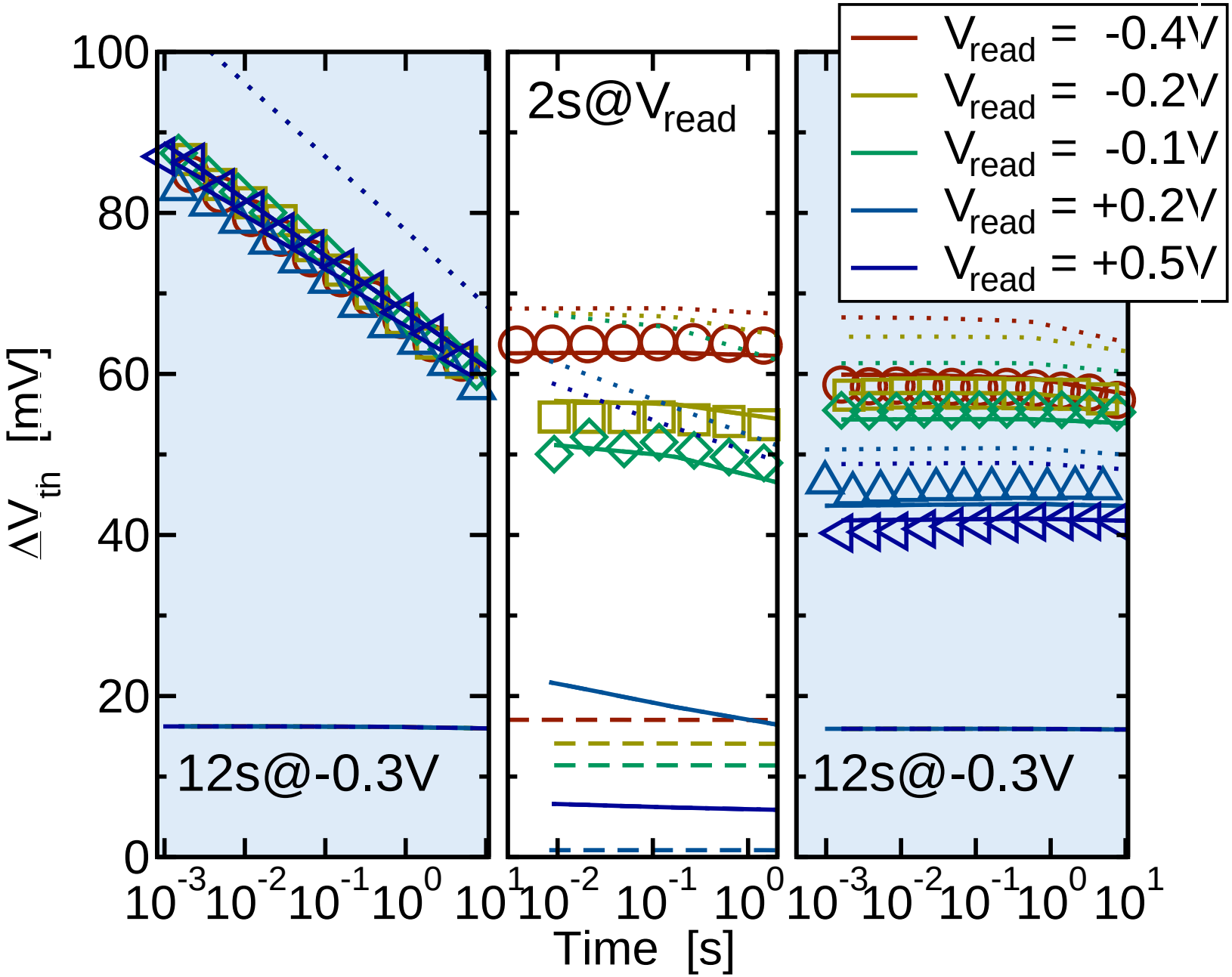
All features can be consistently explained with a general defect model

Differences simple consequences of defect potentials (amorphous oxide!)



NBTI Modeling

NBTI model based on switching traps (Grasser *et al.*, IRPS '09)



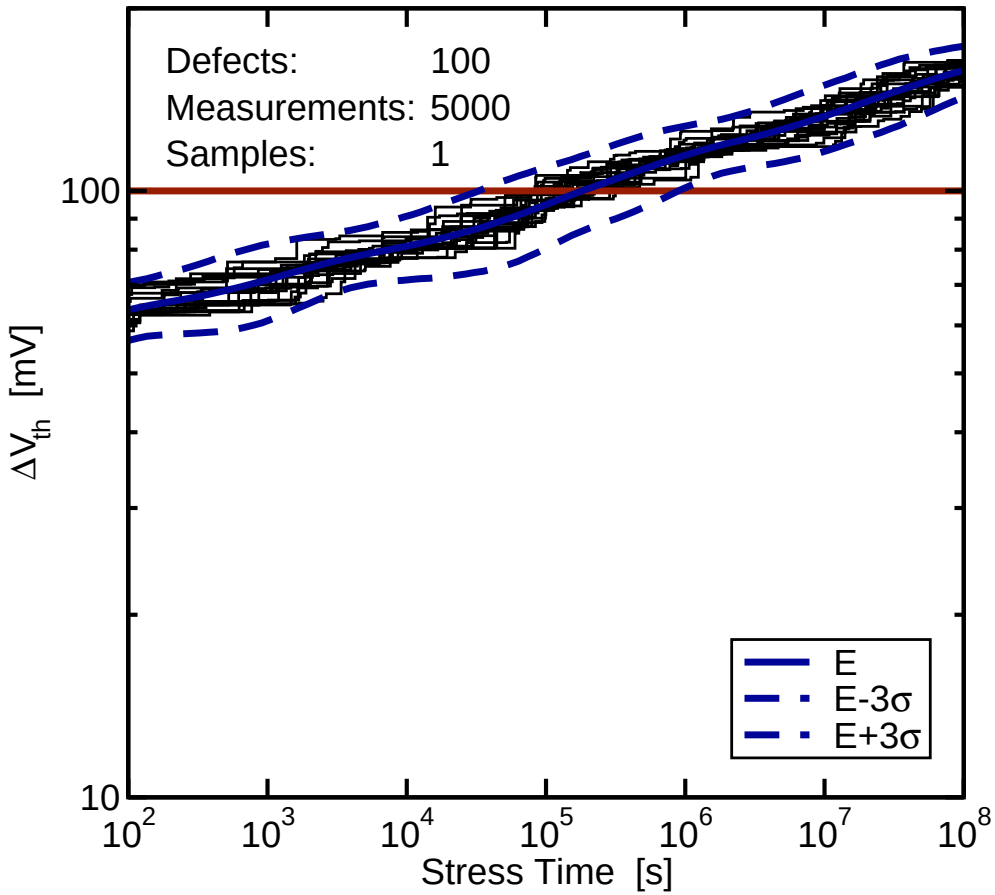
Why Would We Care?

How to Determine the Lifetime?

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

Charge capture/emission stochastic events

Capture and emission times distributed



$N_t = 10^{12}\,\mathrm{cm}^{-2}$; $W \times L = 100\,\mathrm{nm} \times 100\,\mathrm{nm} \Rightarrow 100$ defects;

[1] Grasser *et al.* IEDM '10

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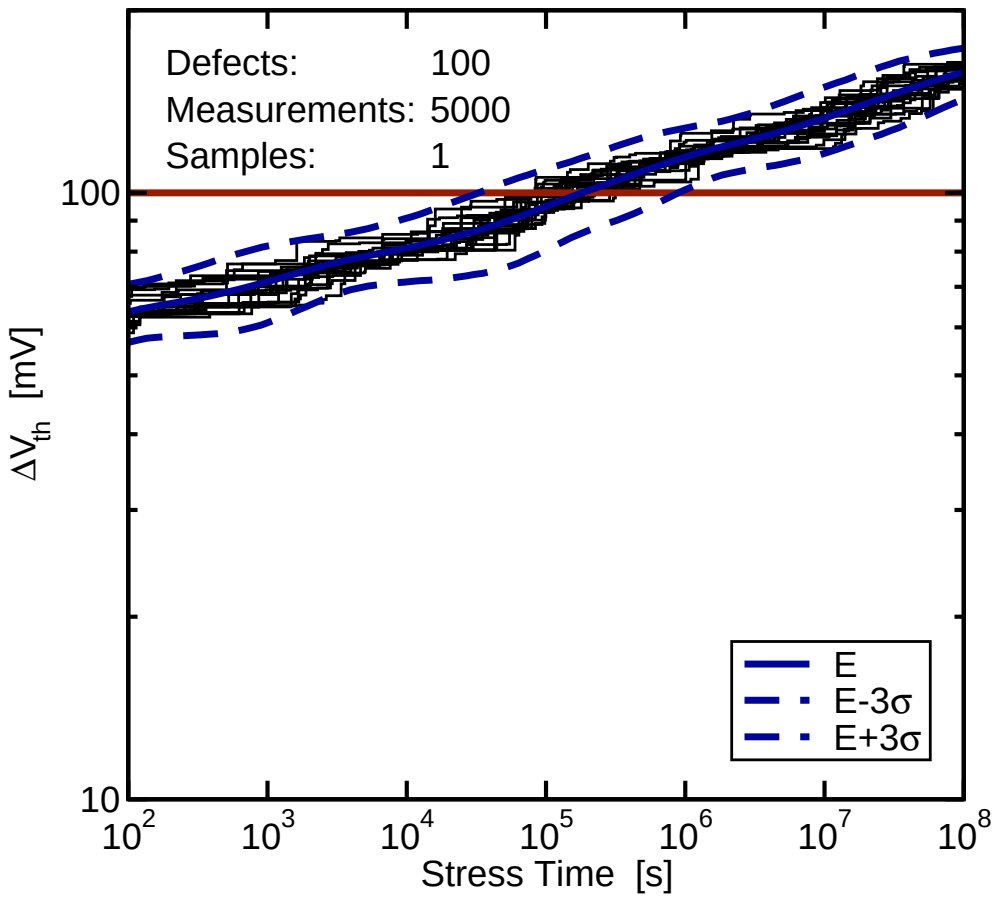
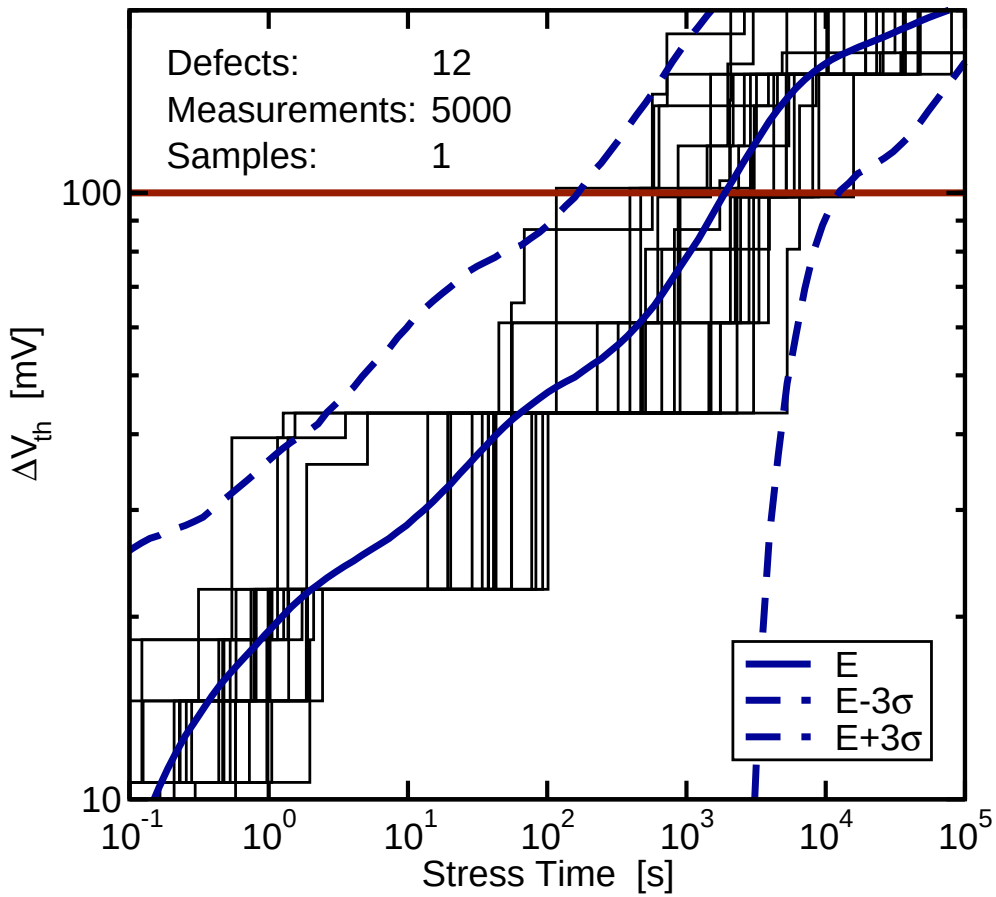




