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Recent Developments in Device Reliability Modeling: The Bias Temperature Instability

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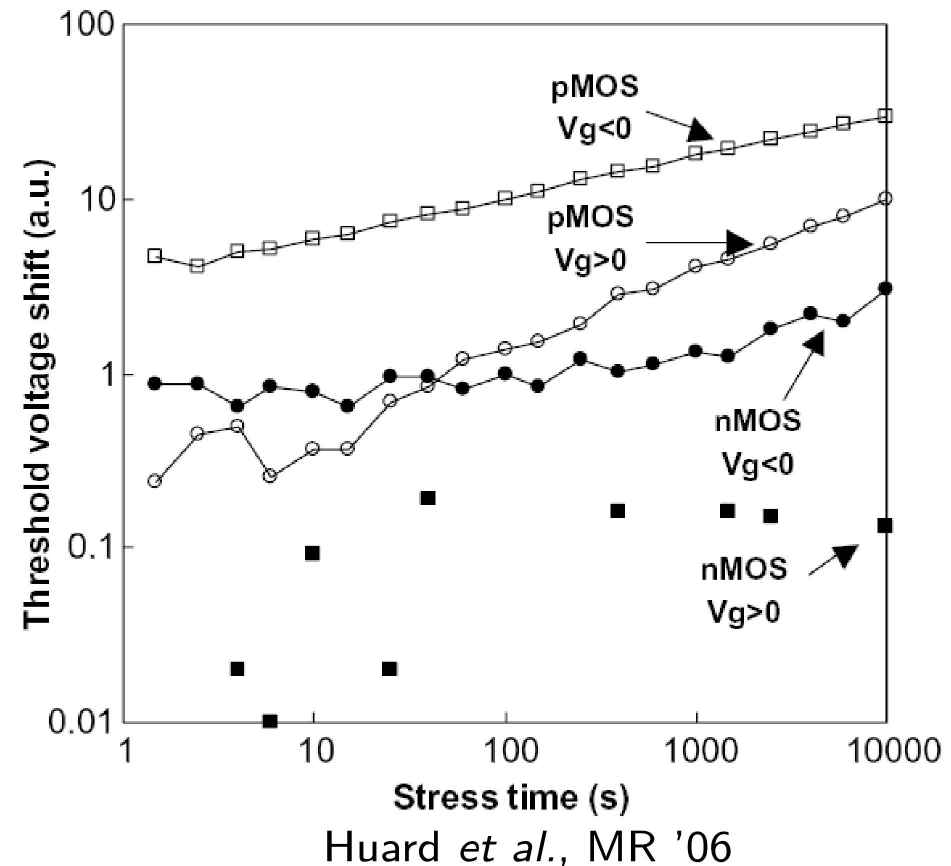
The Negative Bias Temperature Instability

Negative bias temperature stress of pMOSFETs[1] [2] [3]

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

Degradation of critical device parameters

- Threshold voltage
- Subthreshold slope
- Transconductance
- Mobility
- Drain current
- ...



Huard *et al.*, MR '06

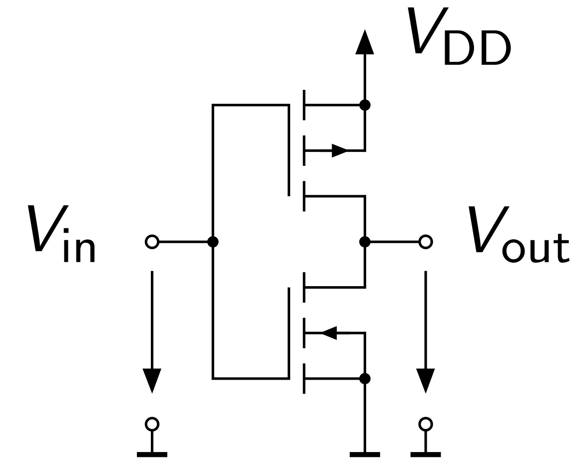
Occurs in all four configurations

- Strongest in pMOS with negative bias

Serious reliability concern in pMOSFETs

[1] Schroder and Babcock, JAP '03 [2] Alam and Mahapatra, MR '05 [3] Huard *et al.*, MR '06

The Negative Bias Temperature Instability



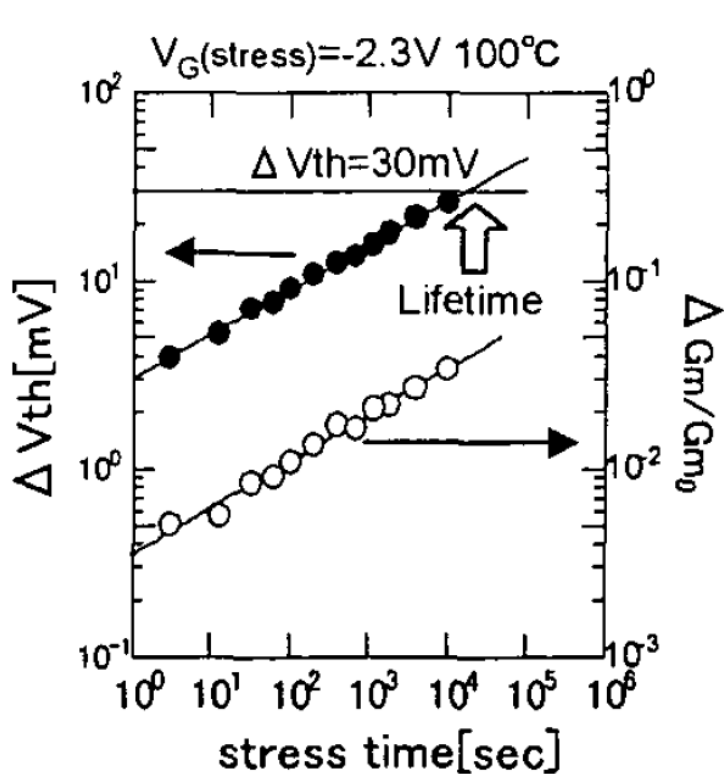
When does the NBTI scenario occur?

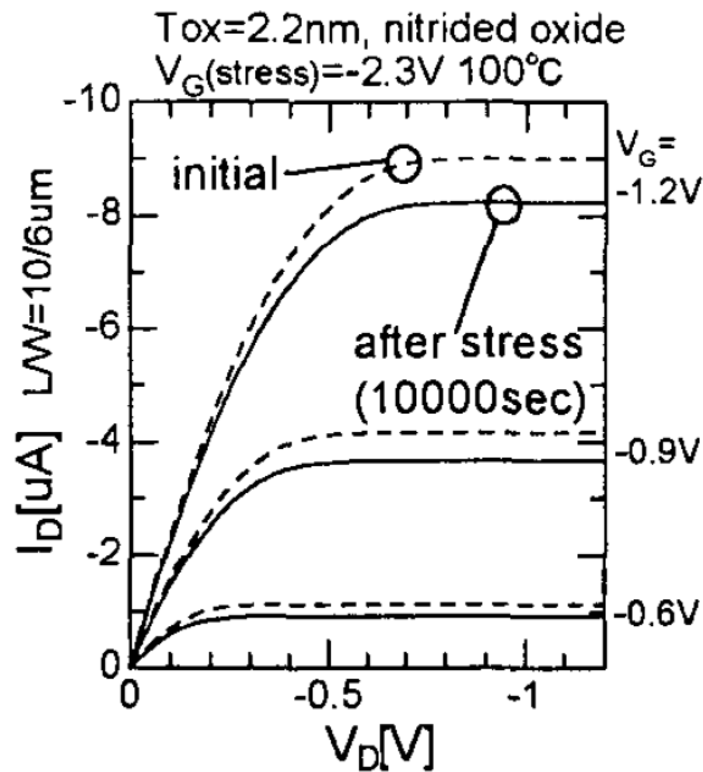
NBTI: $V_G \ll 0\,\mathrm{V}$, $V_S = V_D = 0\,\mathrm{V}$

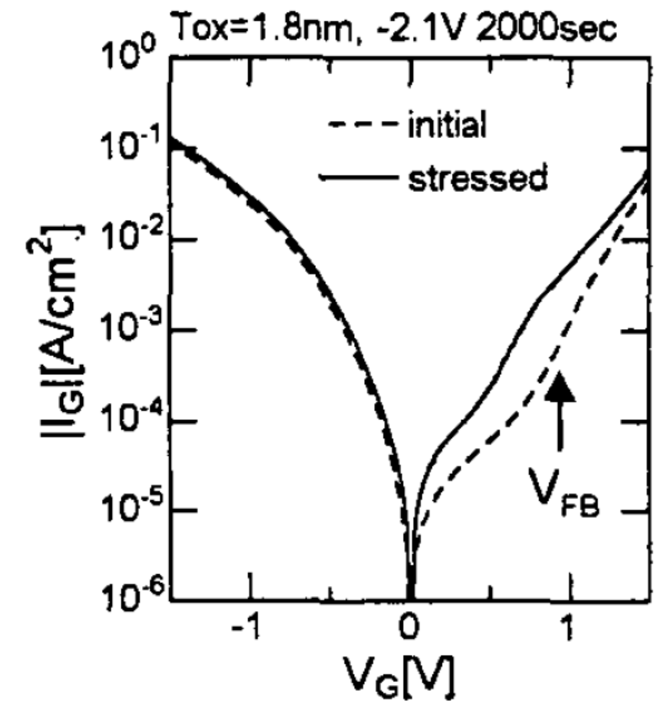
Example: inverter with $V_{in} = 0\,\mathrm{V}$

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

What happens to the pMOS transistor?







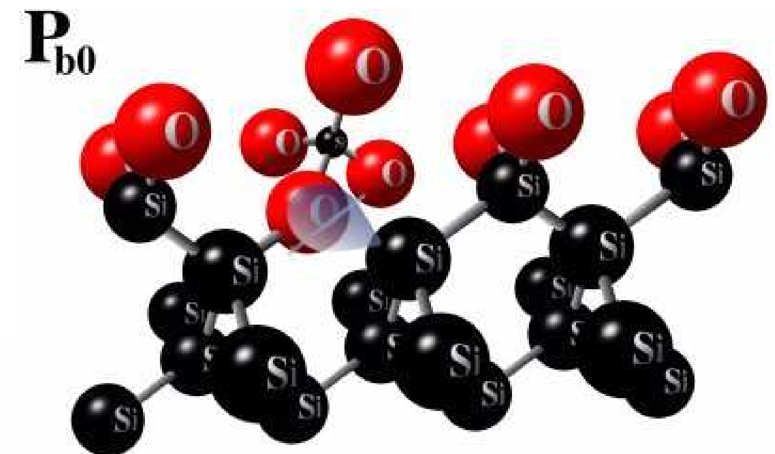
Kimizuka *et al.*, VLSI Symp. '00

Origin of the Negative Bias Temperature Instability

What happens during negative bias temperature stress?

Creation of SiO_2/Si interface defects (dangling Si bonds, P_b centers)

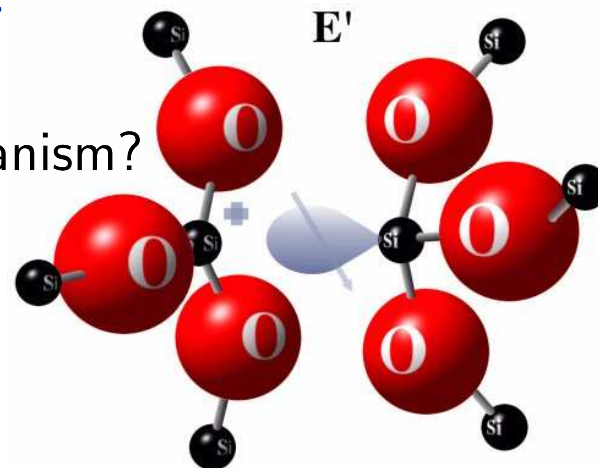
- Pre-existing, but passivated by hydrogen anneal
- Si–H bonds can be broken
- Results in trapping sites inside the Si bandgap
- Universally acknowledged [1] [2]
- Different defect in SiON and high-k? [3]



[Courtesy: PennState Univ.]

Creation of oxide charge

- Most likely E' centers
- Charge exchange mechanism?
- Controversial! [4]



[Courtesy: PennState Univ.]

[1] Mahapatra *et al.*, IRPS '07 [2] Huard *et al.*, MR '06 [3] Campbell *et al.*, TDMR '07 [4] Mahapatra *et al.*, IRPS '07

NBTI Measurement Techniques

Main problem: it is impossible to perfectly measure NBTI

- As soon as stress is removed, extremely fast recovery is observed [1] [2]
- Strong bias dependence, in particular to positive bias [3] [4] [5]

A number of techniques have been suggest and used

- Conventional Measure/Stress/Measure [6]
- On-the-fly (during stress, no interruption) [7]
- Charge-pumping and DCIV techniques [8]

Various problems

- Delays lead to recovery
- How to quantify the degradation (ΔV_{th}, ΔI_{D}, ???)

Biggest problem: results do not match!!!

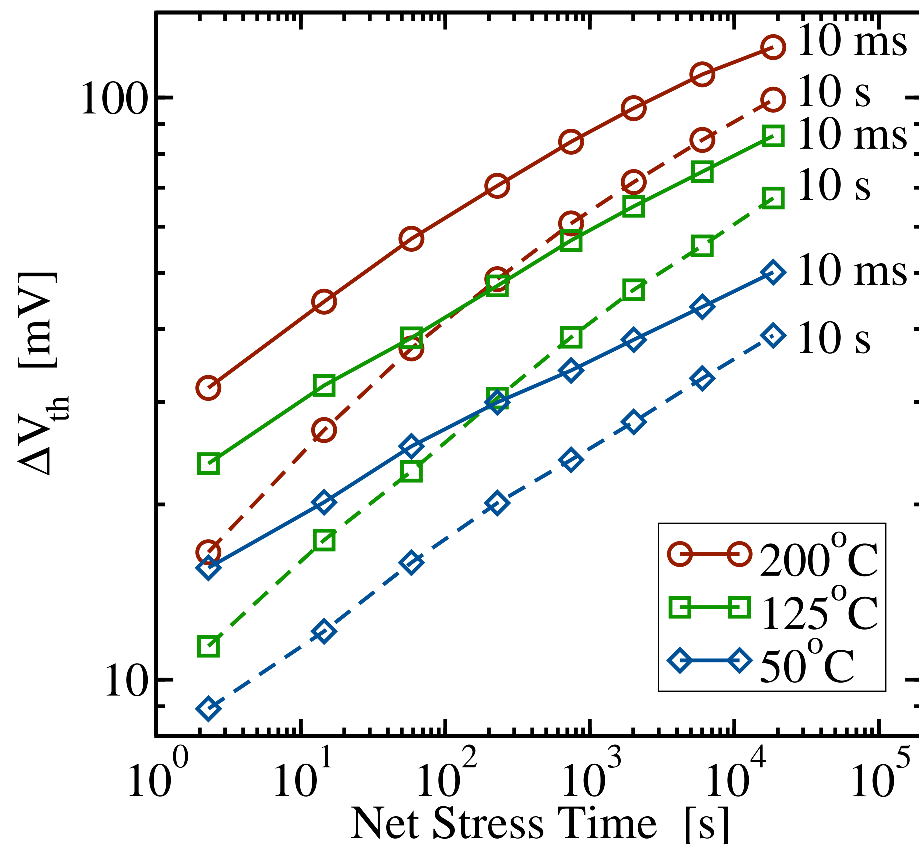
- No exact theory available that unanimously links and explains all the data

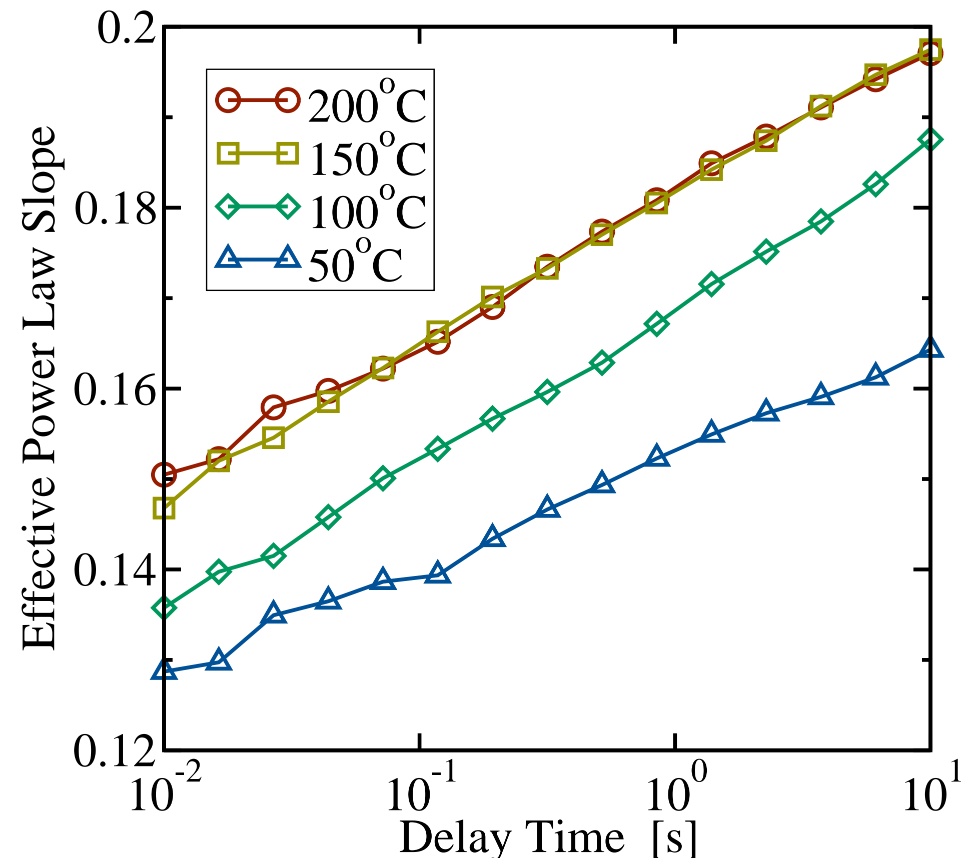
[1] Ershov *et al.*, IRPS '03 [2] Reisinger *et al.*, IRPS '06 [3] Ang, EDL '06 [4] Huard *et al.*, MR '06
[5] Grasser *et al.*, IEDM '07 [6] Kaczer *et al.*, IRPS '05 [7] Denais *et al.*, IEDM '04
[8] Neugroschel *et al.*, IEDM '06

Influence of Delay

Measurement delay has a significant impact on measurement[1] [2] [3]

- Curvature in data becomes more obvious, larger (time-dependent) 'slope'
- Impact of delay does not disappear at longer stress times
- Impact of delay is temperature dependent





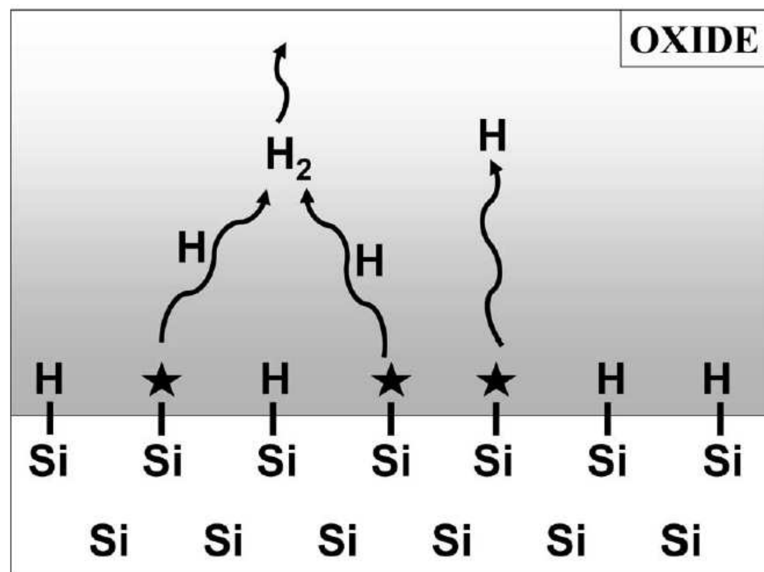
[1] Ershov *et al.*, IRPS '03 [2] Denais *et al.*, IEDM '04 [3] Kaczer *et al.*, IRPS '05

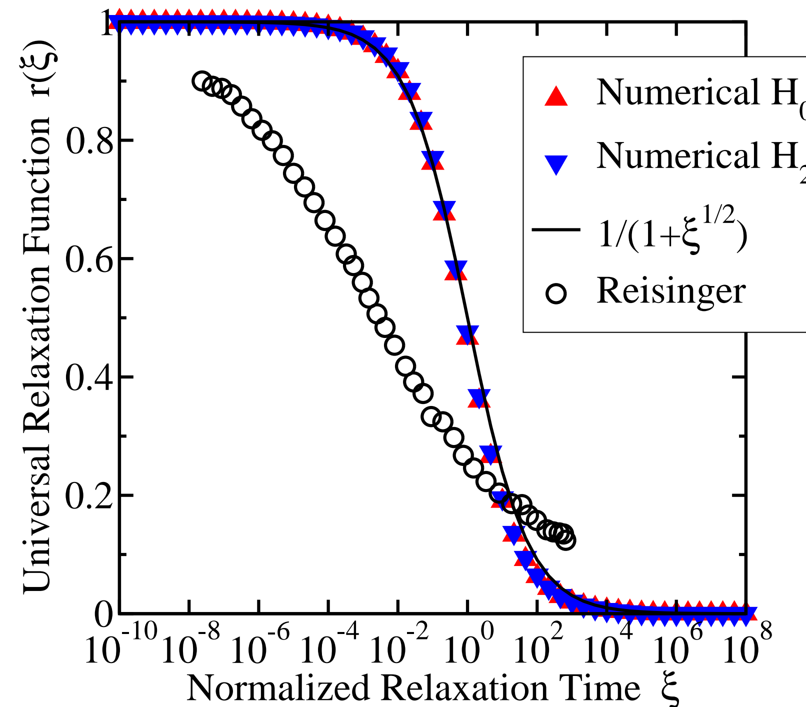
Standard Model: Reaction-Diffusion Model

Successful in describing constant bias stress[1] [2]

Cannot describe relaxation[3] [4] [5]

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





Model is wrong!!! [6] [7] [8] [9] [10]

[1] Alam *et al.*, MR '06 [2] Kufluoglu *et al.*, T-ED '07 [3] Kaczer *et al.*, IRPS '05 [4] Grasser *et al.*, IRPS '07
[5] Huard *et al.*, IEDM '07 [6] Grasser *et al.*, IEDM '10 [7] Grasser *et al.*, IRPS '10 [8] Reisinger *et al.*, IRPS '10
[9] Kaczer *et al.*, IRPS '10 [10] Huard *et al.*, IRPS '10

Overview

Introduction

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

New measurement technique

The time dependent defect spectroscopy

Anomalous defect behavior

Present in all defects

Stochastic model

Additional metastable states, multiphonon theory

Compact modeling attempt

RC ladders

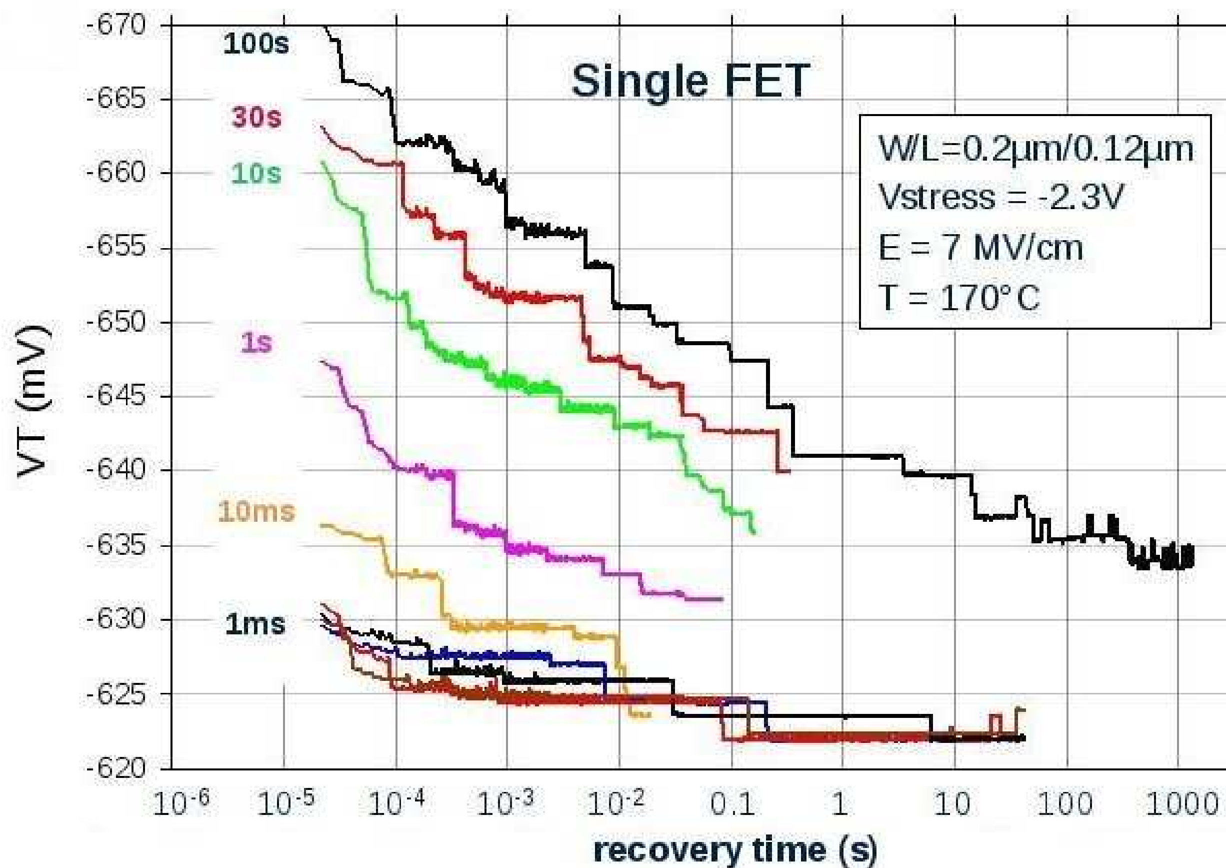
Implications on lifetimes

Conclusions

What is Really Going On?

Study of NBTI recovery on small-area devices [1] [2] [3] [4] [5] [6]

Stochastic and discrete charge emission events, no diffusion



[1] Huard *et al.*, IIRW '05 [2] Reisinger *et al.*, IIRW '09 [3] Grasser *et al.*, IEDM '09 [4] Kaczer *et al.*, IRPS '10
[5] Grasser *et al.*, IRPS '10 [6] Reisinger *et al.*, IRPS '10

Recoverable NBTI due to the same Defects as RTN

Quasi-equilibrium:

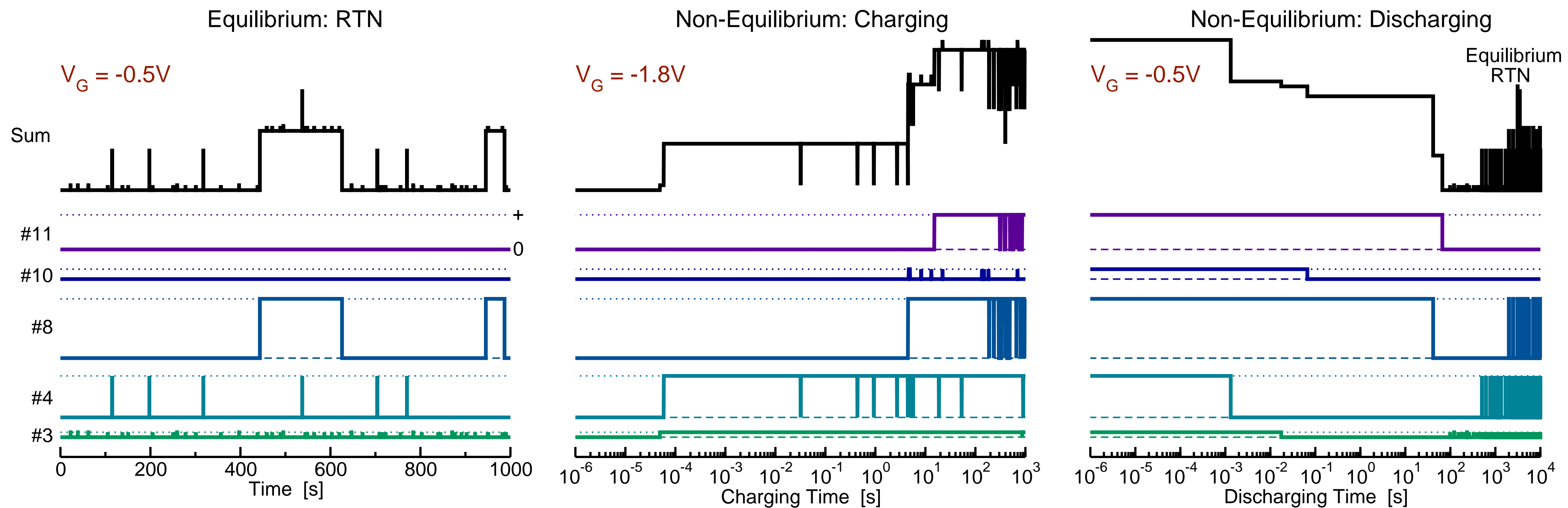
Some defects neutral, others positive, a few produce random telegraph noise (RTN)

Stress:

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

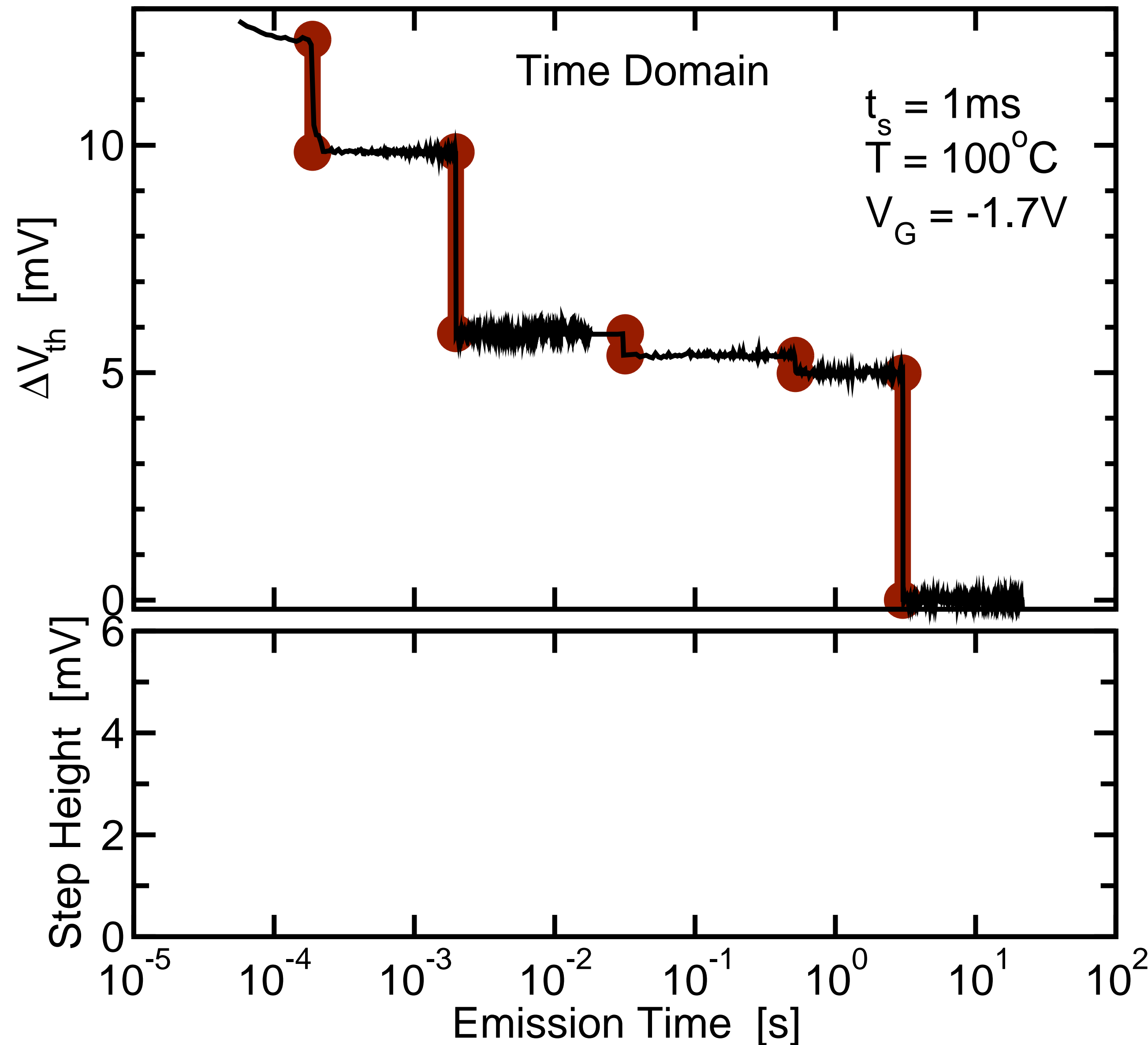
Recovery:

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



The Time Dependent Defect Spectroscopy (TDDS)

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



[1] Grasser *et al.*, IRPS '10 [2] For a discussion on the step heights see Kaczer *et al.*, IRPS '10

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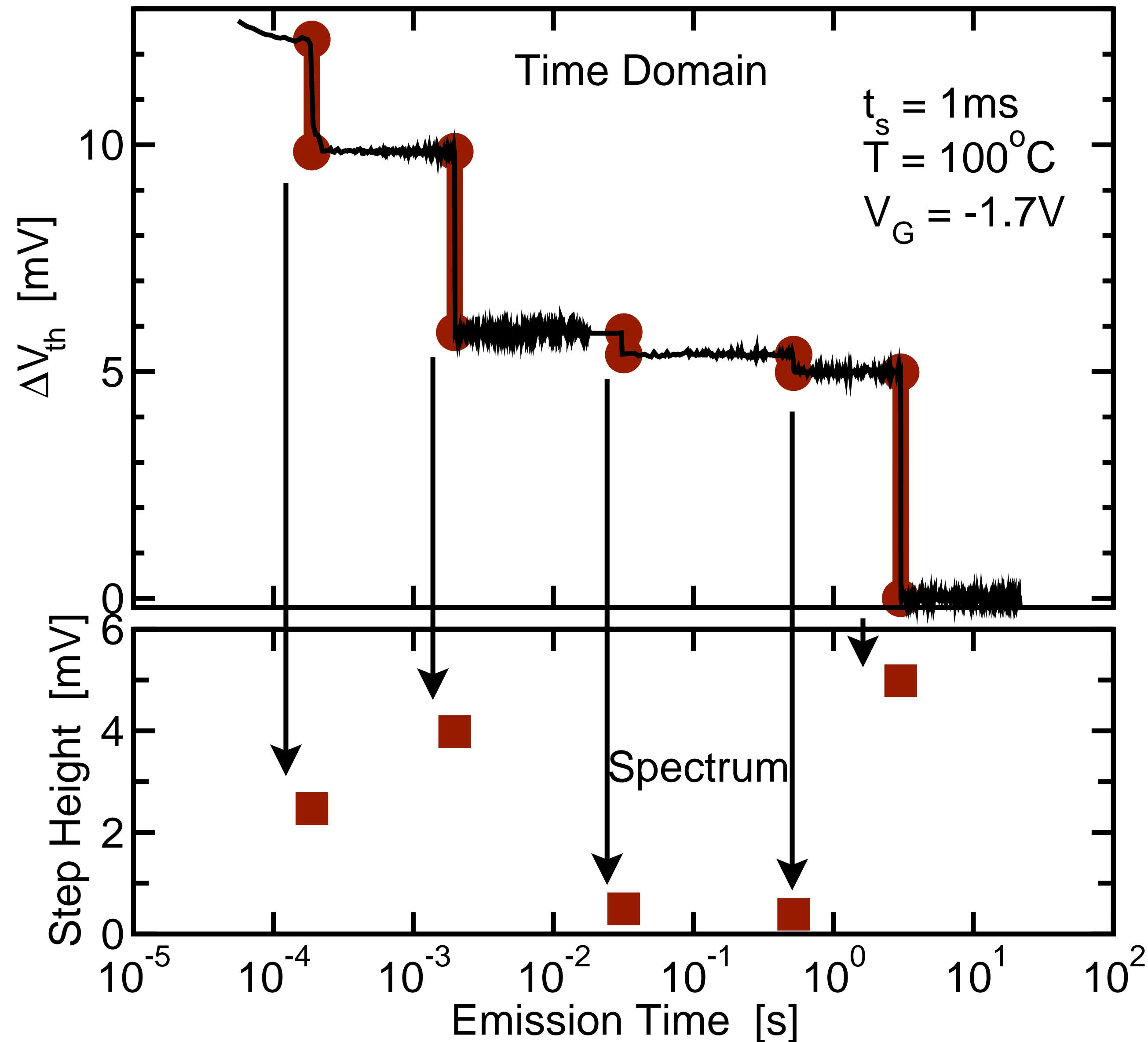