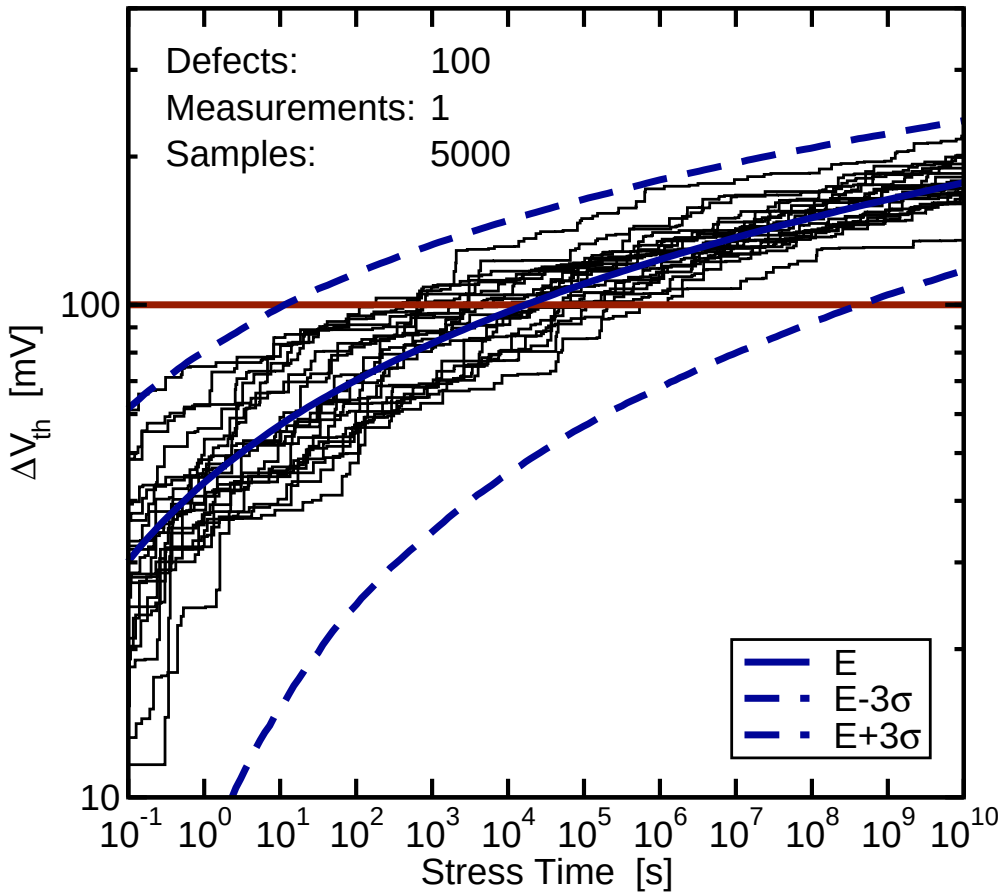
$N_t = 10^{12}\,\mathrm{cm}^{-2}$; $W \times L = 100\,\mathrm{nm} \times 100\,\mathrm{nm} \Rightarrow 100$ defects;

$35\,\mathrm{nm} \times 35\,\mathrm{nm} \Rightarrow 12$ defects

How to Determine the Lifetime?

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



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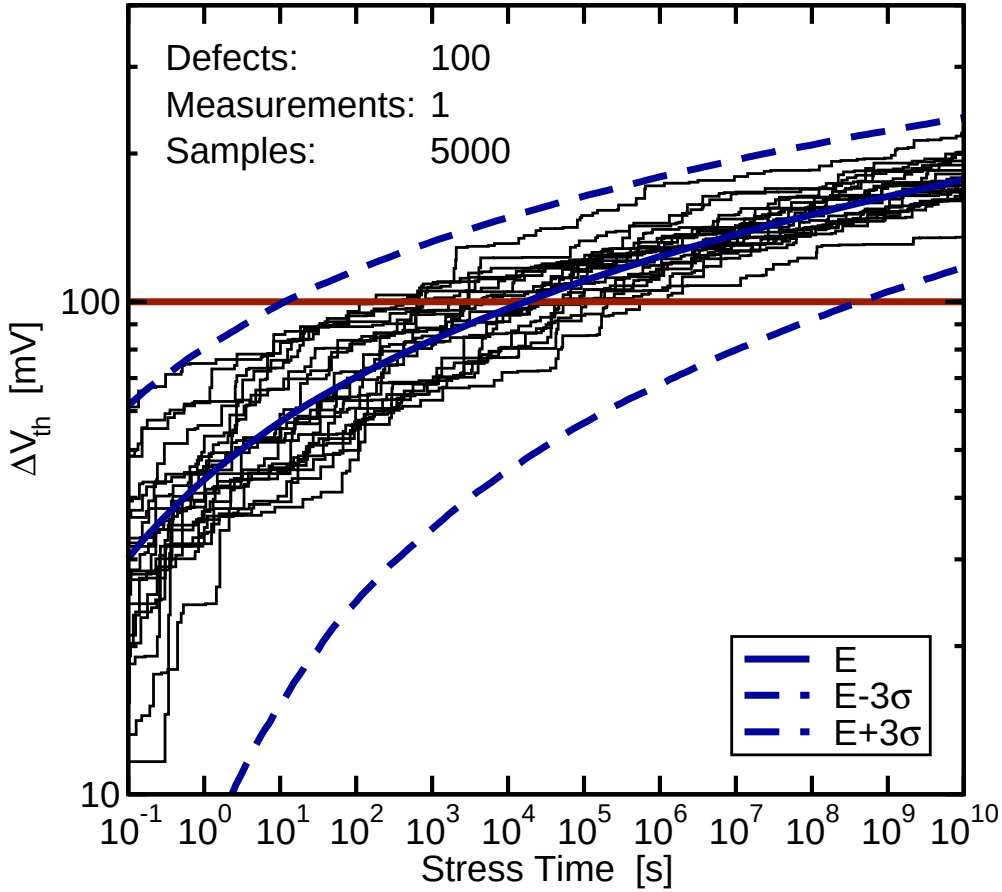