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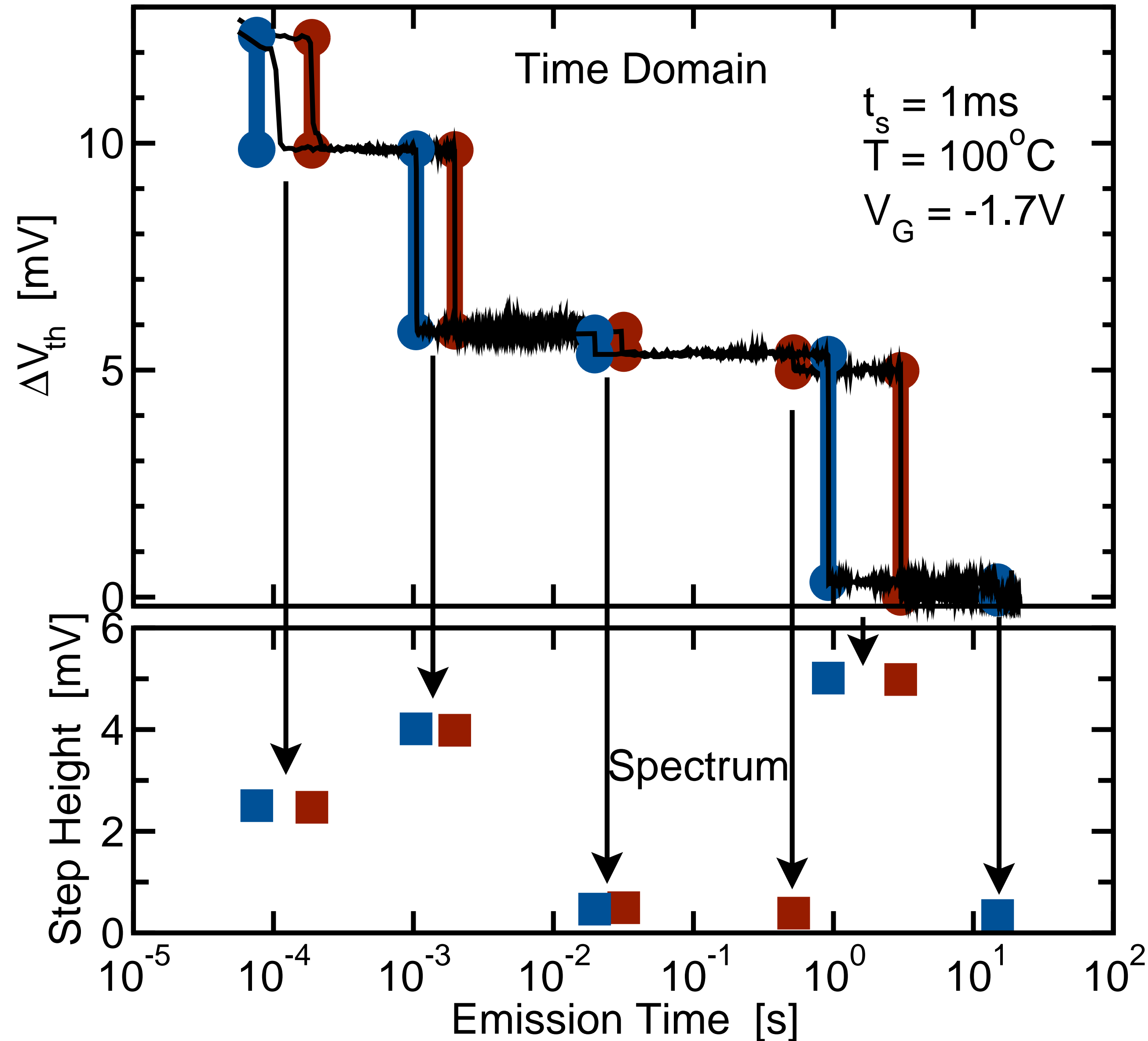

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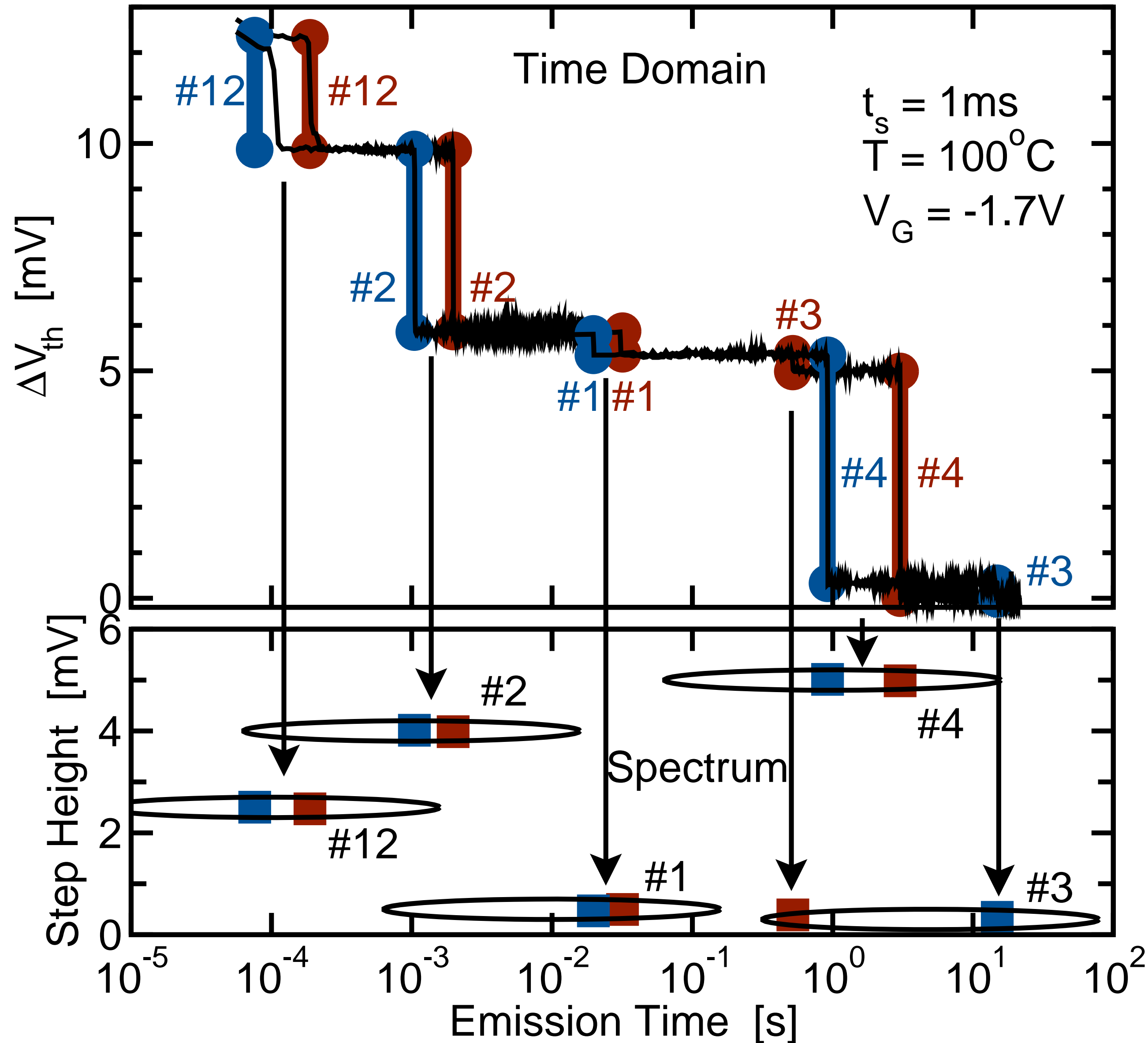
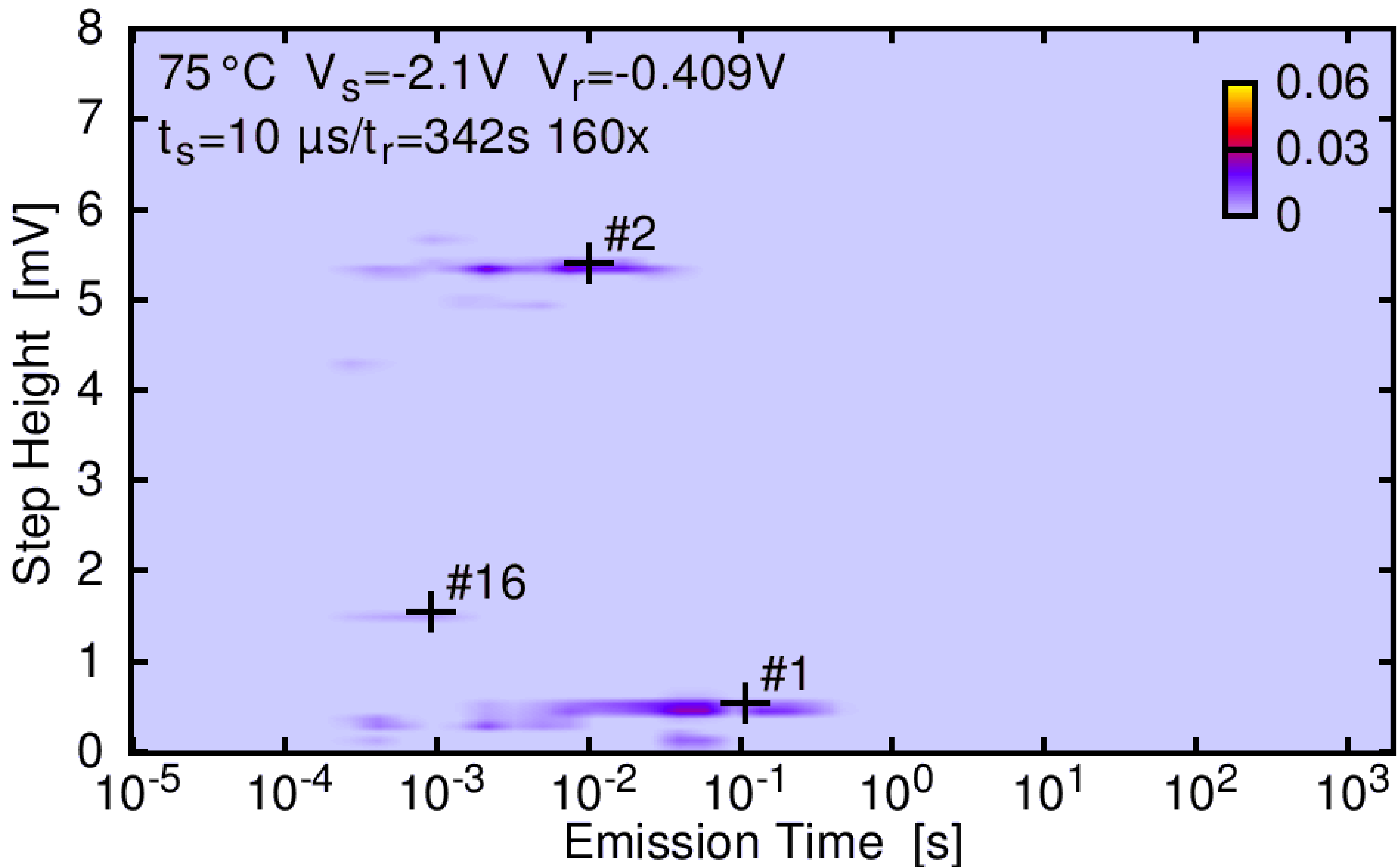


The Time Dependent Defect Spectroscopy

Function of stress time t_s



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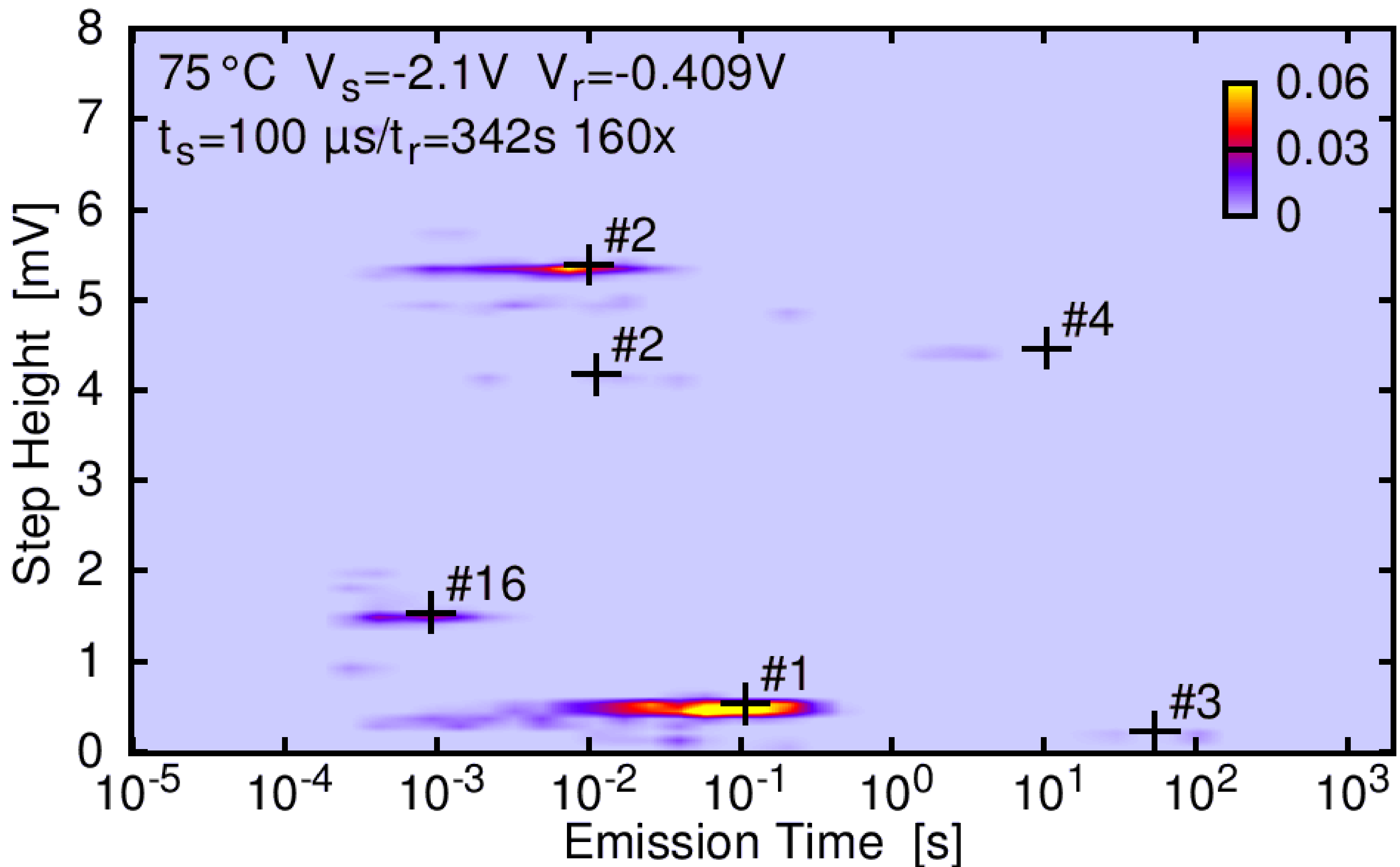

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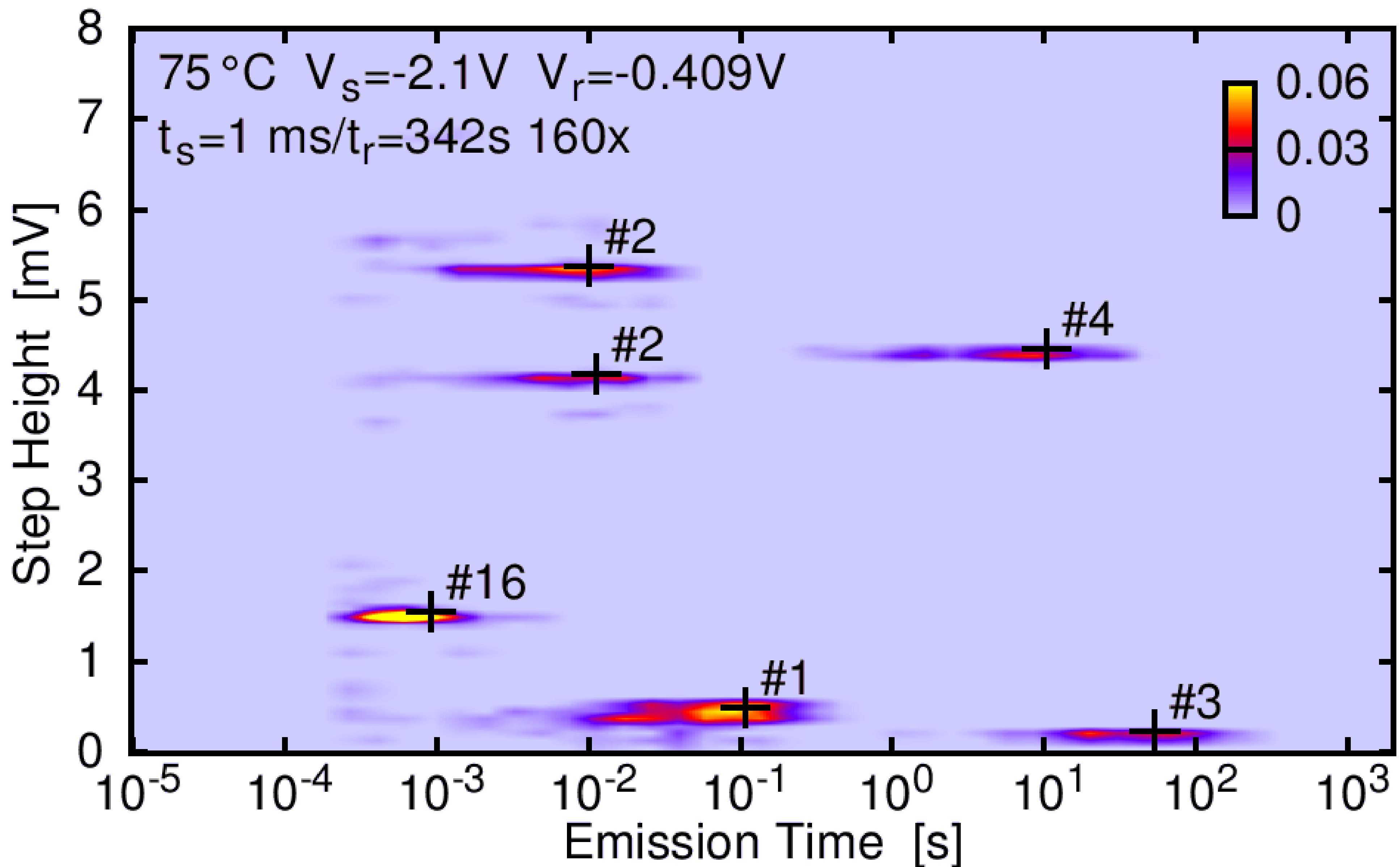