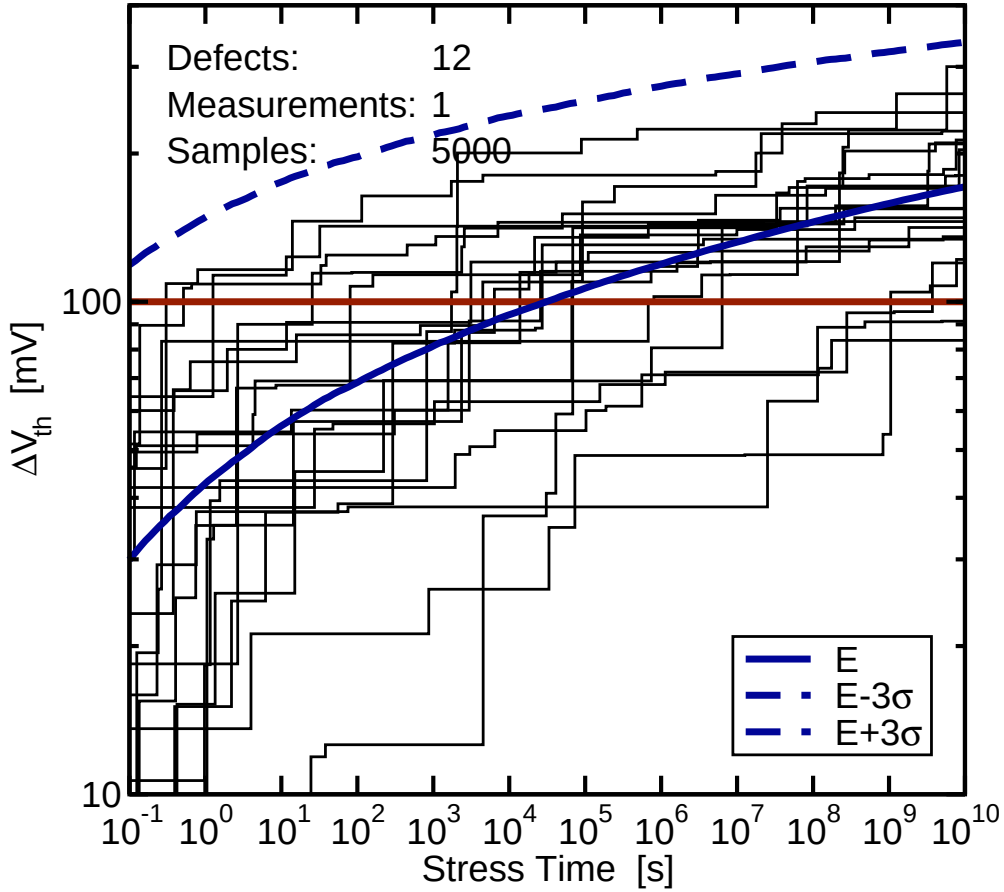

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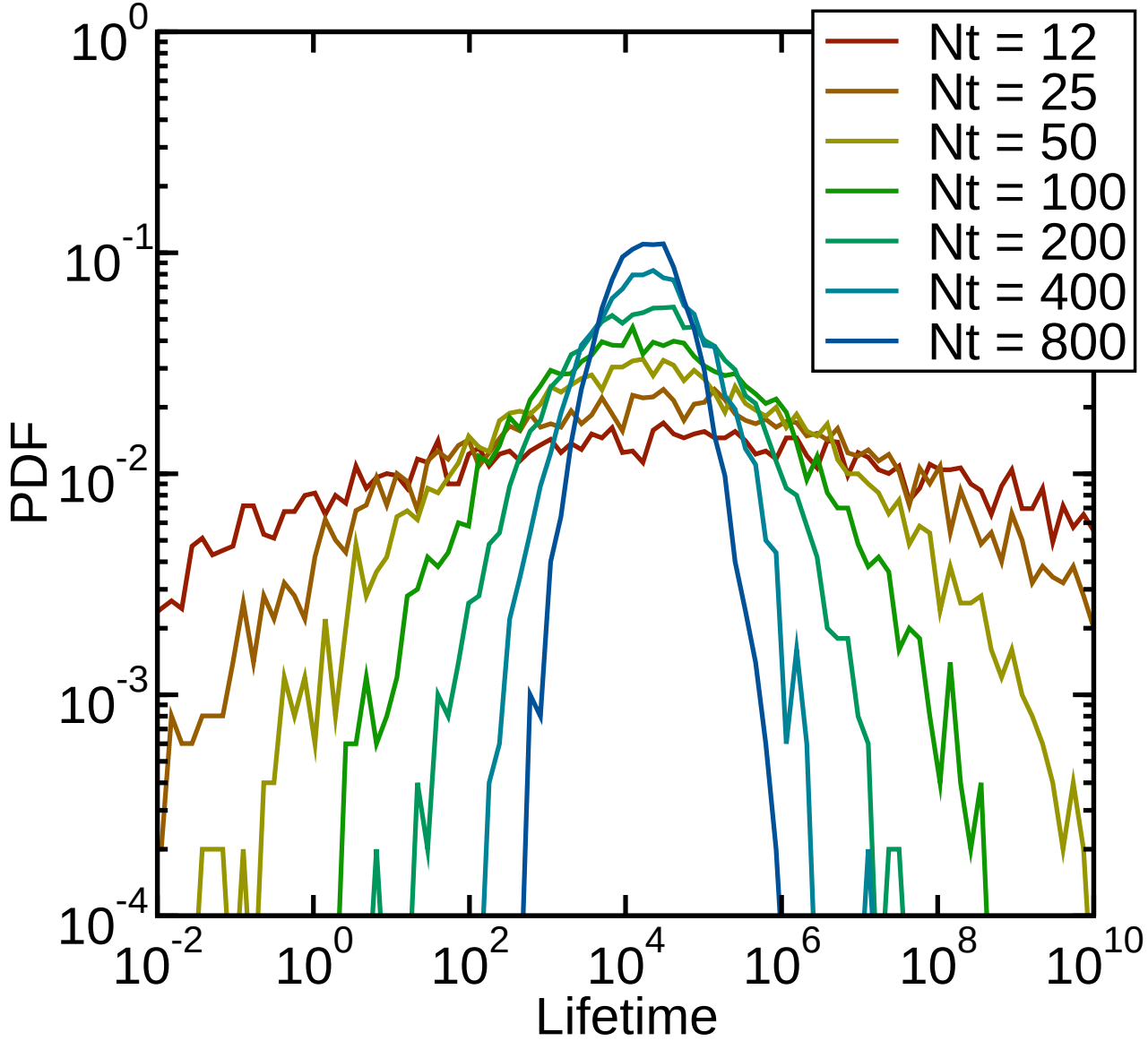
$35\,\mathrm{nm} \times 35\,\mathrm{nm} \Rightarrow 12$ defects

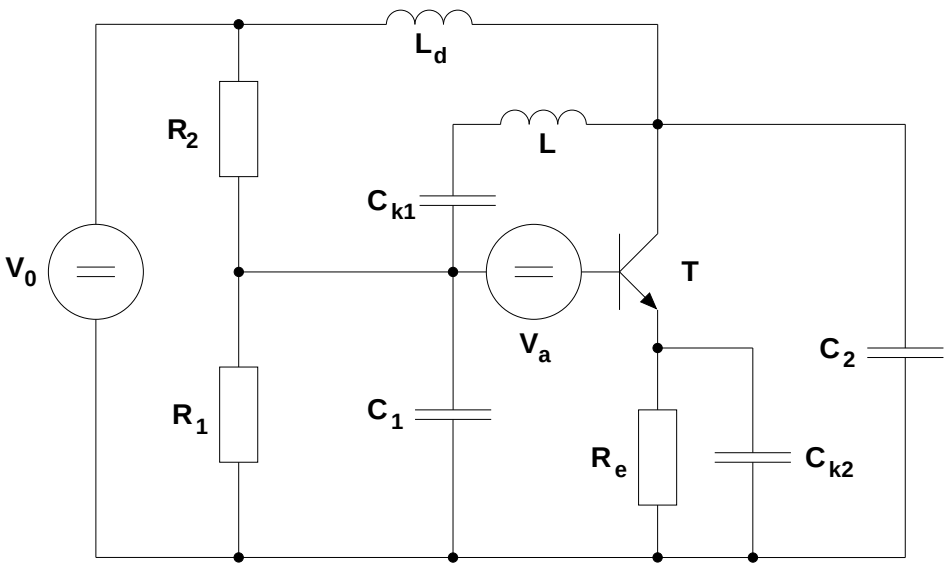
Stochastic Lifetimes

Distribution of lifetime[1]

Variance increases with decreasing number of defects



How to Model This with SPICE?



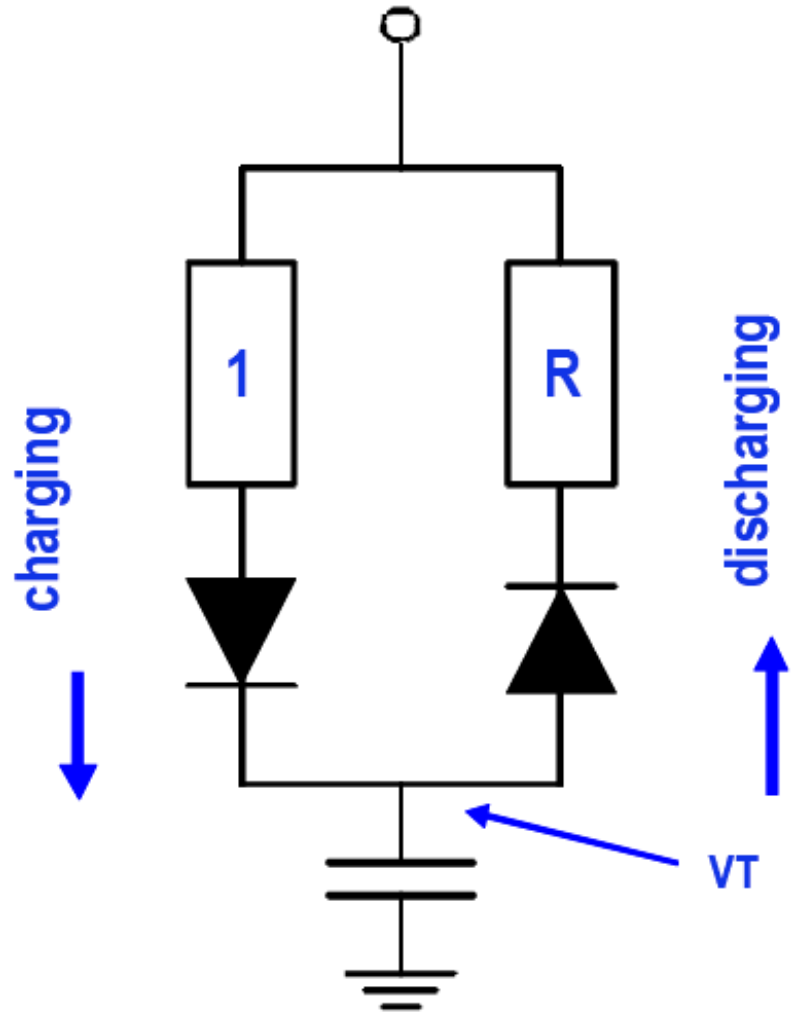
Compact Modeling

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

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

Differential equation for a two-state model

- Corresponds to an RC equivalent circuit
- Two branches: charging vs. discharging

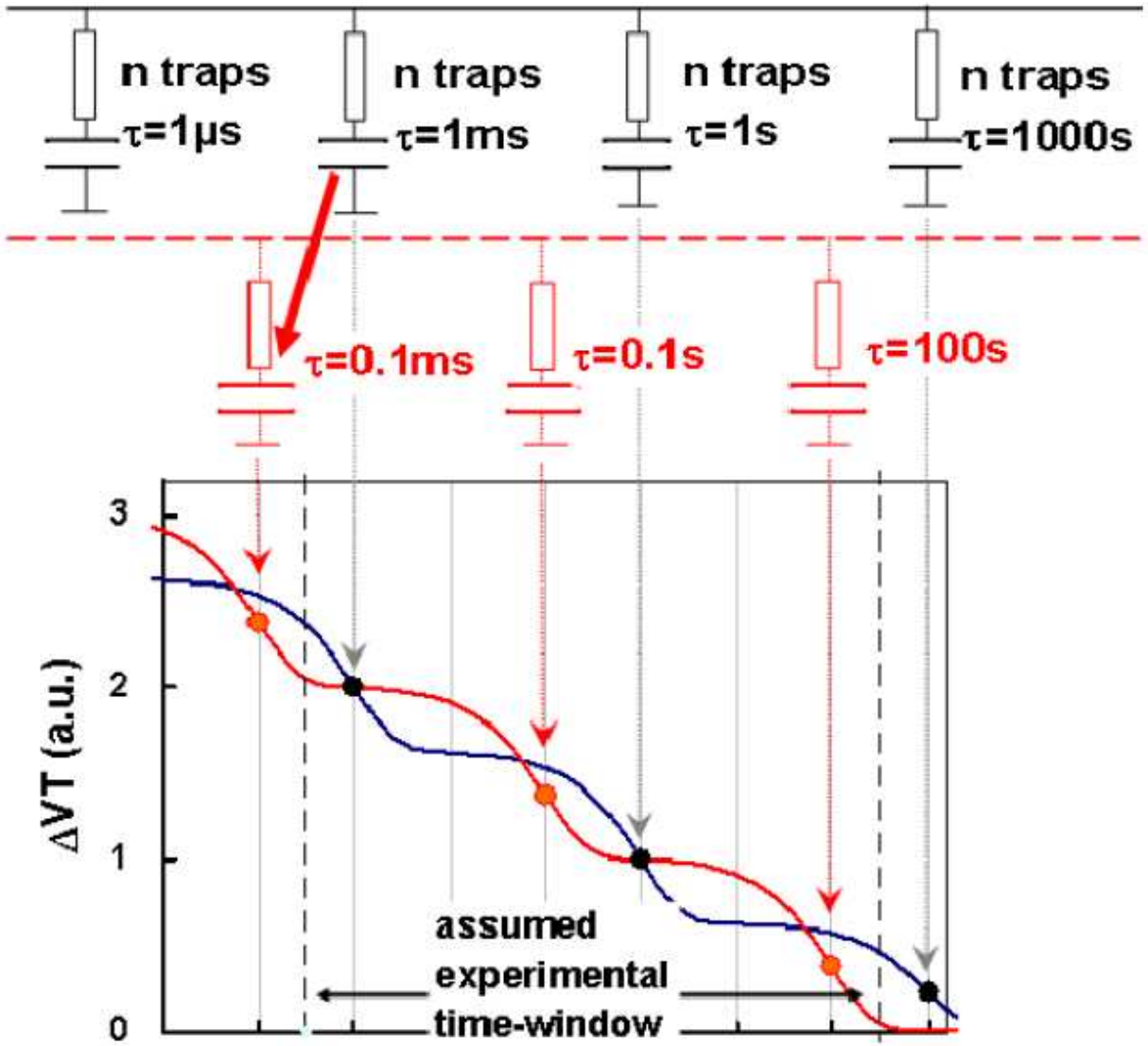


[1] Kaczer *et al.*, IRPS '10 [2] Reisinger *et al.*, IRPS '10

Compact Modeling

Example: modeling of recovery[1]

Crude approximation: 1 RC element every 3 decades

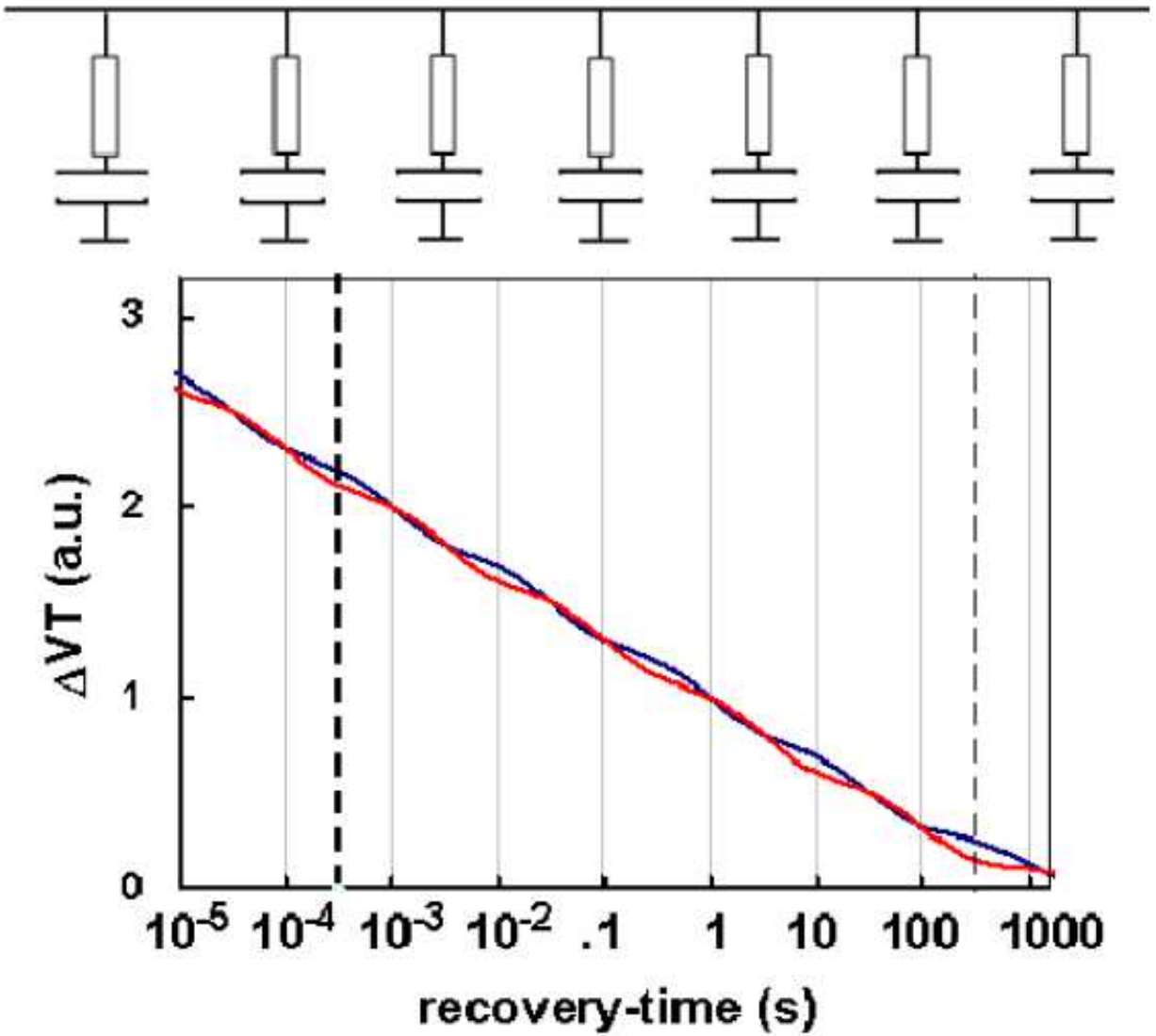


[1] Reisinger *et al.*, IRPS '10

Compact Modeling

Example: modeling of recovery[1]

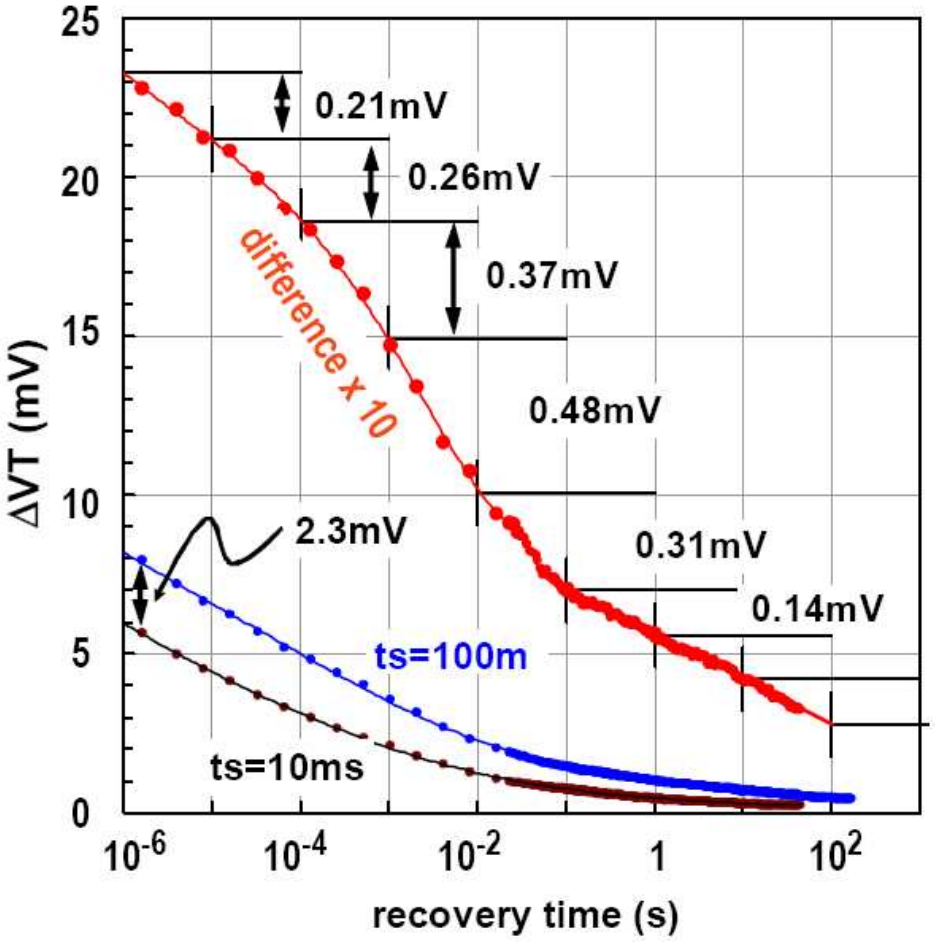
Finer approximation: 2 RC elements every 3 decades

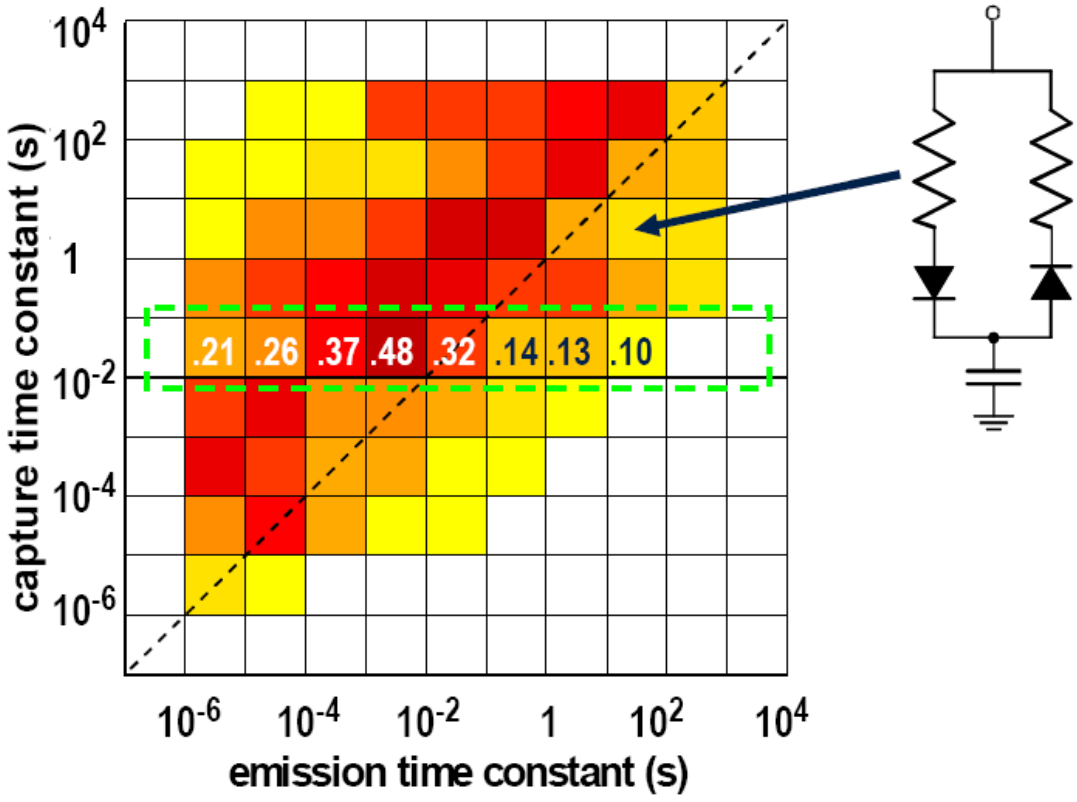


[1] Reisinger *et al.*, IRPS '10

Compact Modeling

Extraction of the time constants[1]