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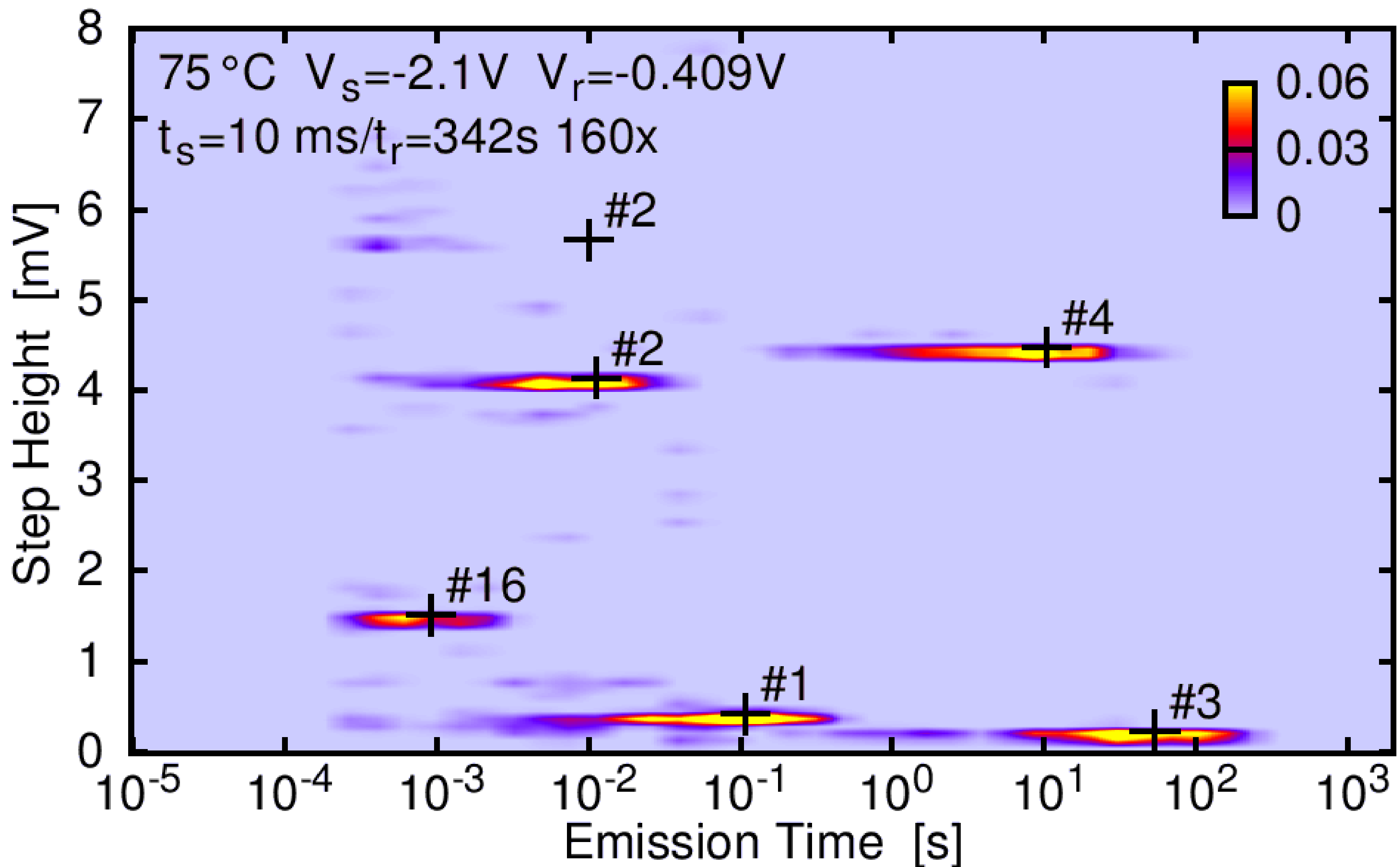
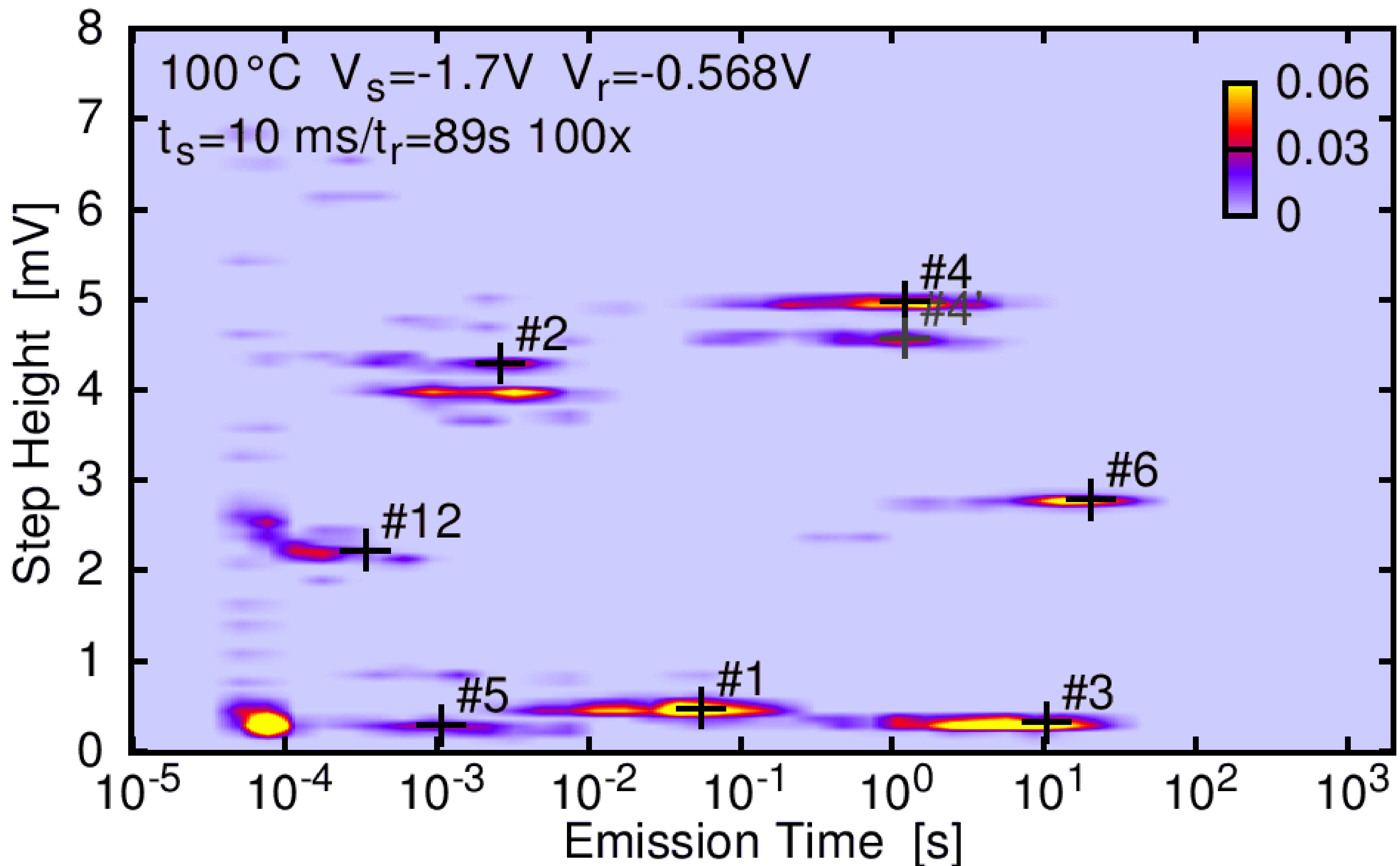


Function of temperature



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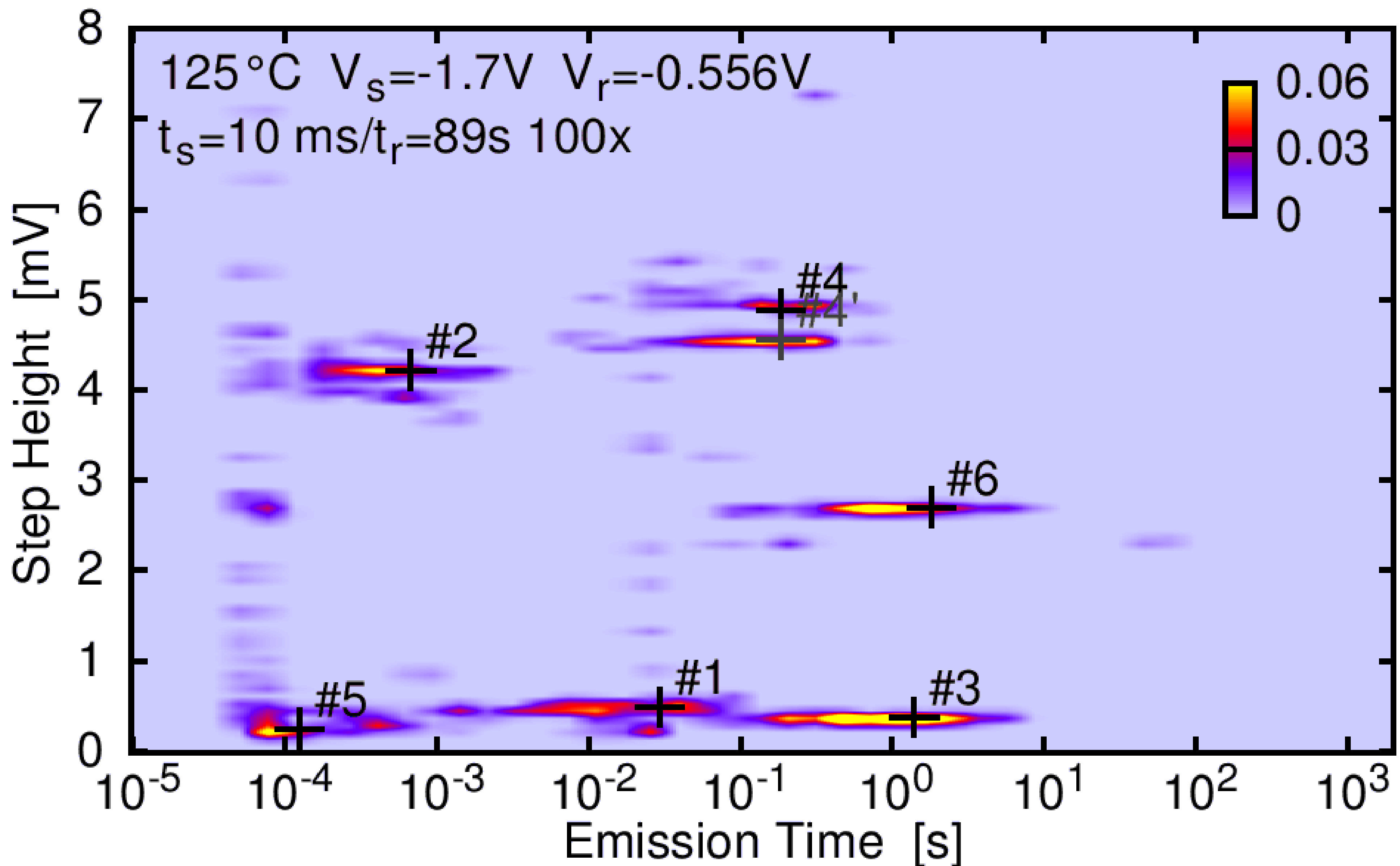

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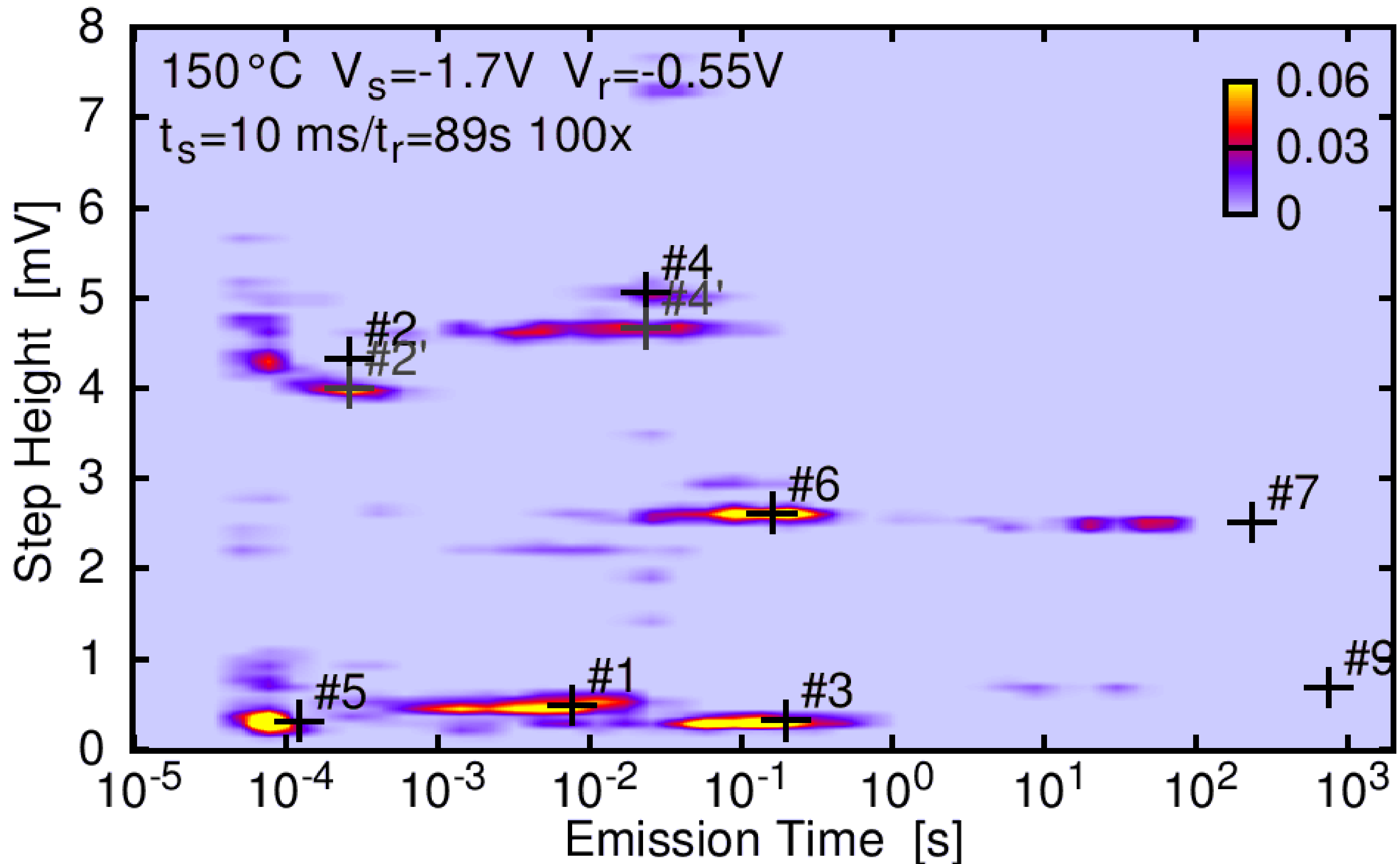