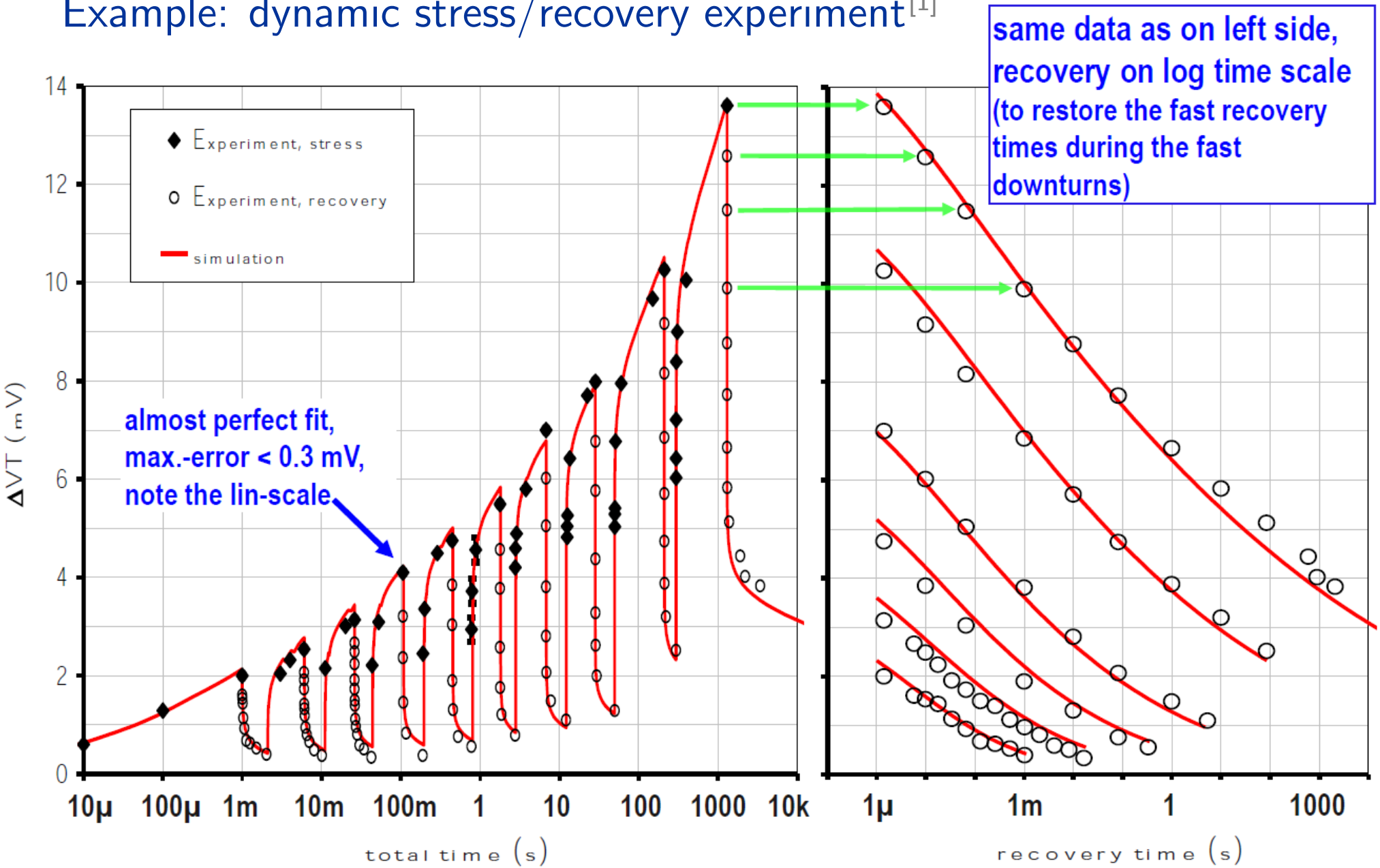




[1] Reisinger *et al.*, IRPS '10

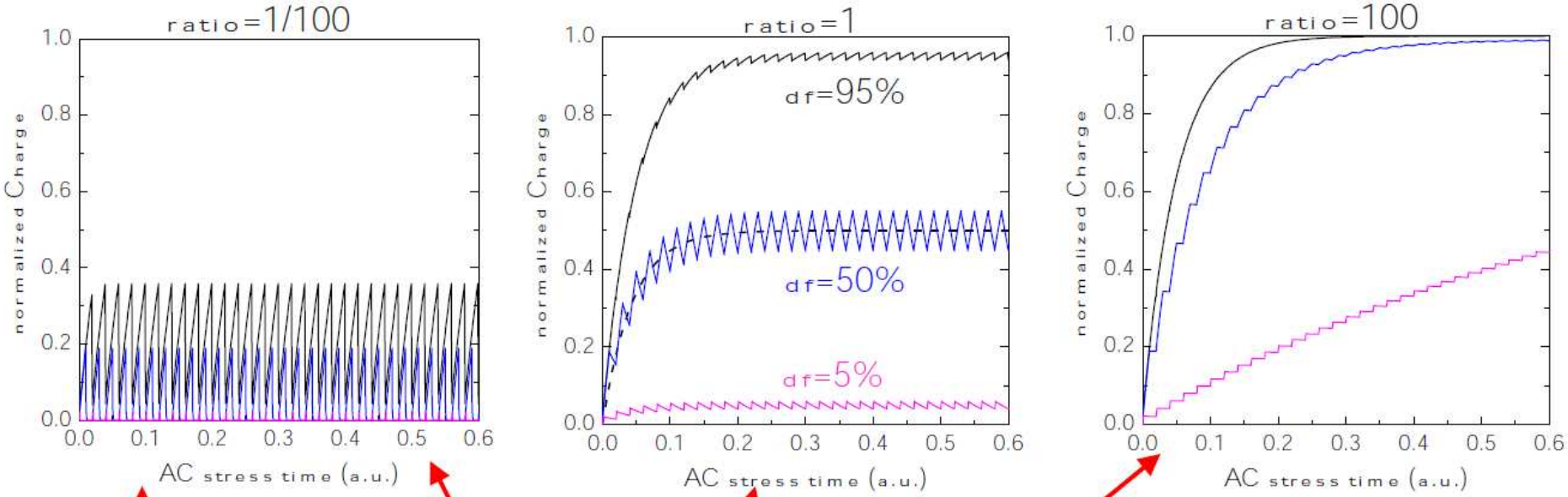
Compact Modeling

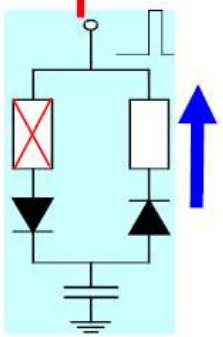
Example: dynamic stress/recovery experiment[1]



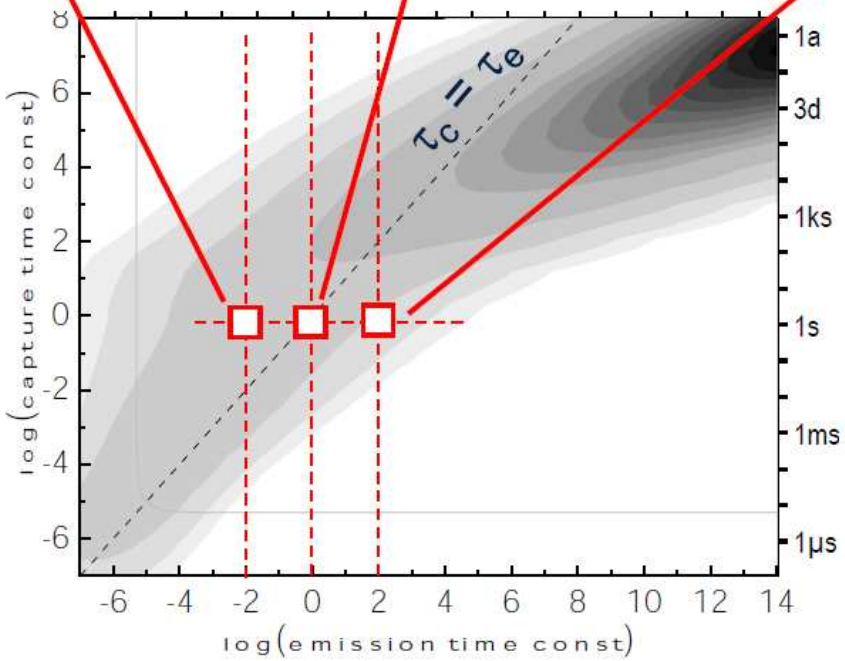
[1] Reisinger *et al.*, IRPS '10 and IRPS '11 (Tutorial)