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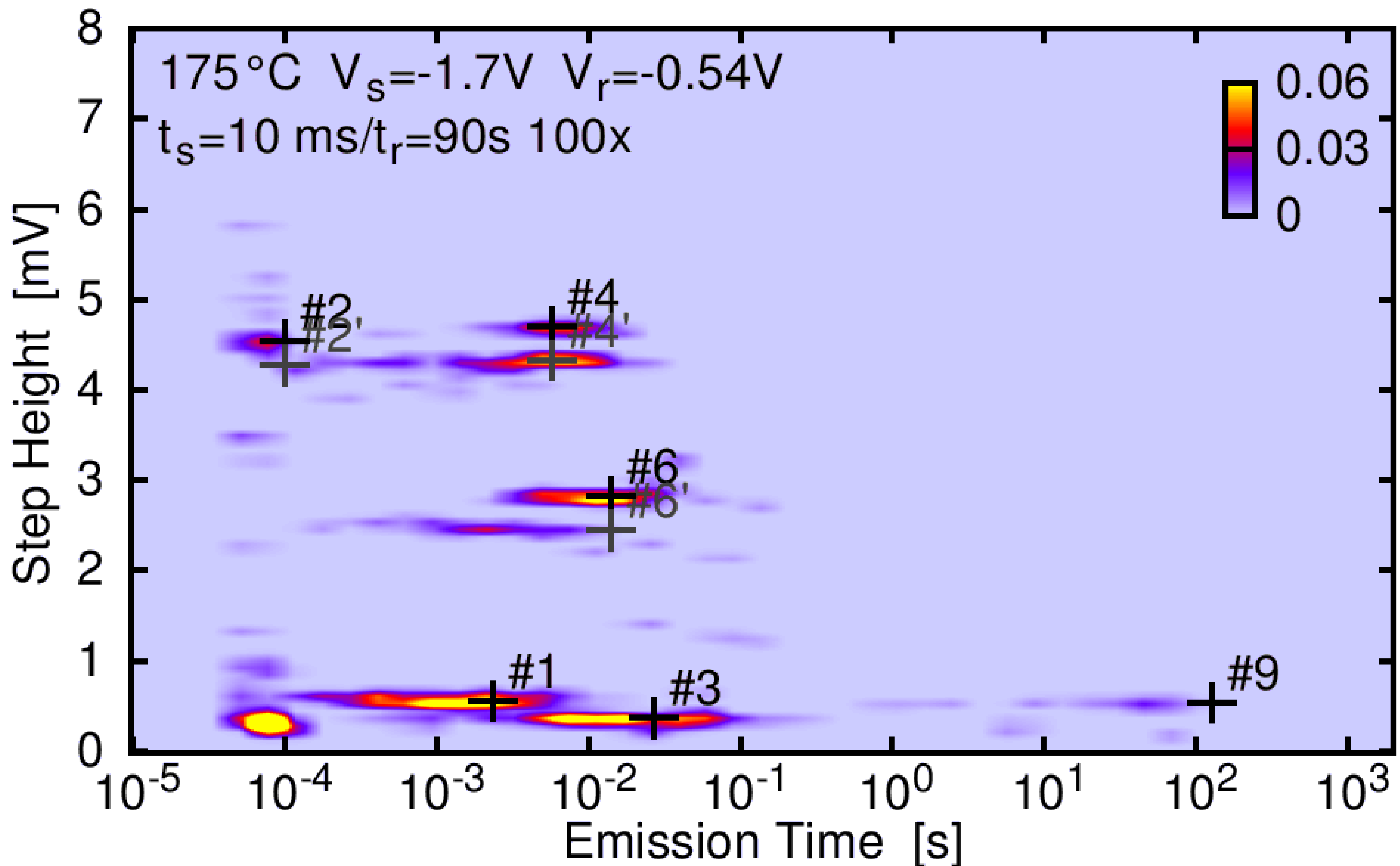
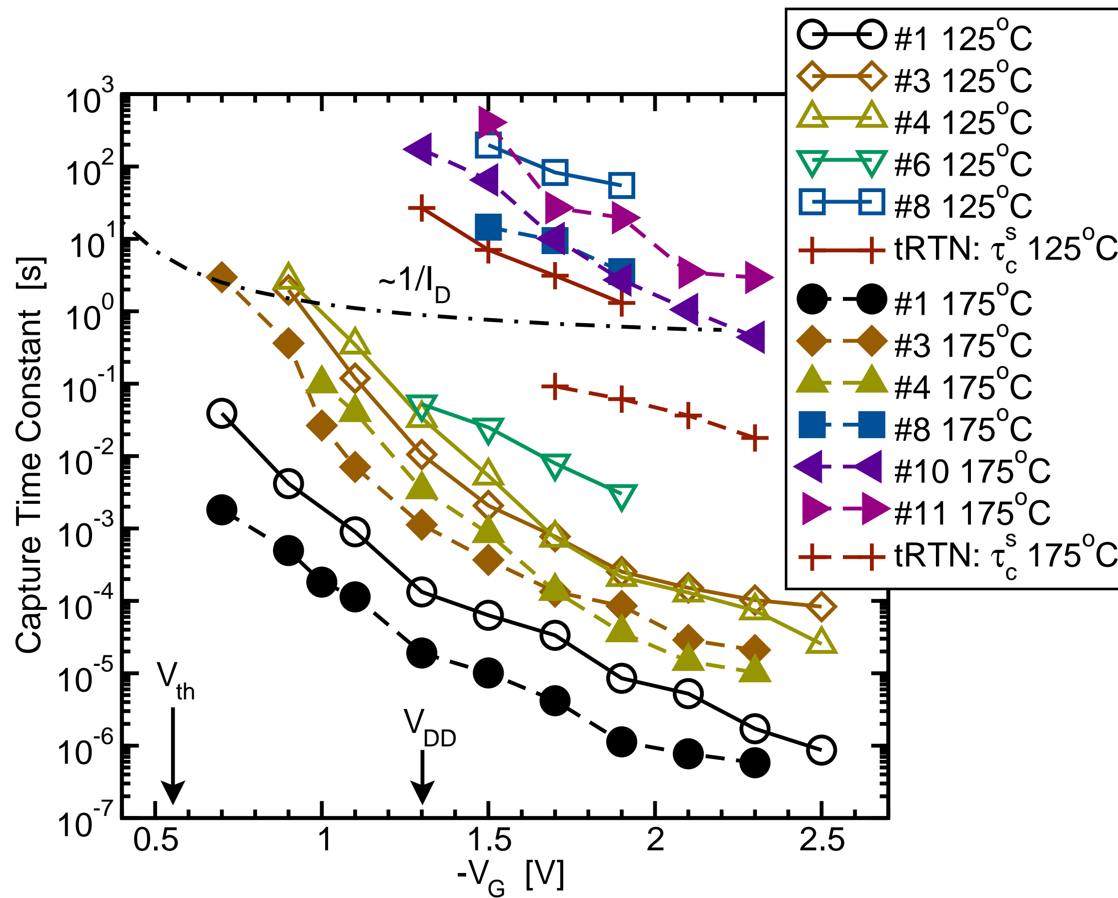
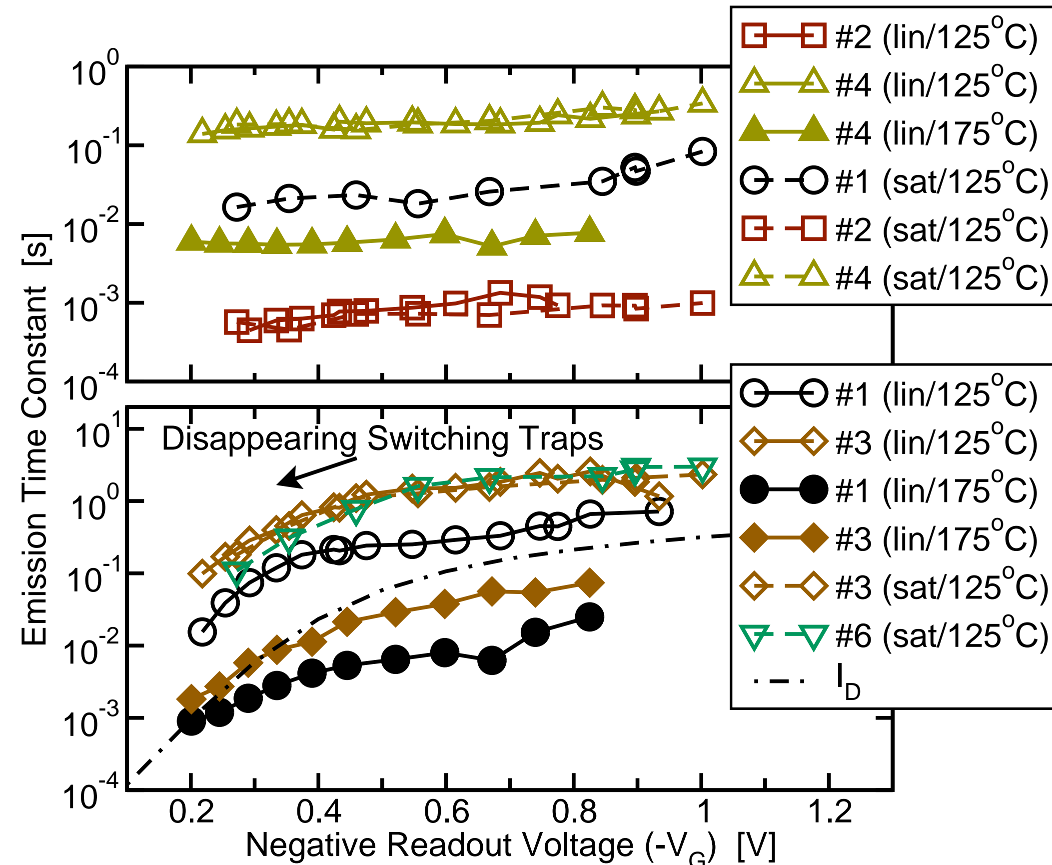


The Time Dependent Defect Spectroscopy

Different non-linear field dependence of the capture time constants

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



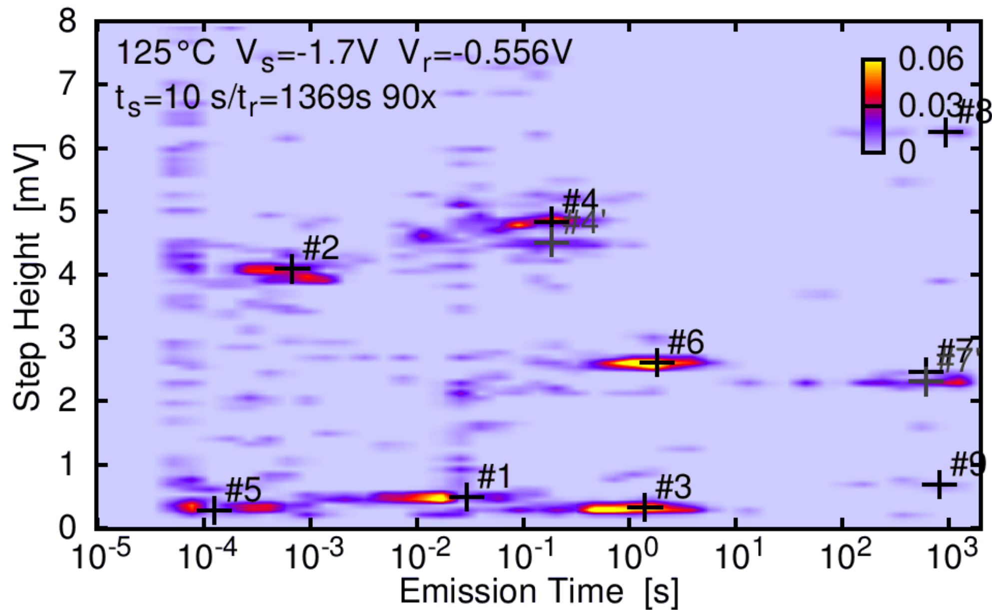


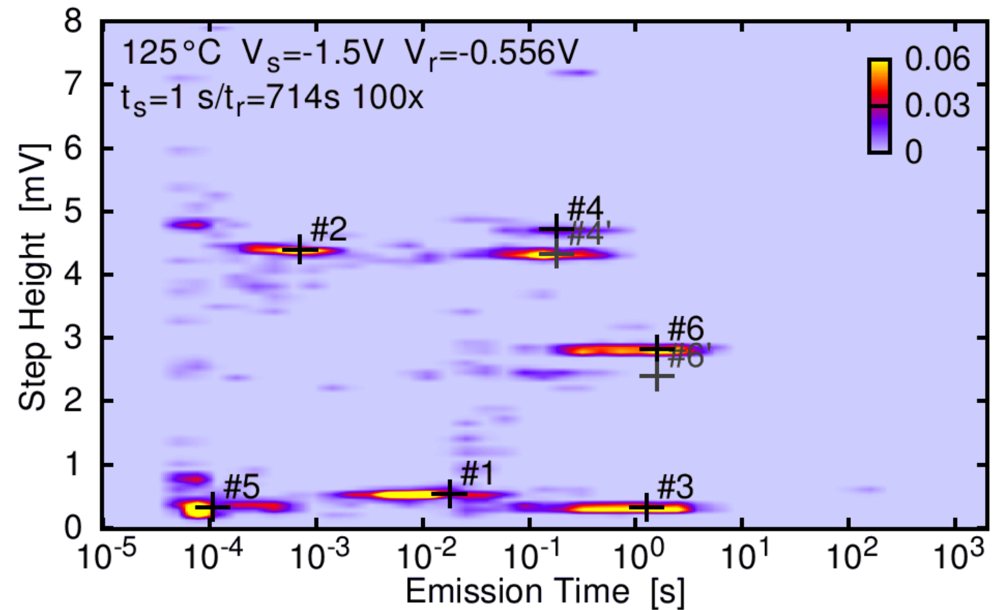
Compare SRH-like model: $\tau_c = \tau_0 \, e^{\beta \Delta E_B} \, \frac{N_v}{p}$

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

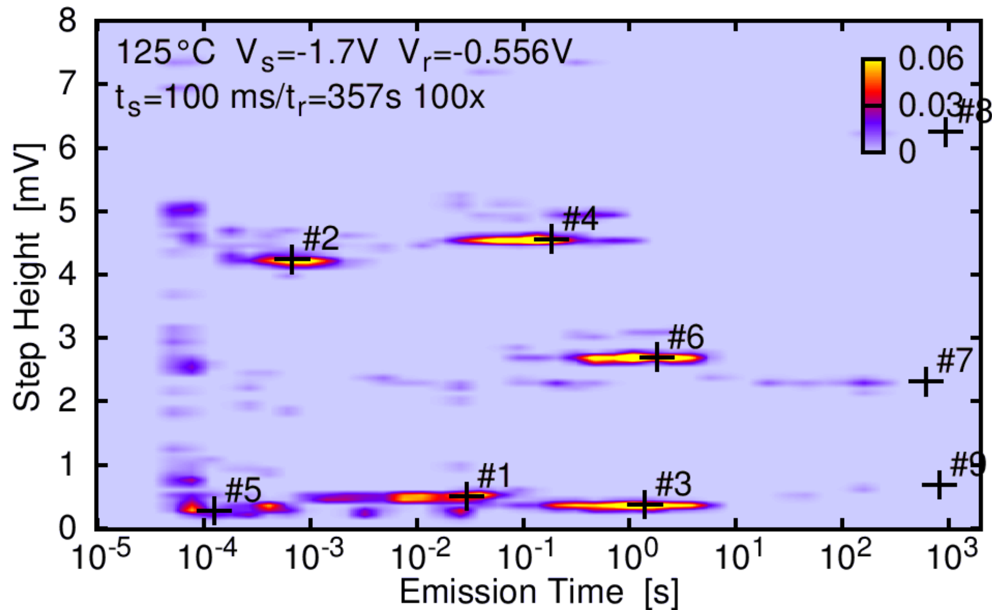
Anomalous Defect Behavior

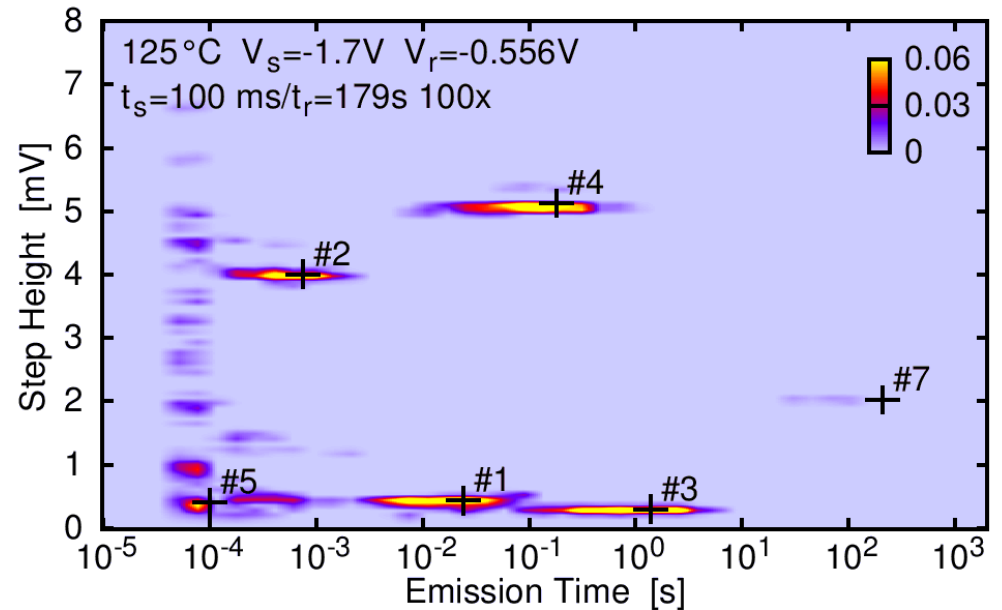
Defects disappear temporarily from the map (#7)





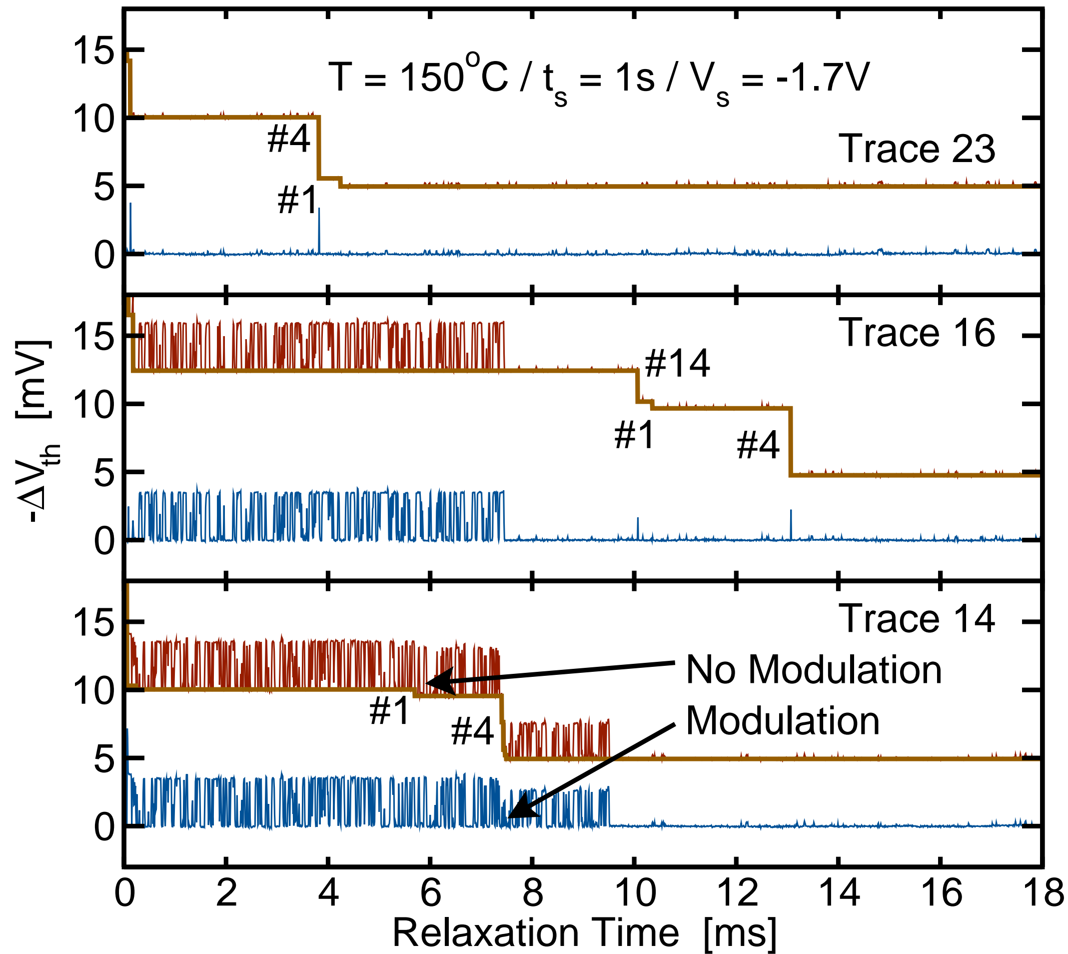
Long term stability: defect #6 missing for a few months now

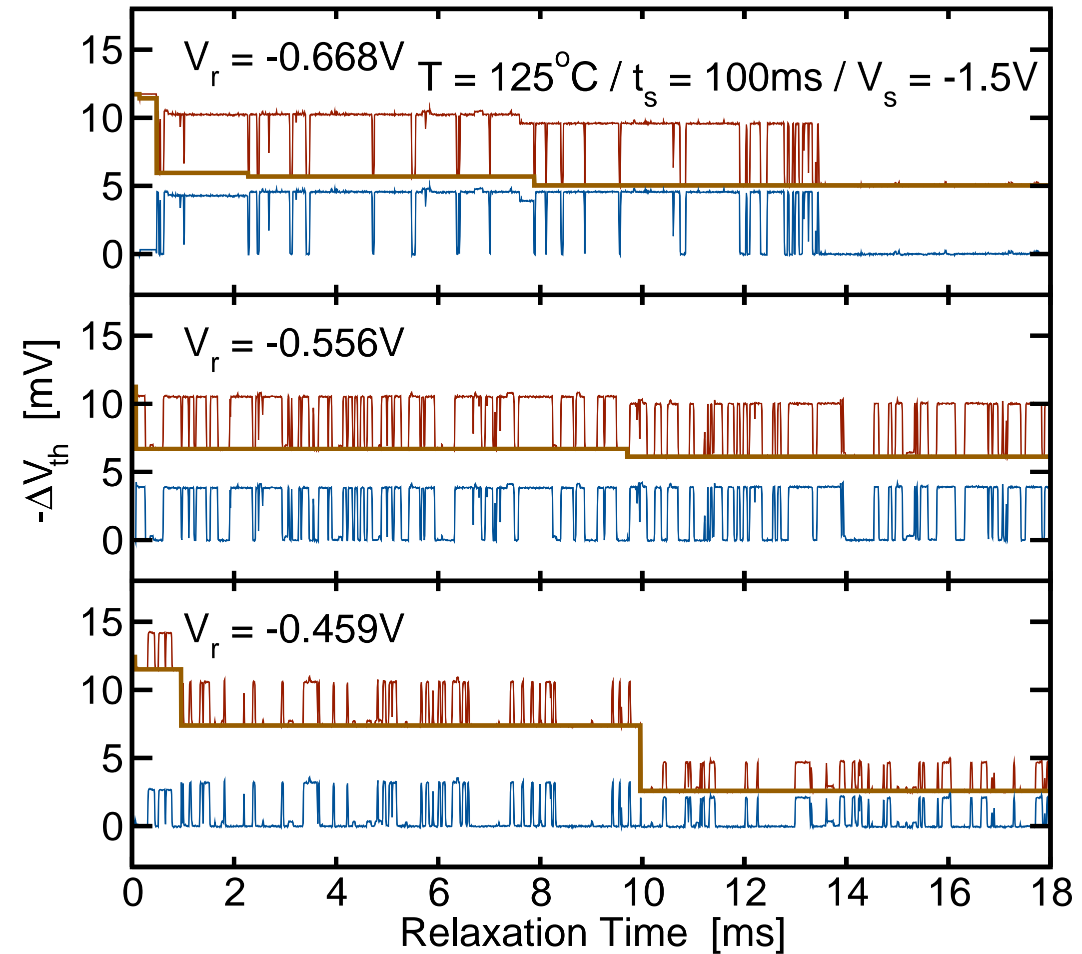




Anomalous Defect Behavior

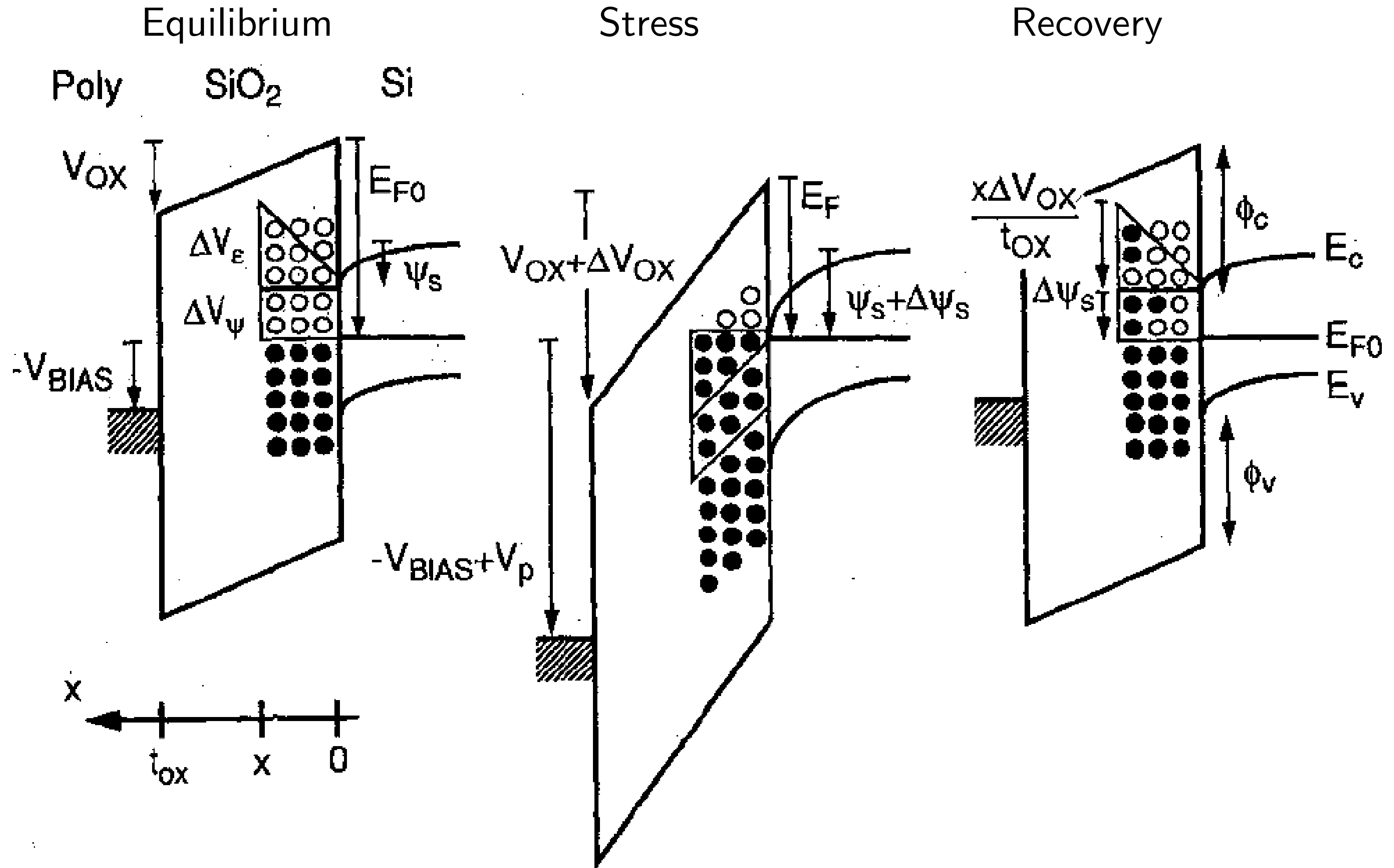
Temporary random telegraph noise (tRTN)





Tewksbury Model

Tewksbury model[1]: charging and discharging of traps via elastic tunneling



[1] Tewksbury and Lee, SSC '94

How Can We Model All That Properly?

Standard Model for RTN

Model suggested by Kirton & Uren[1]

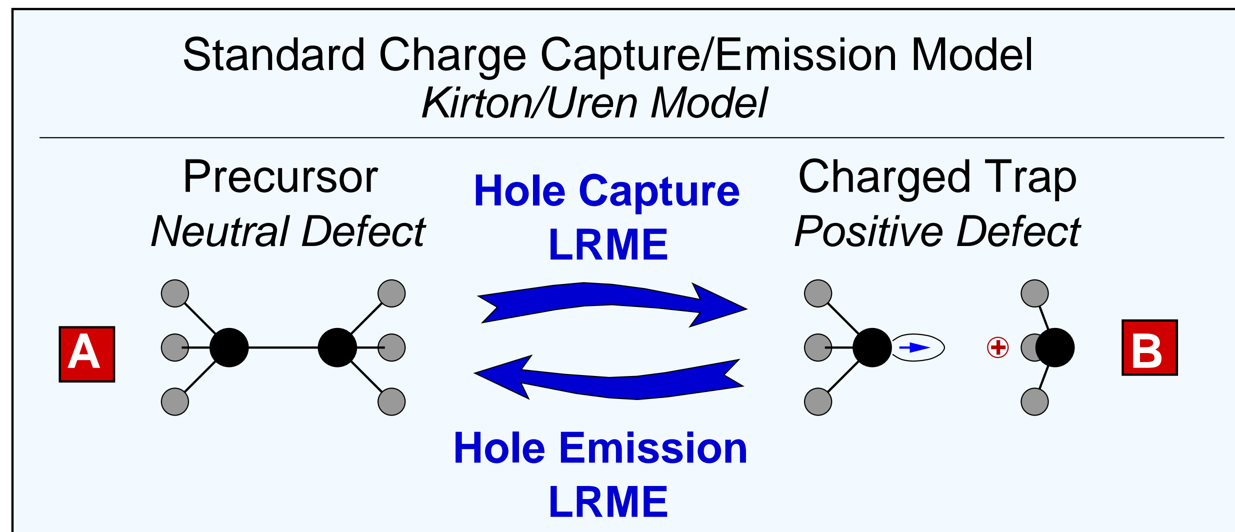
Noticed that elastic tunneling cannot be 'it'

Also used lattice-relaxation multiphonon emission (LRME)

Time constants depend on activation energy ΔE_B and depth x

$$\tau_\mathrm{c} = \tau_0\,\mathrm{e}^{\beta\Delta E_\mathrm{B}}\,\frac{N_\mathrm{v}}{p} \qquad \tau_0^{-1} = N_\mathrm{v}\,v_\mathrm{th}\,\sigma\,\mathrm{e}^{-x/x_0}$$

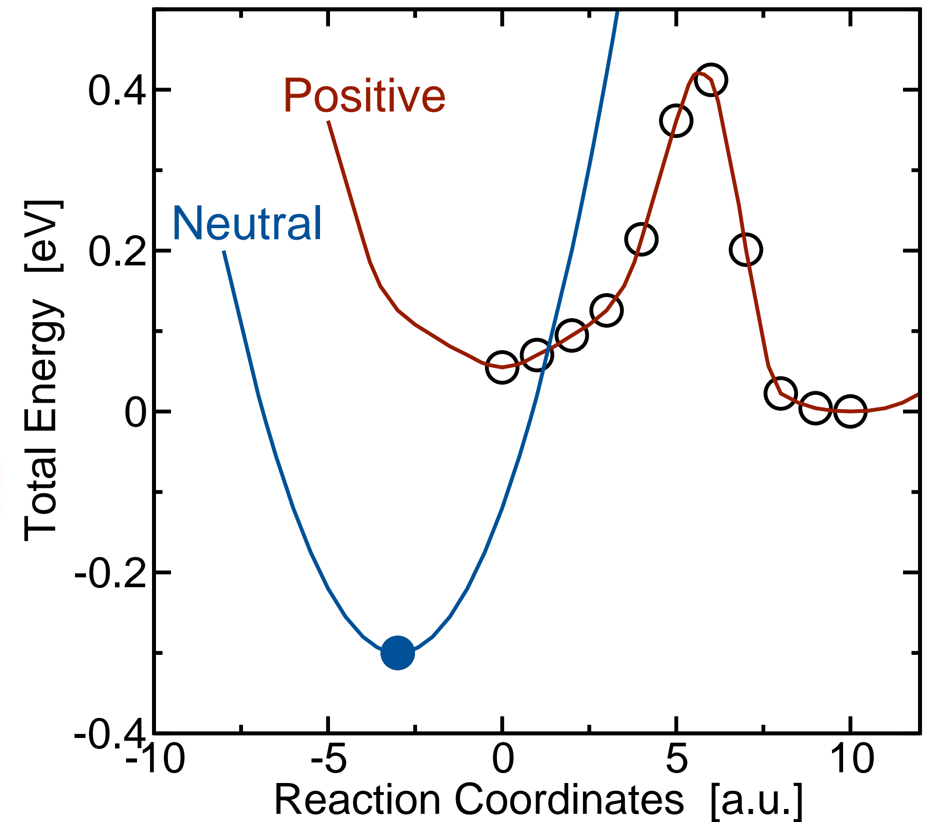
$$\tau_\mathrm{e} = \tau_0\,\mathrm{e}^{\beta\Delta E_\mathrm{B}}\,\mathrm{e}^{\beta\Delta E_\mathrm{T}}\,\mathrm{e}^{xF/V_\mathrm{T}}$$



[1] Kirton & Uren, Adv.Phys '89

Lattice Relaxation and Metastability

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



Silicon

Oxygen

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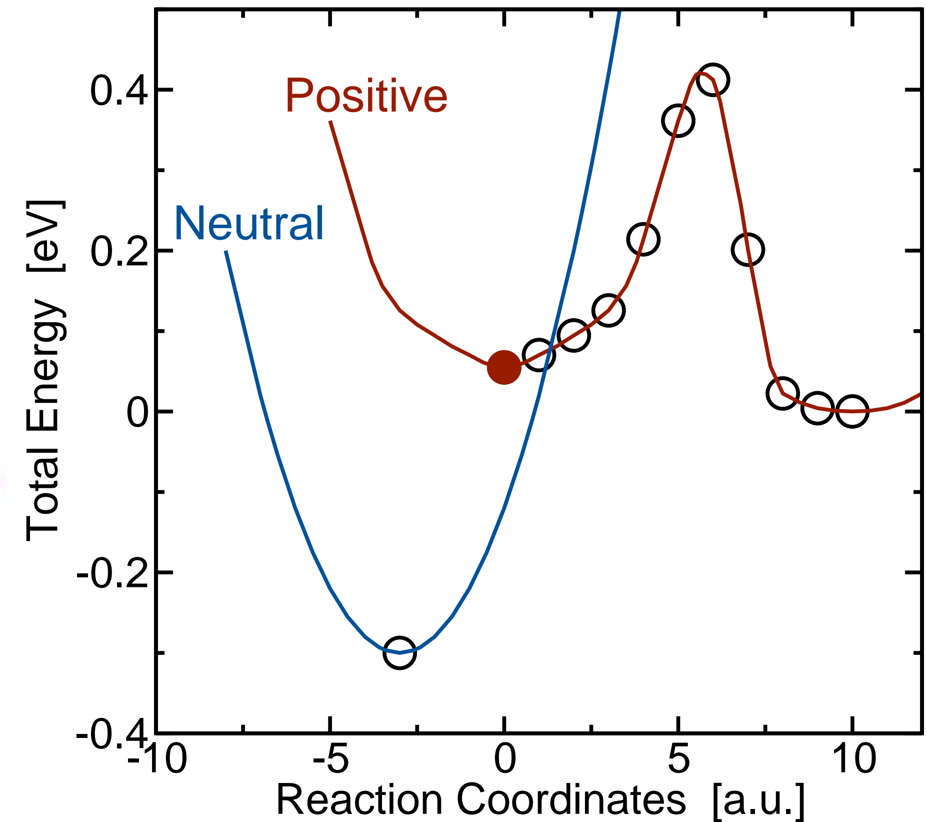

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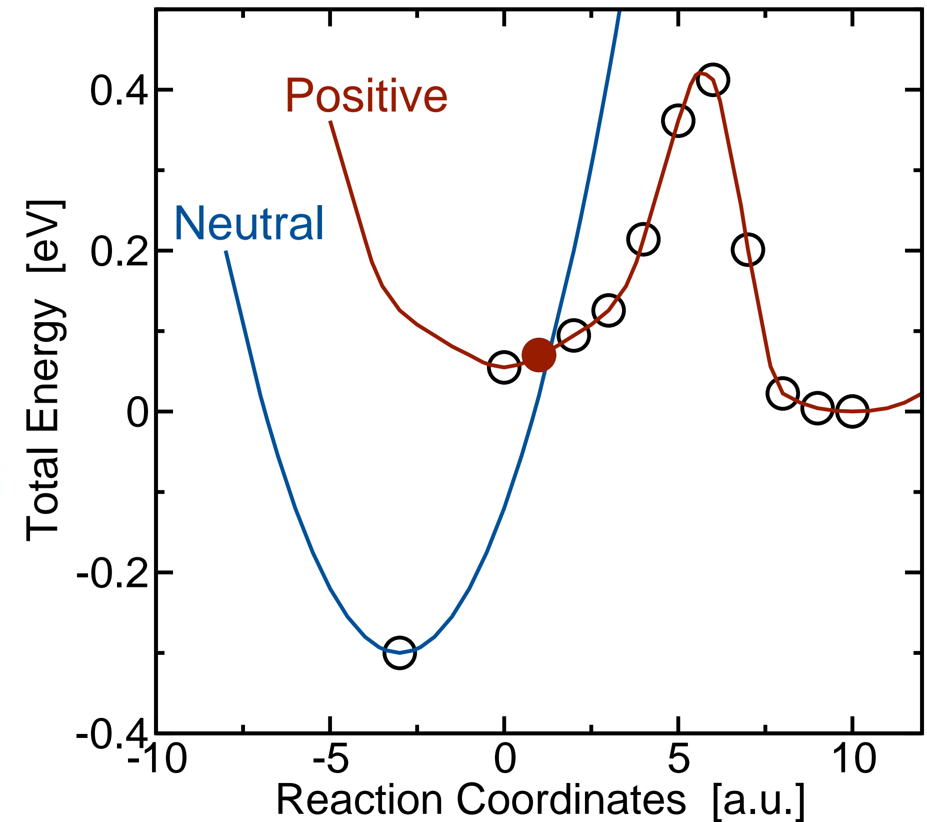