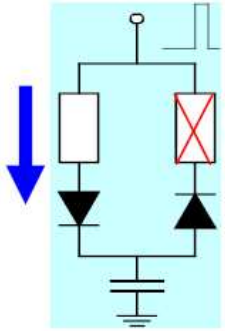
Compact Modeling: Duty Factor Dependence





charging is slower than discharging



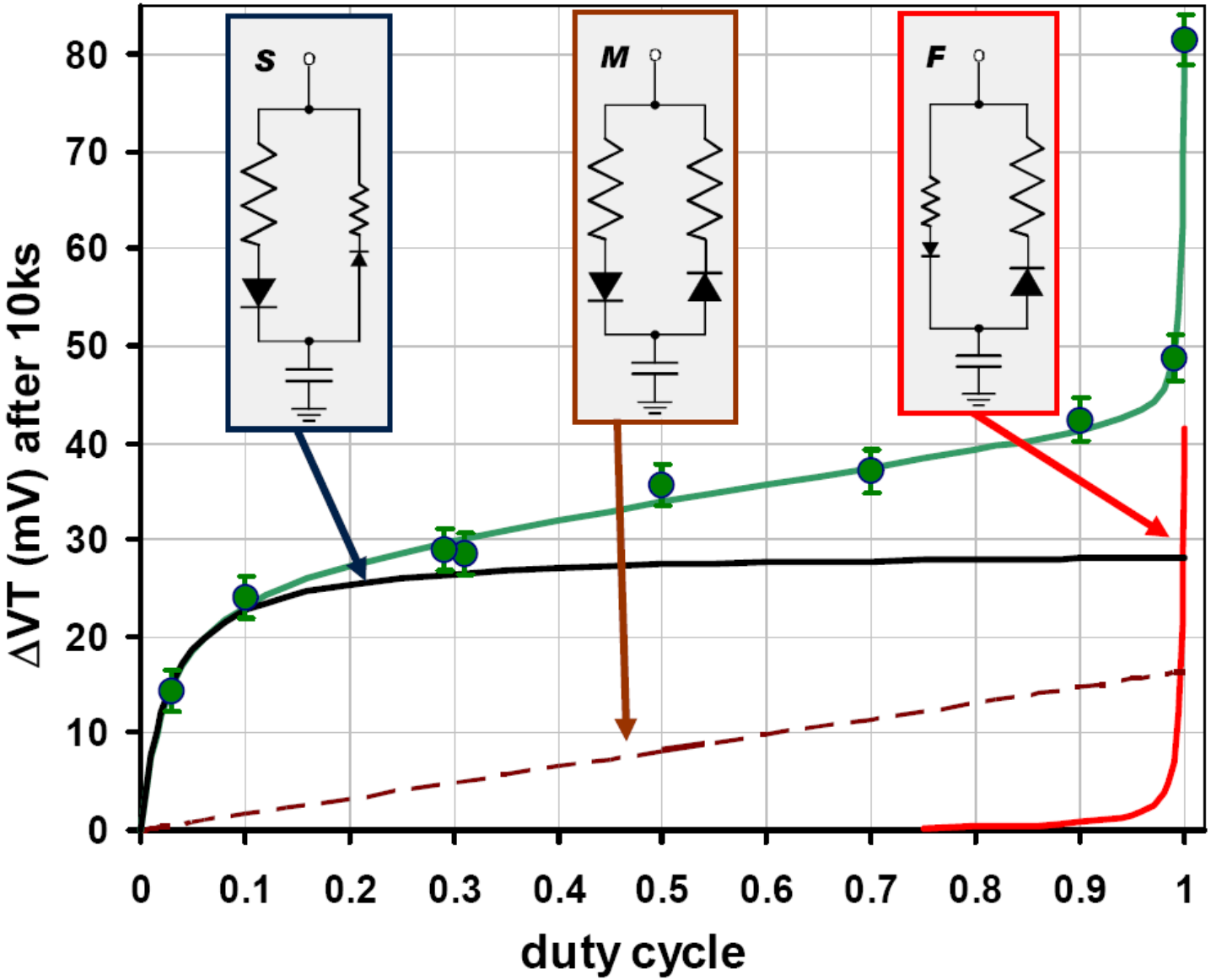


charging is faster than discharging; behaves like a peak-detecting rectifier

[1] Grasser *et al.*, IEDM '07 [2] Grasser *et al.*, IRPS '08 (Tutorial) [3] Reisinger *et al.*, IRPS '10/IRPS '11 (Tut.)

Compact Modeling: Duty Factor Dependence

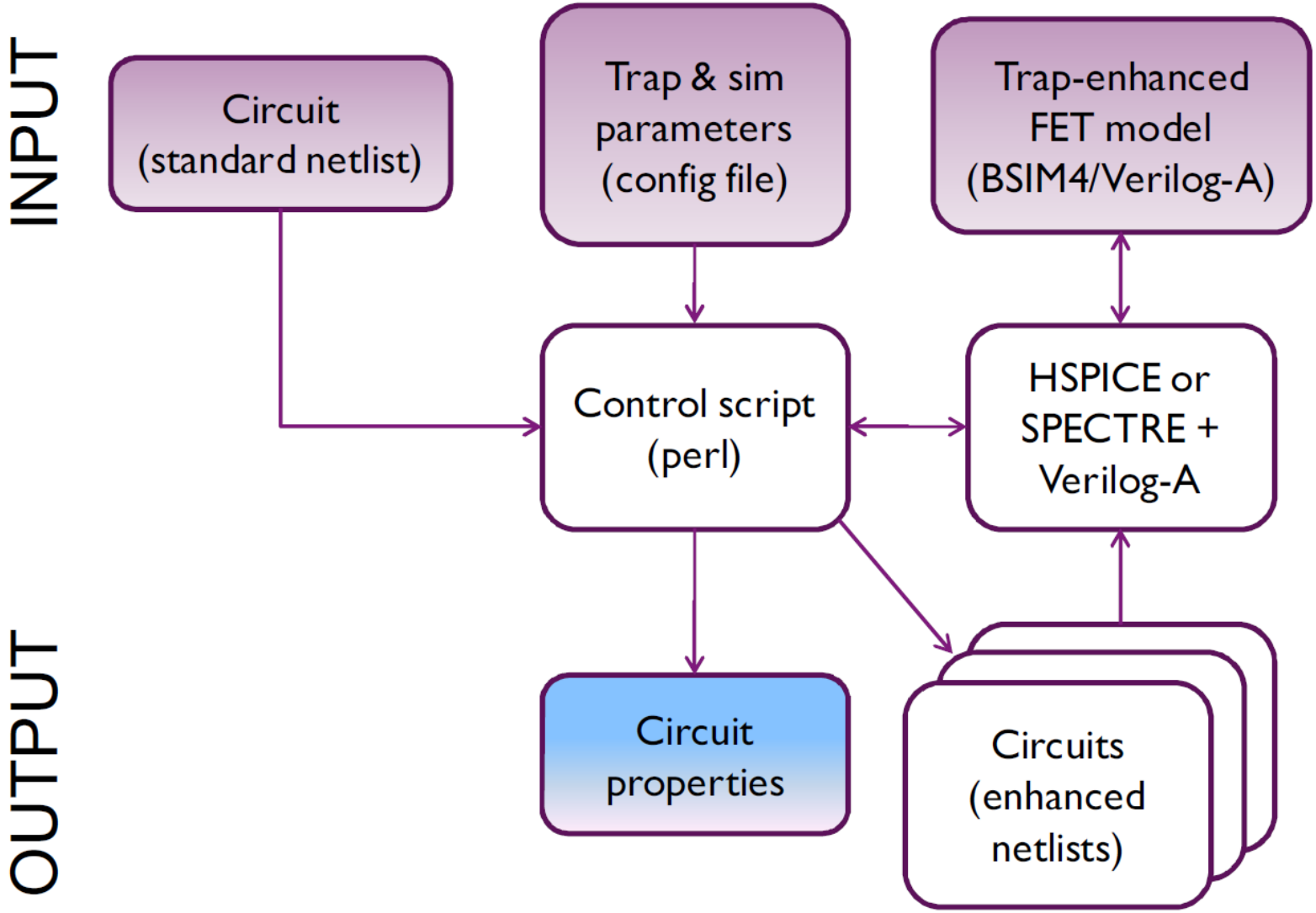
Notorious problem[1] [2] [3]



[1] Grasser *et al.*, IEDM '07 [2] Grasser *et al.*, IRPS '08 (Tutorial) [3] Reisinger *et al.*, IRPS '10/IRPS '11 (Tut.)

Stochastic Impact on Circuit

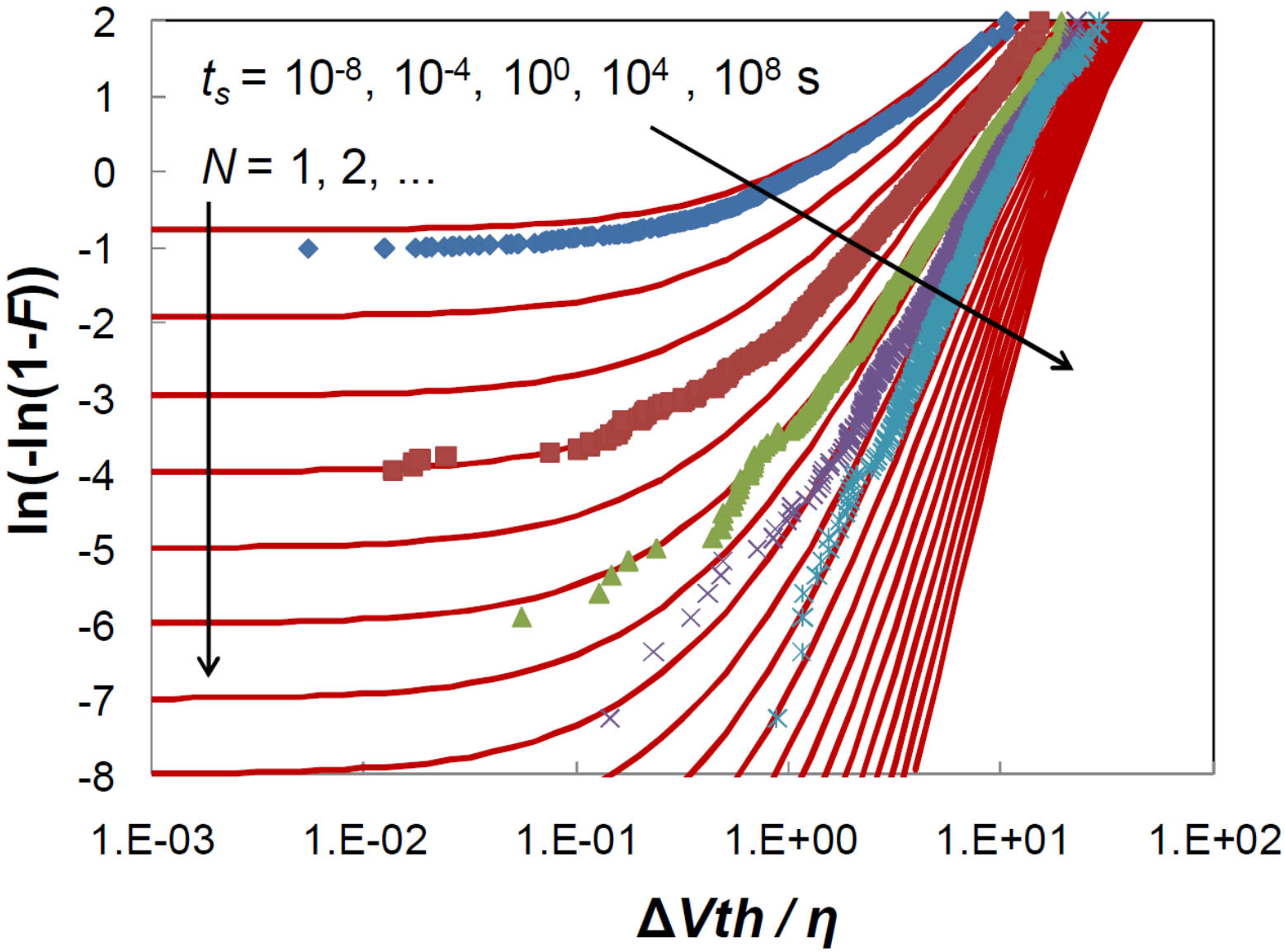
Implementation of stochastic behavior of distributed traps in VERILOG[1]