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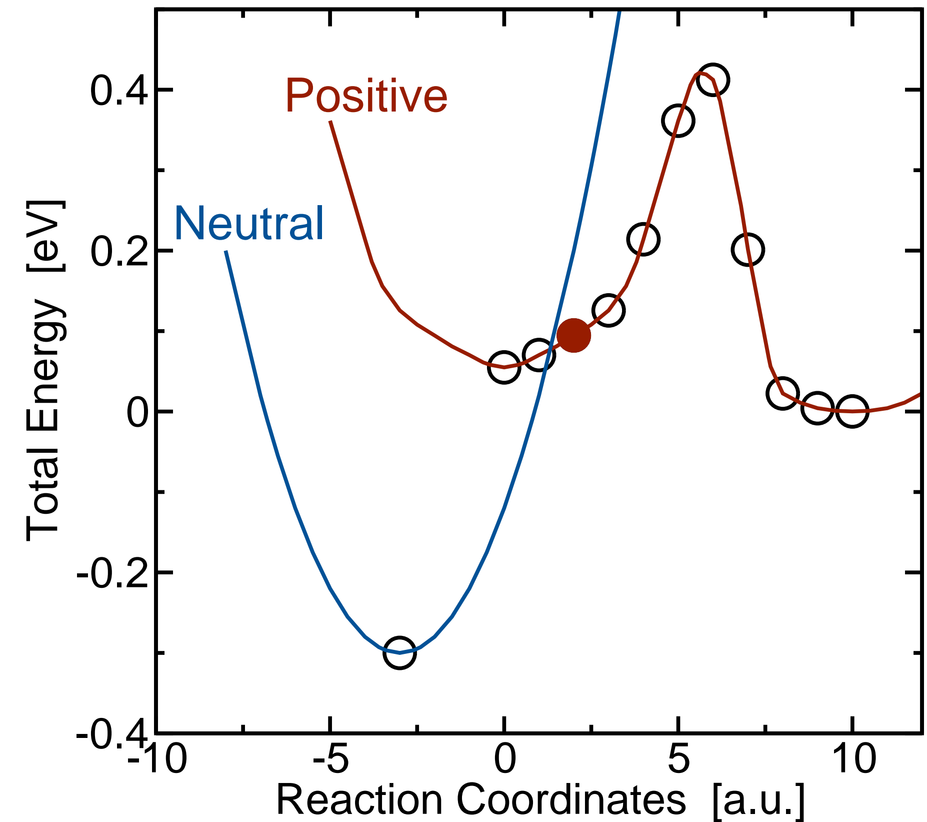

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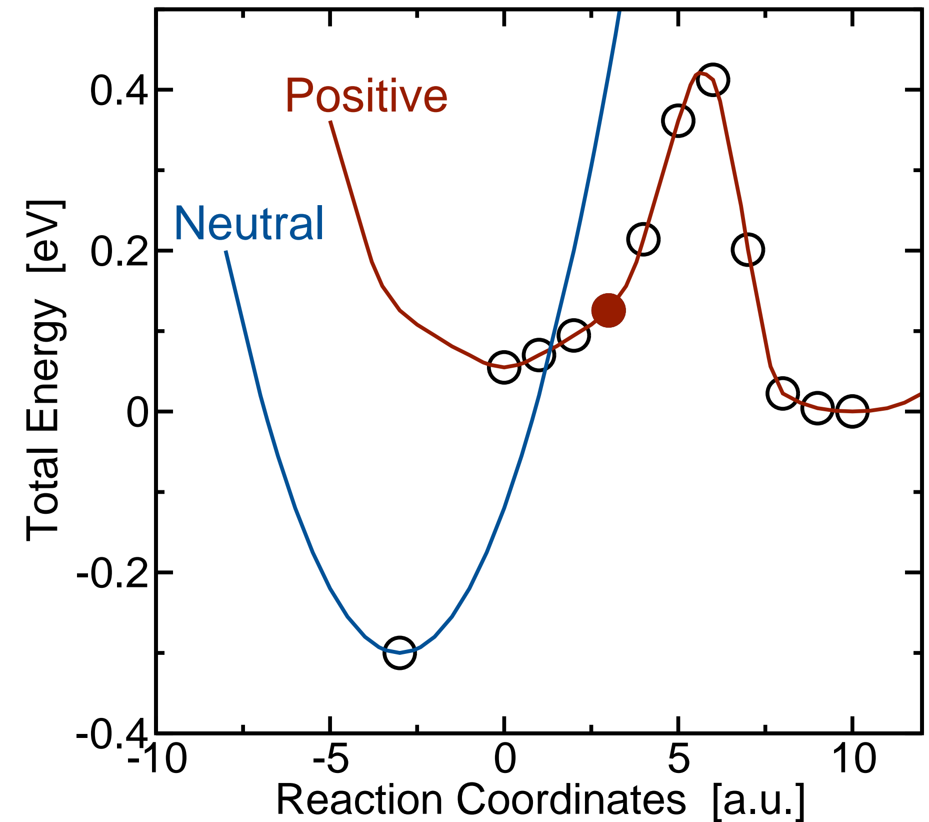

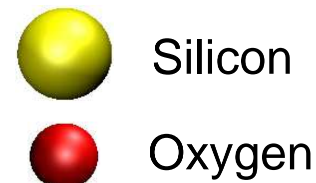

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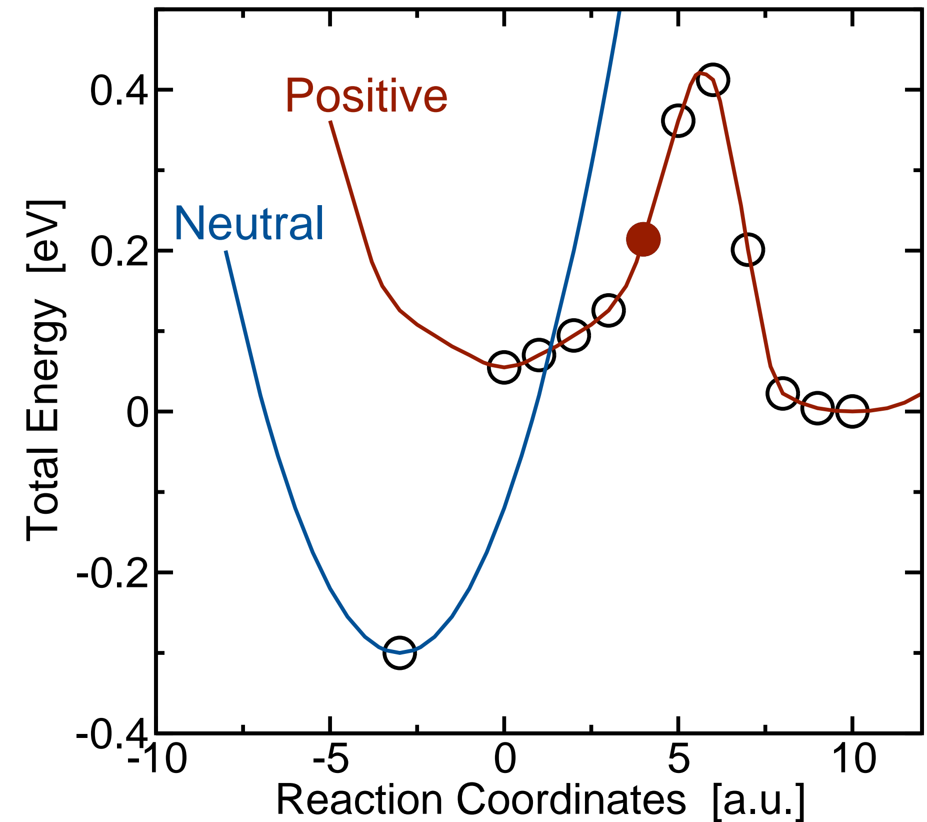

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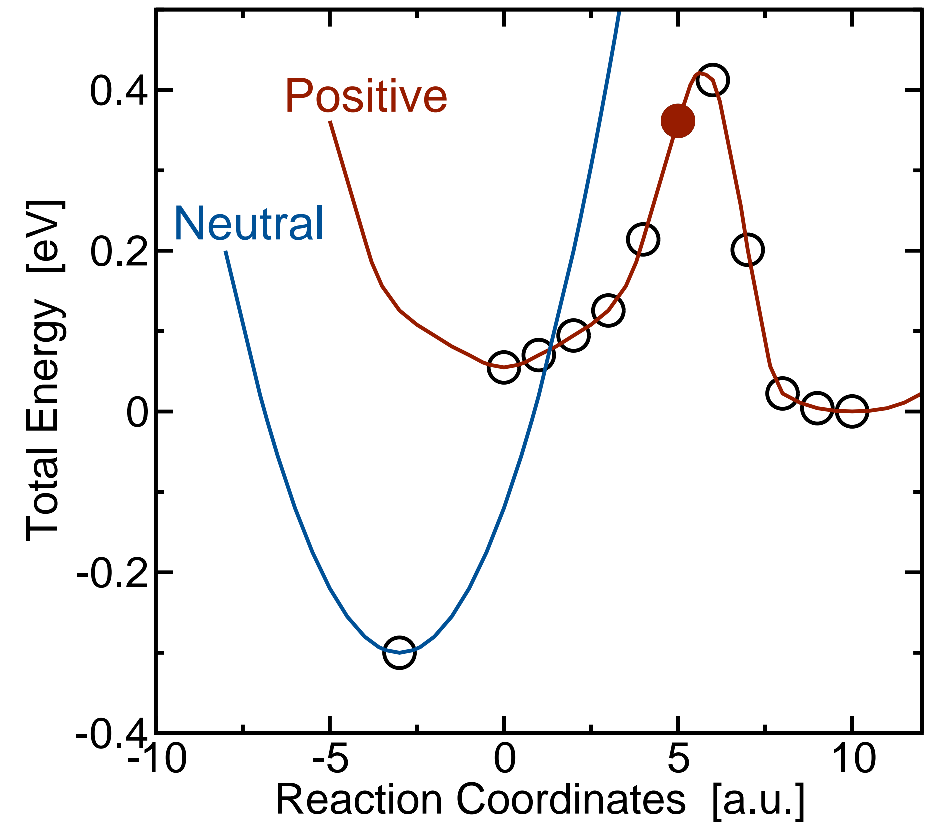

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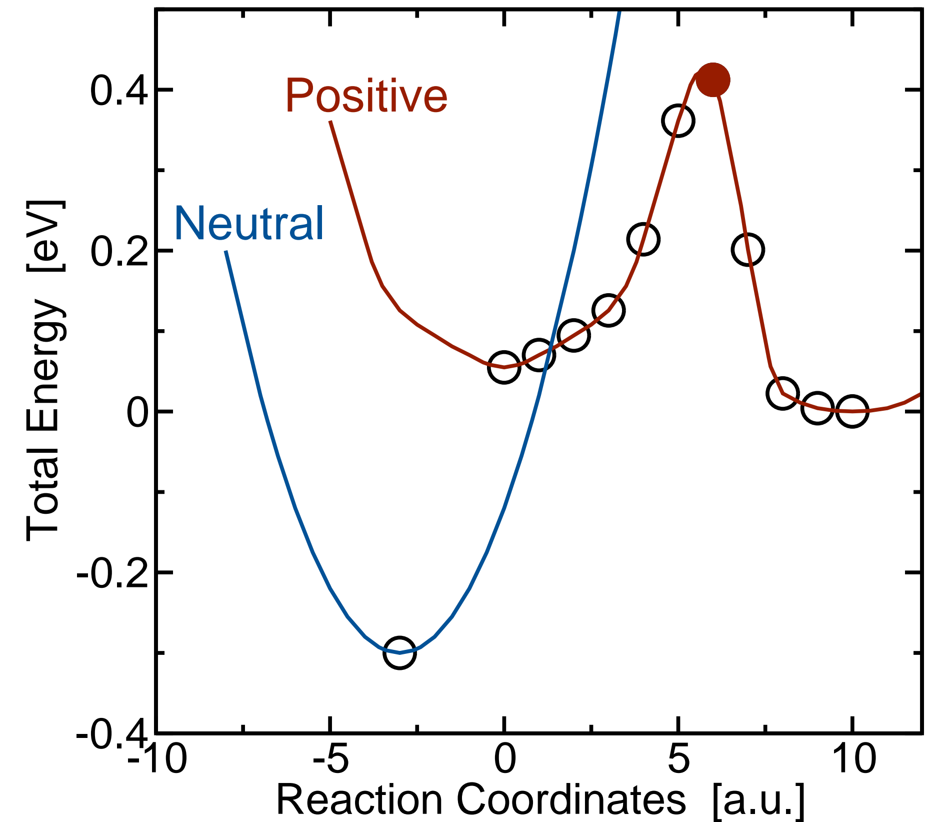

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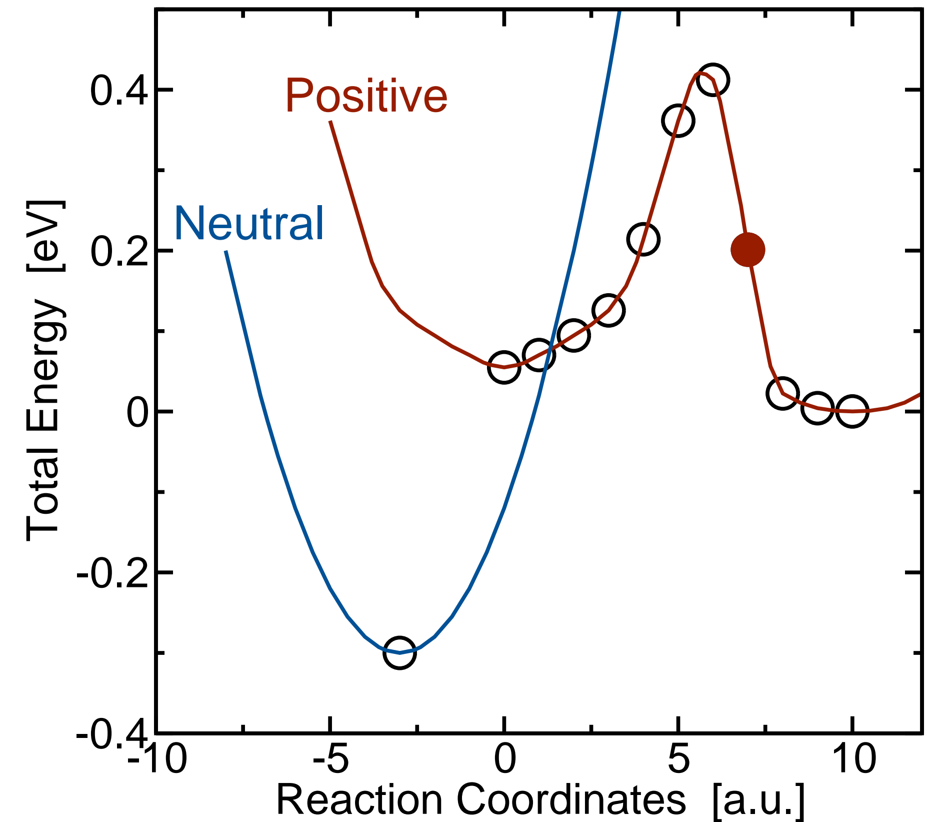

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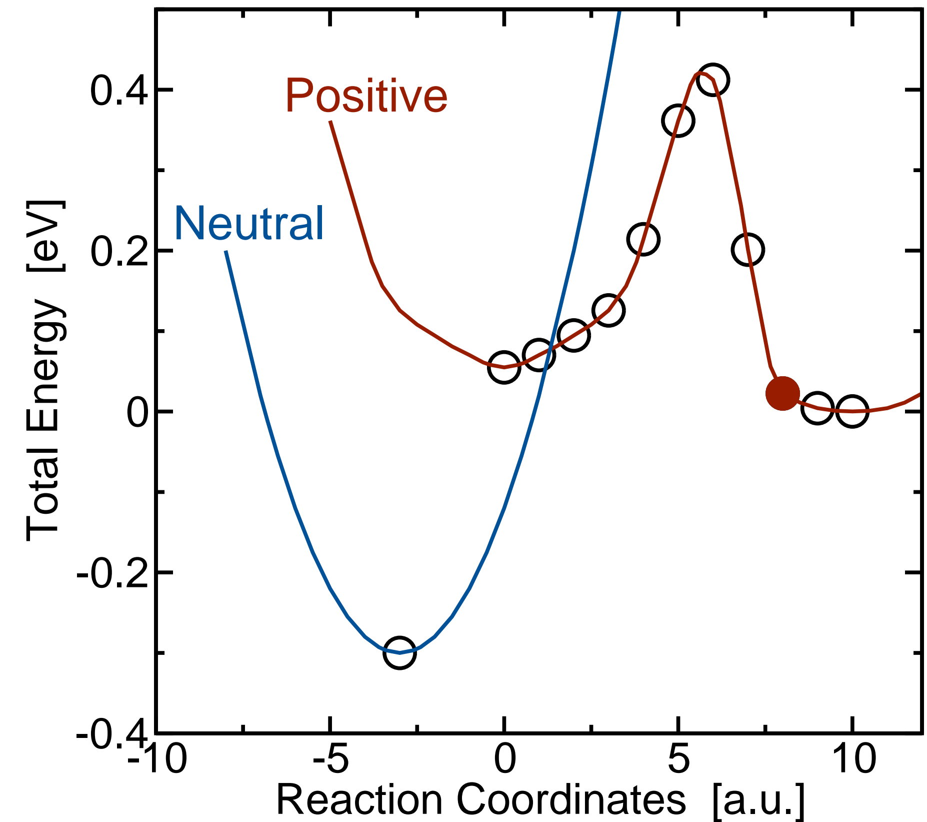