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

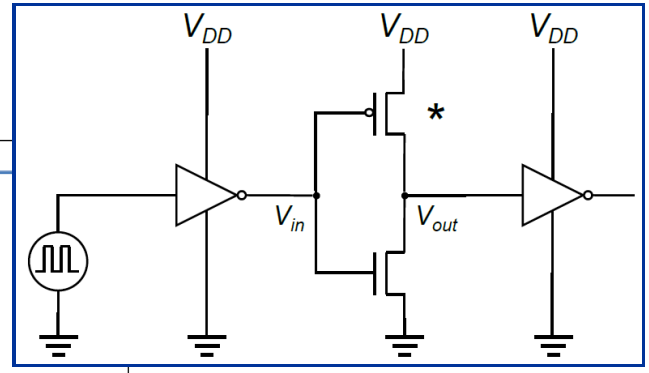
Stochastic Impact on Circuit

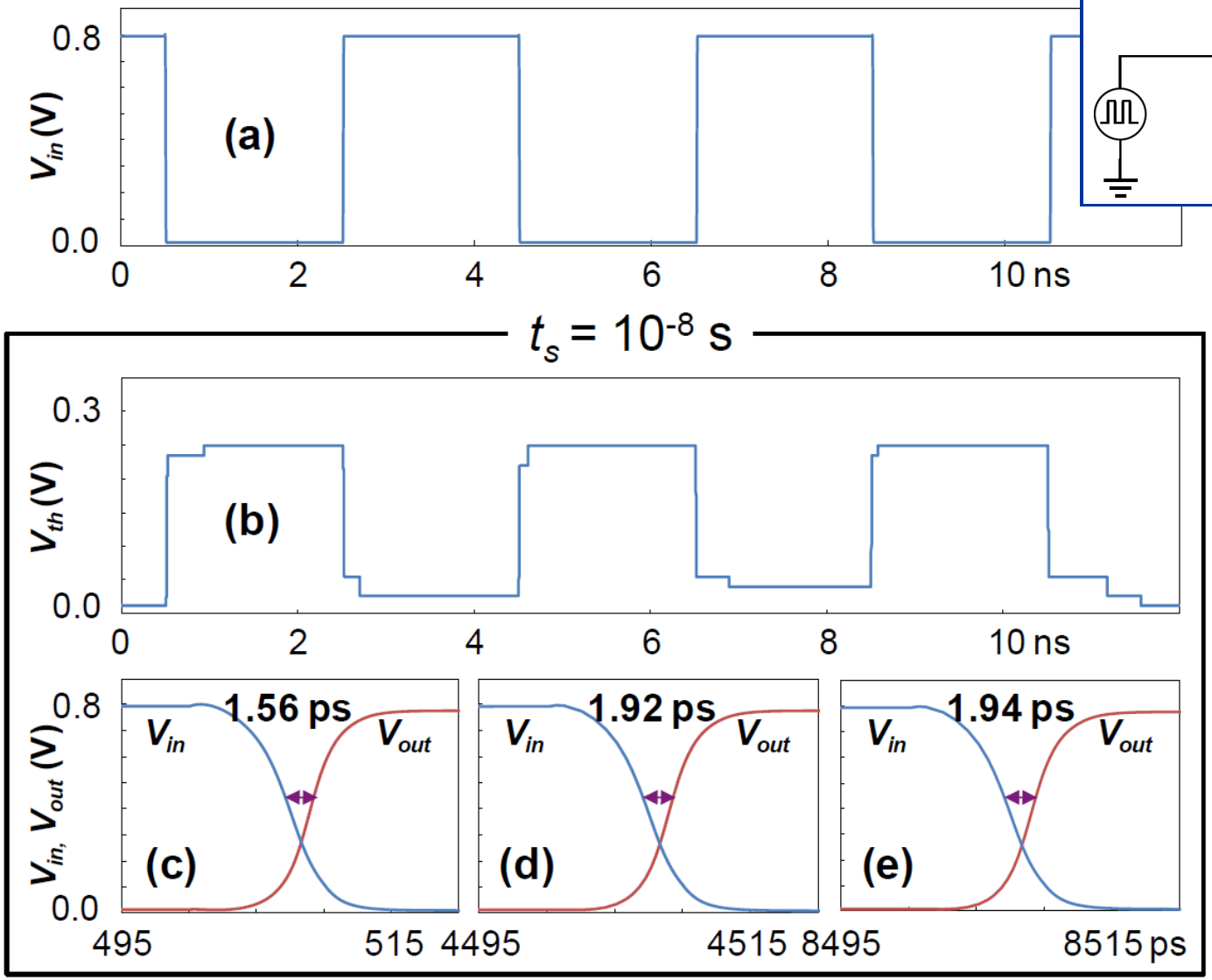
Model correctly incorporates distribution of ΔV_{th}



Stochastic Impact on Circuit

Example circuit with inverter: Jitter vs. NBTI[1]

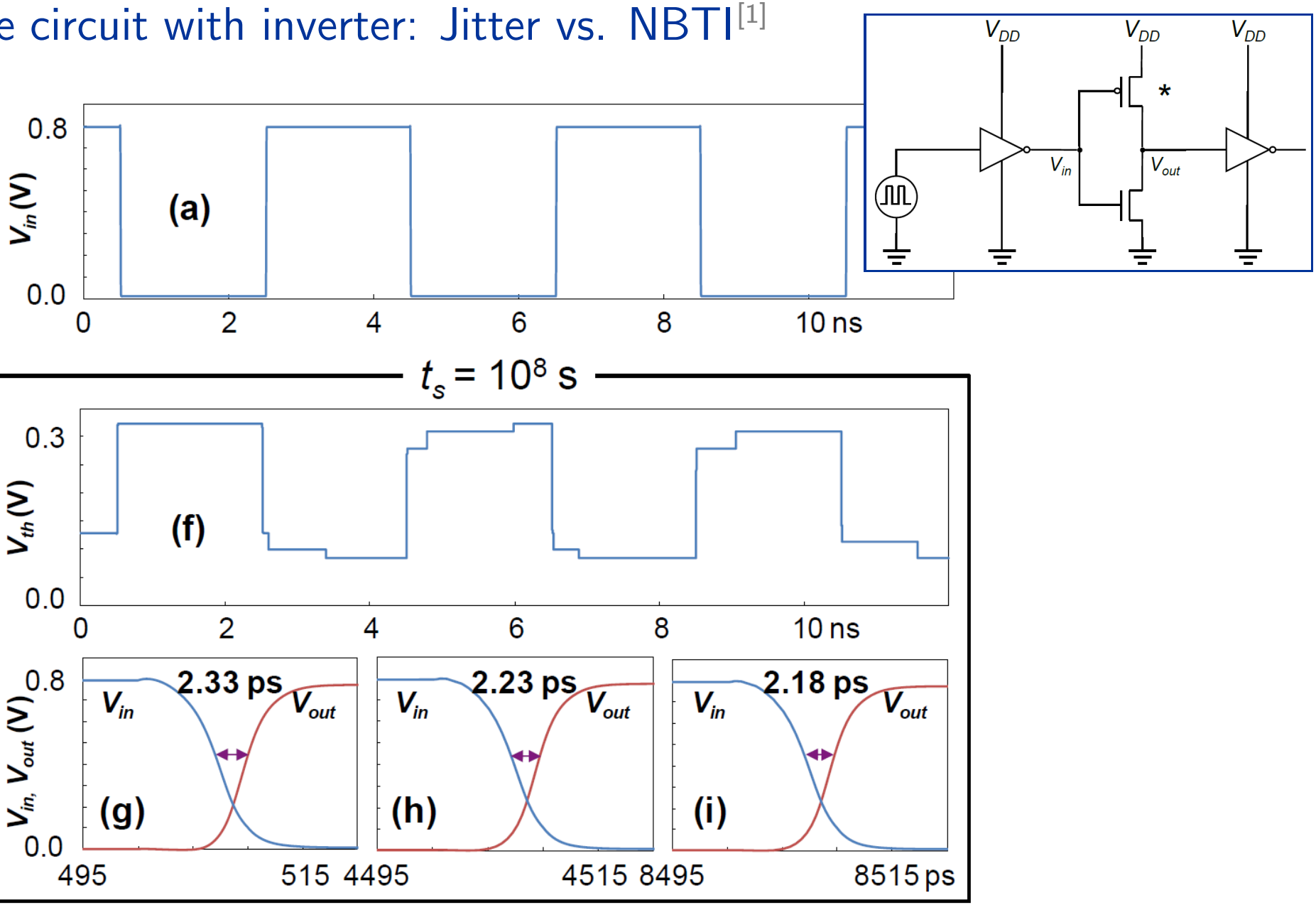




[1] Kaczer *et al.*, IRPS '11

Stochastic Impact on Circuit

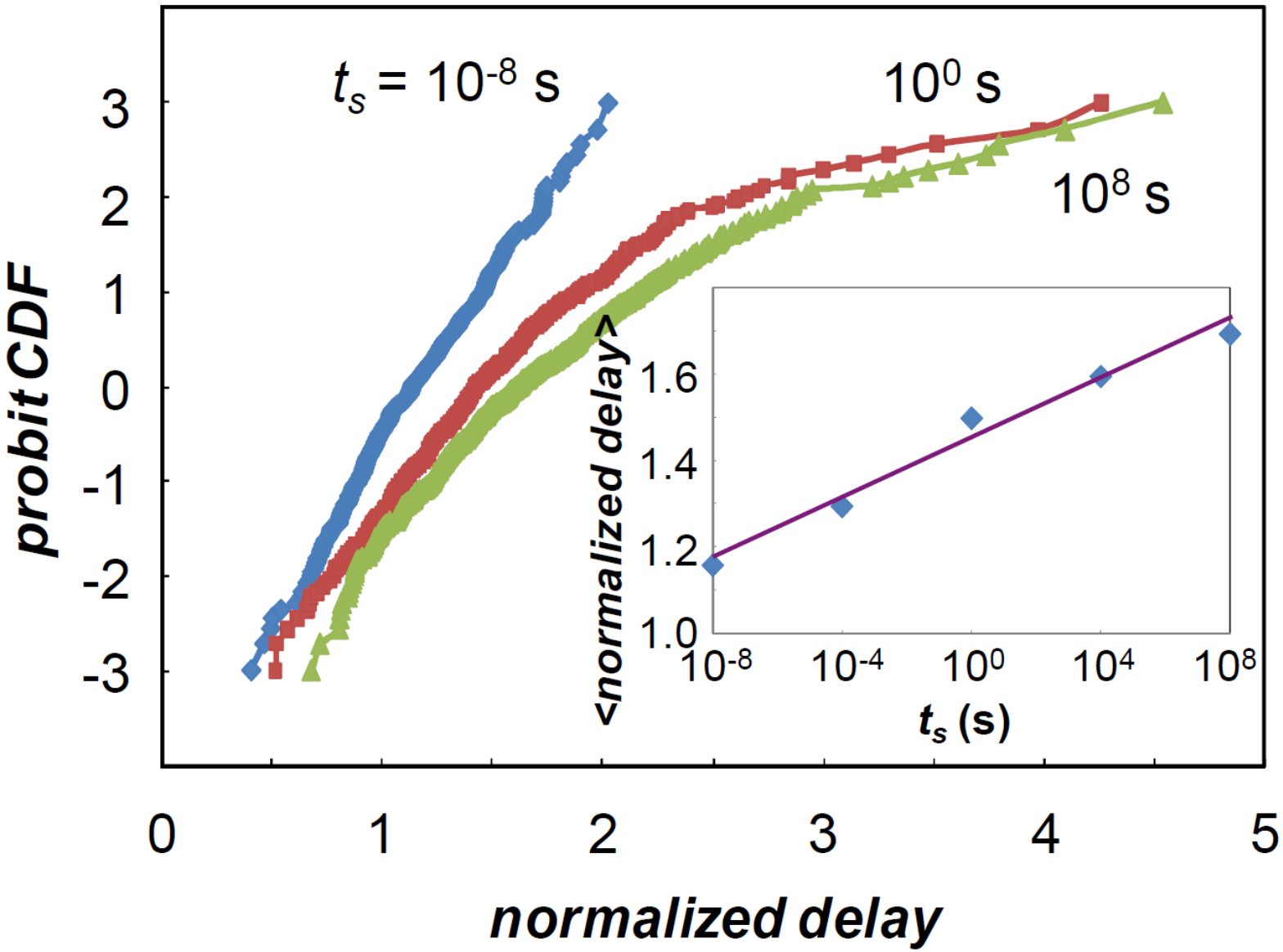
Example circuit with inverter: Jitter vs. NBTI[1]



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

Stochastic Impact on Circuit

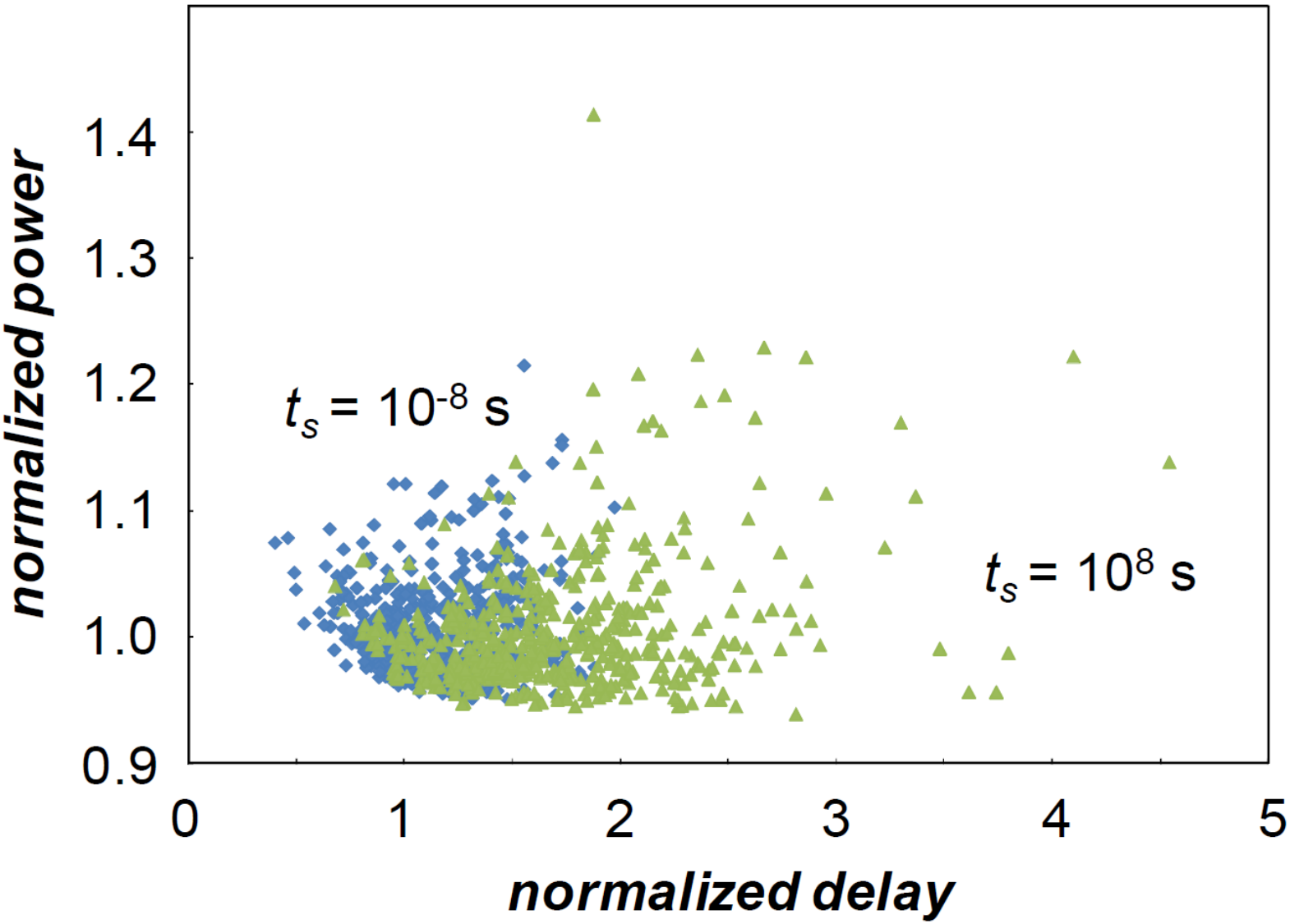
Distribution of delay widens with time[1]



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

Stochastic Impact on Circuit

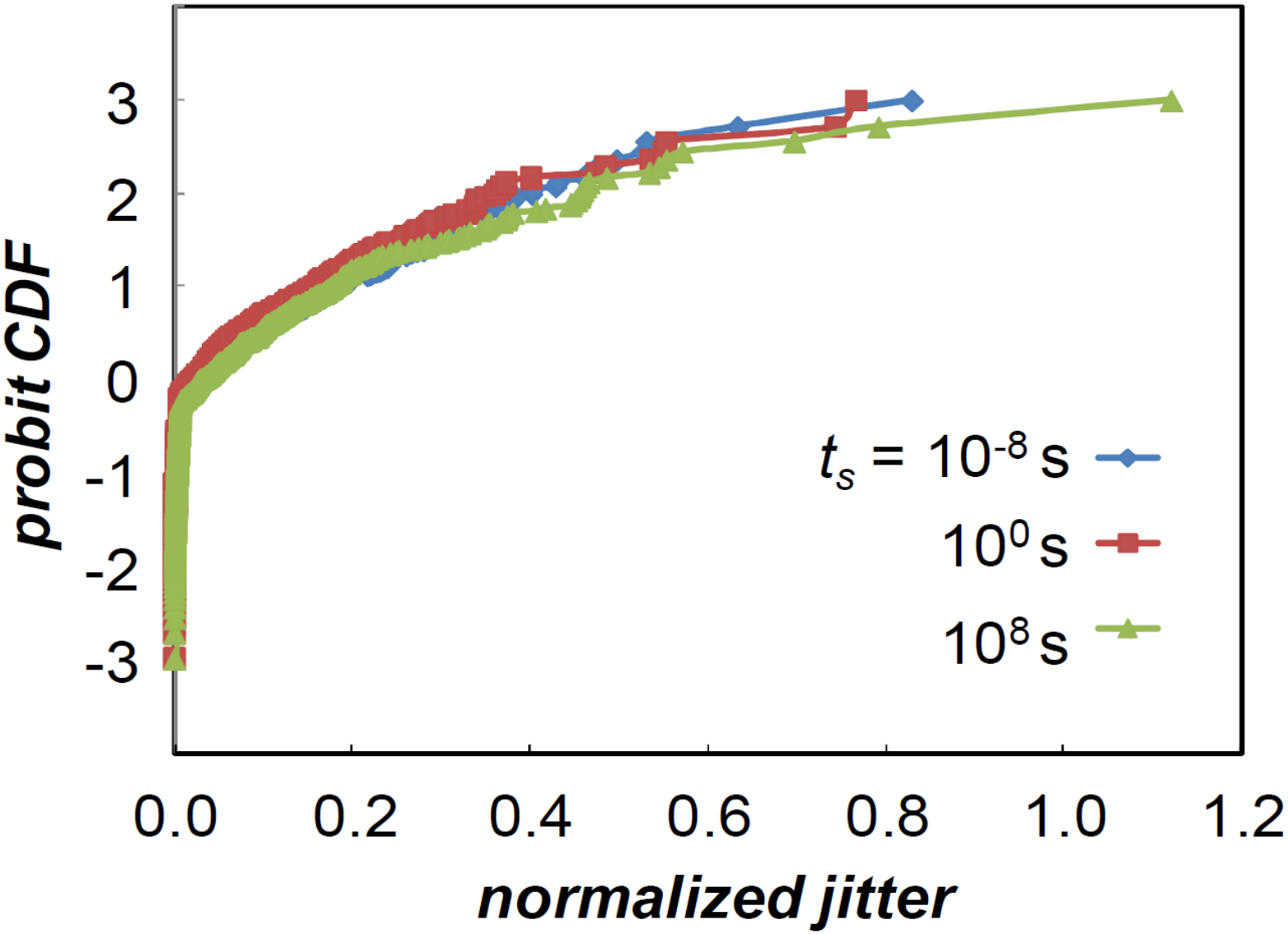
Normalized delay-power plot shifts and widens with time[1]



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

Stochastic Impact on Circuit

In this model, jitter is independent of aging[1]



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

Stochastic Impact on Circuit

Runtime penalty of VERILOG implementation

Example circuit with 6 MOSFETs

15 traps per MOSFET (90 traps in total)

SPECTRE 7.1.1 + BSIM4.4	SPECTRE + Verilog-A	SPECTRE + trap-enhanced Verilog-A
16.5 s	69 s	95 s
24%	100%	138%

Conclusions

Statistics of individual defects become important in nanoscale MOSFETs

- Random number of traps
- Random distribution of traps in space
- Random defect properties
- Interaction with random discrete dopants
- Discrete stochastic charge capture and emission events

Measurement method: time dependent defect spectroscopy (TDDS)

- Allows extraction of $\bar{\tau}_e$, $\bar{\tau}_c$, and step-height over very wide range
- Allows simultaneous analysis of multiple defects

Fundamental implications on device reliability

- Lifetime is a stochastic quantity
- Lifetime will have a huge variance

Circuit modeling

- Capture expectation values using distributed RC elements in SPICE
- Capture all features using a VERILOG implementation

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Ultra fast measurement data, discussion/theory

'Reliability community'

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