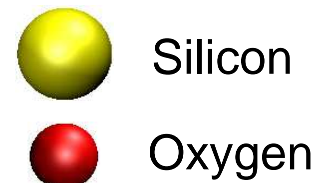

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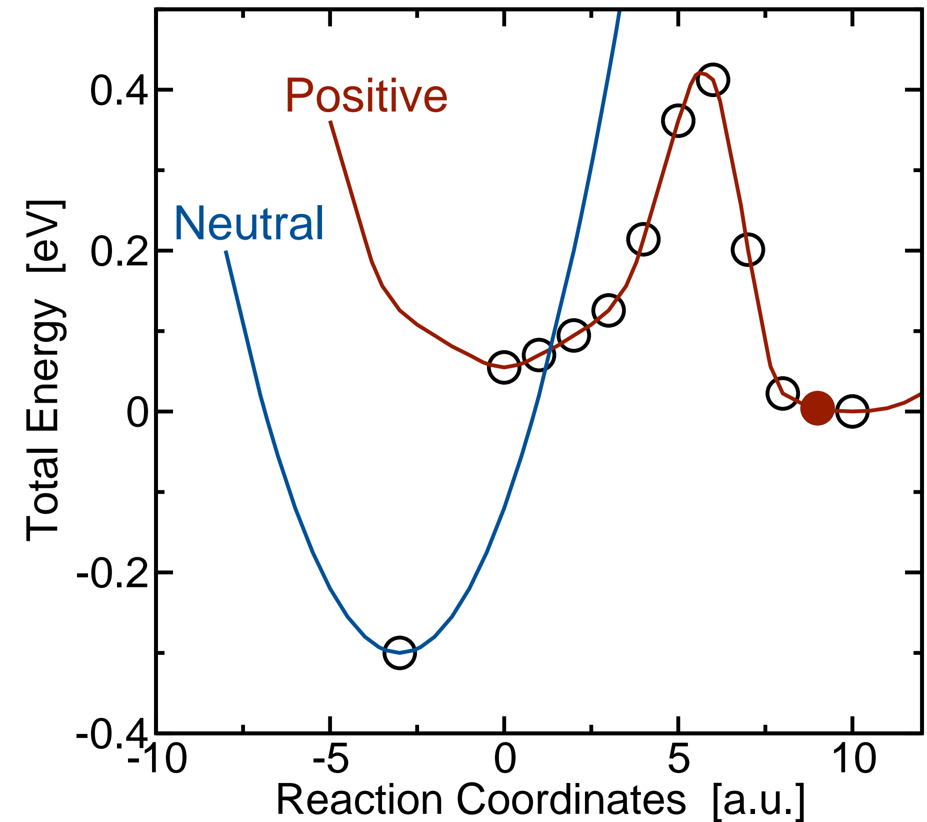

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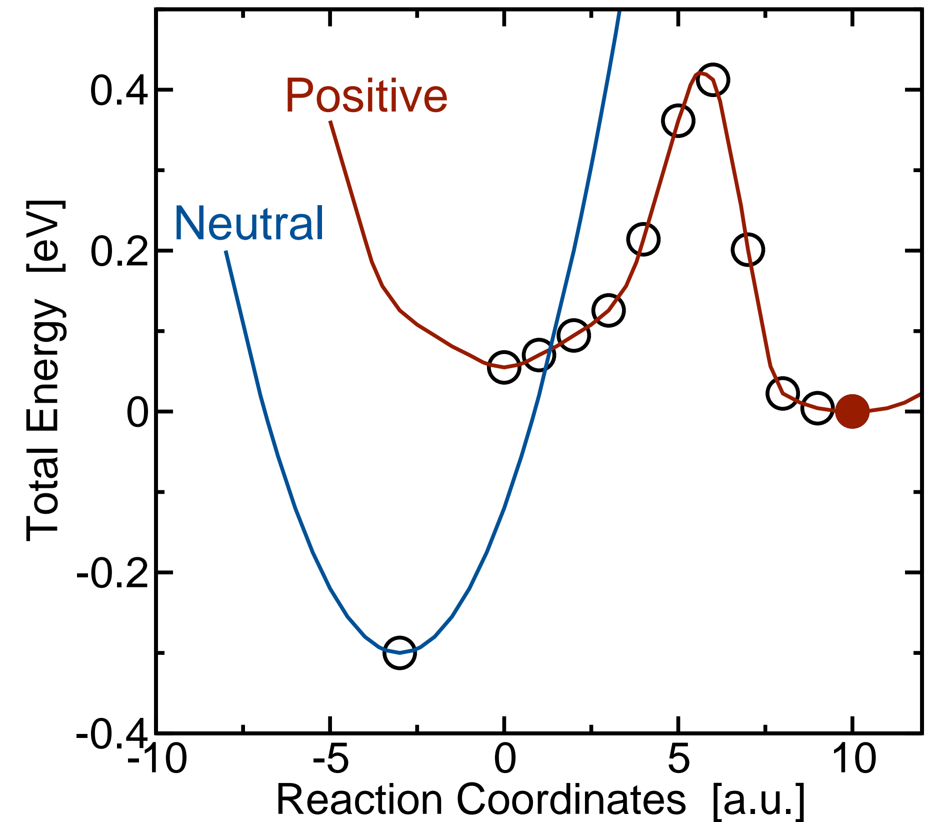

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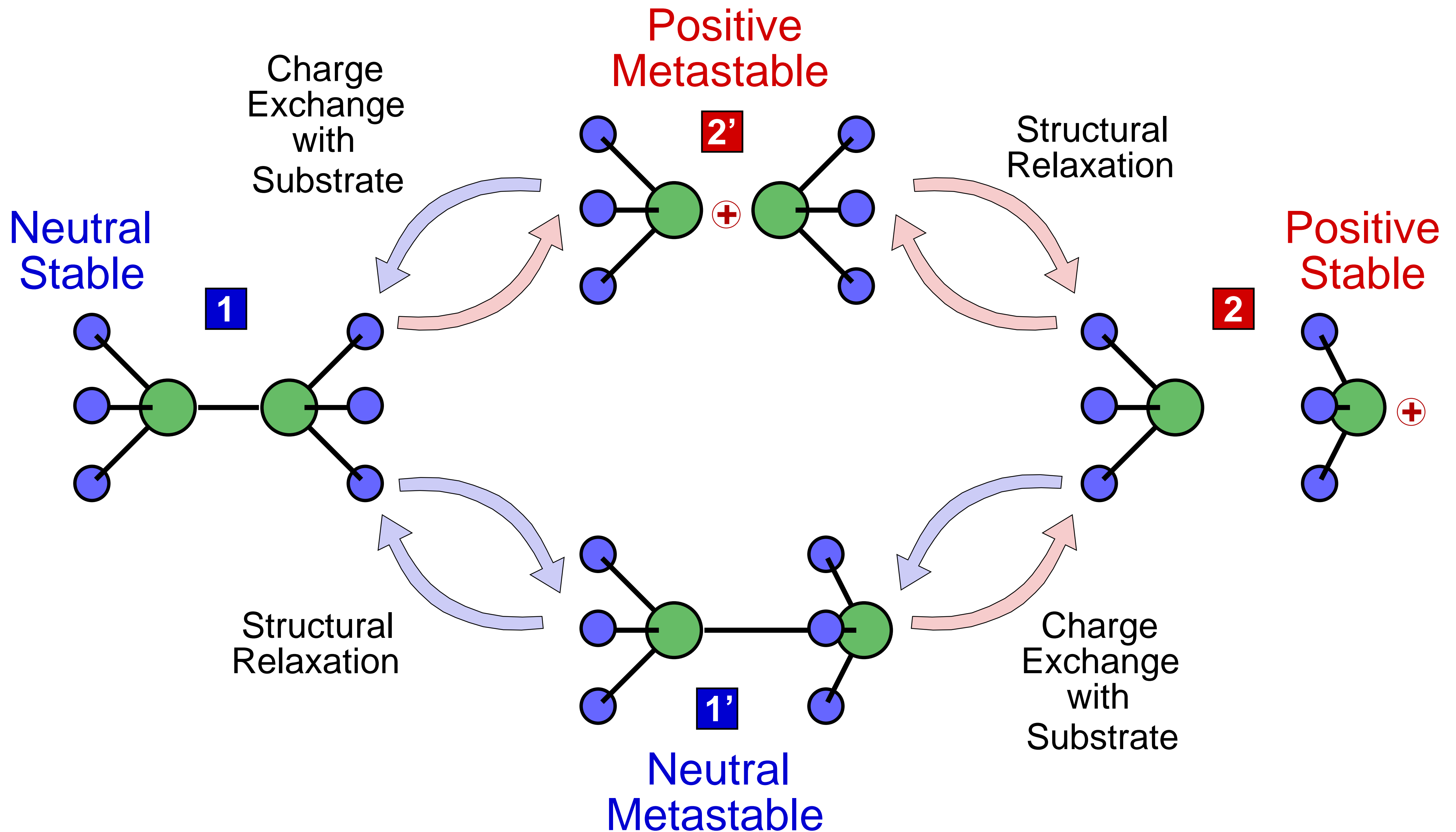
Oxygen

Detailed Defect Model Required



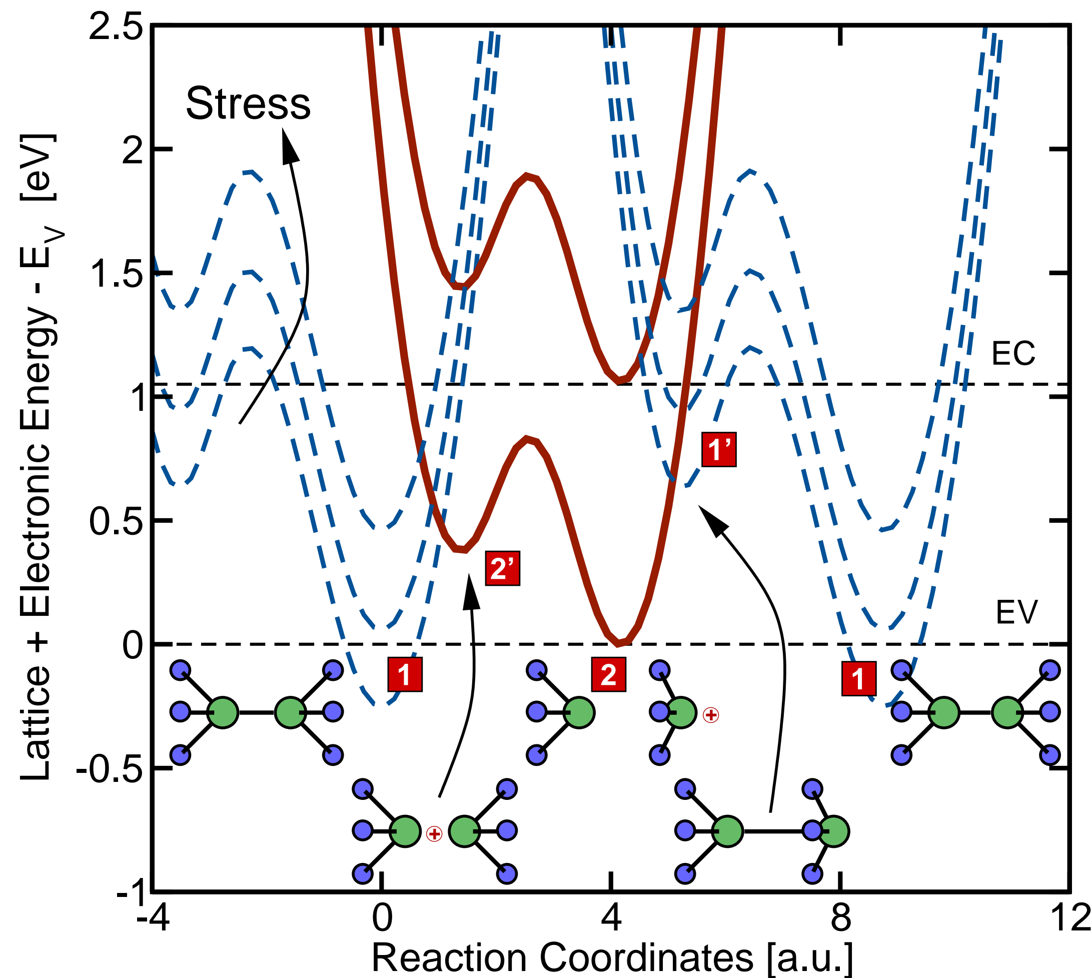
Model

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

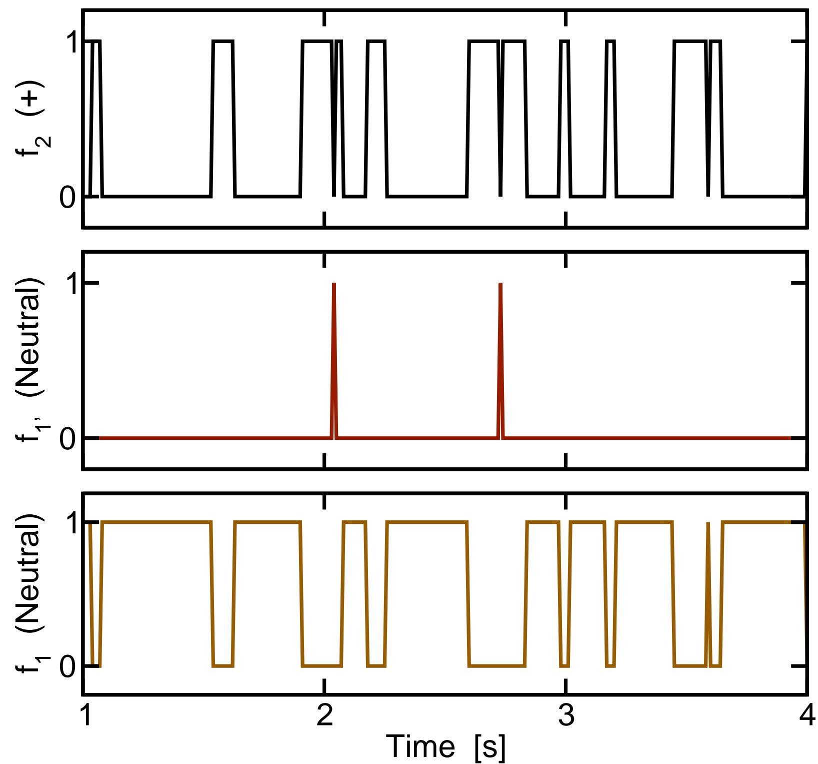
Stochastic Markov-model for defect kinetics based on multiphonon theory

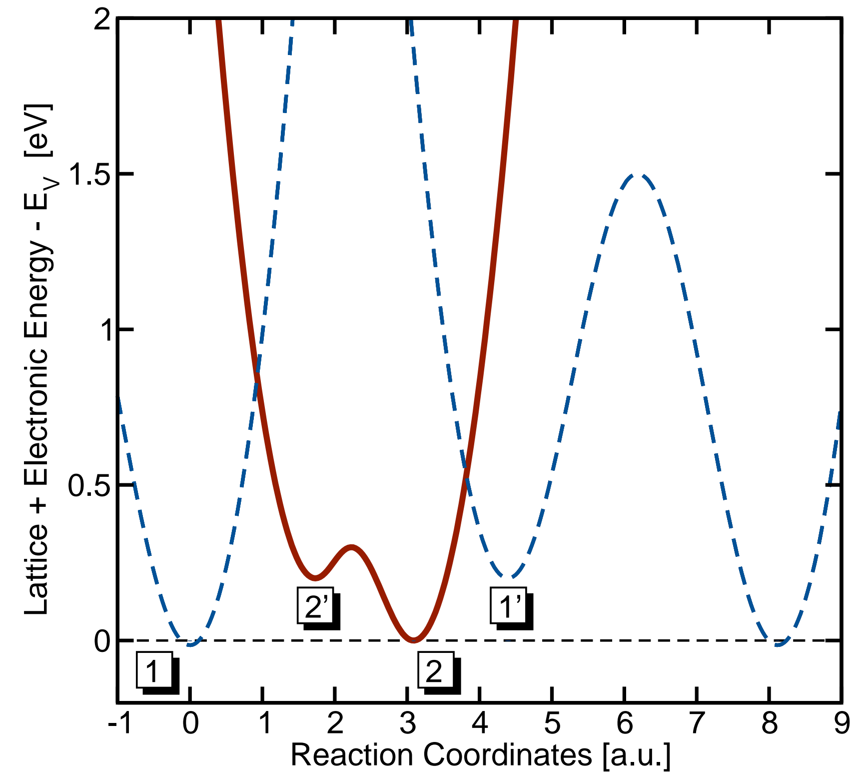


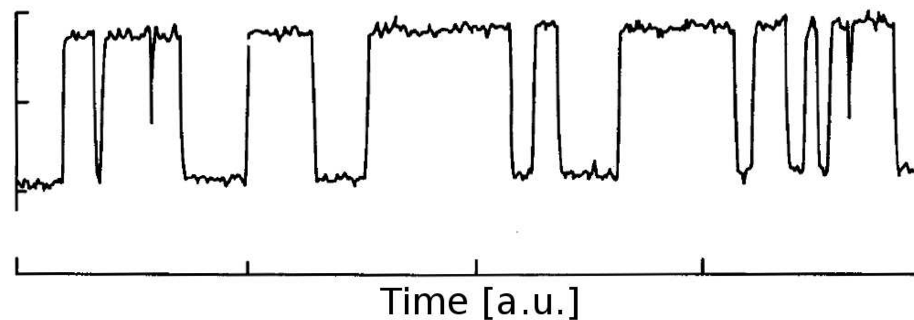
Qualitative Model Evaluation

Normal random telegraph noise (RTN)

Very similar energetical position of the minimas 1 and 2





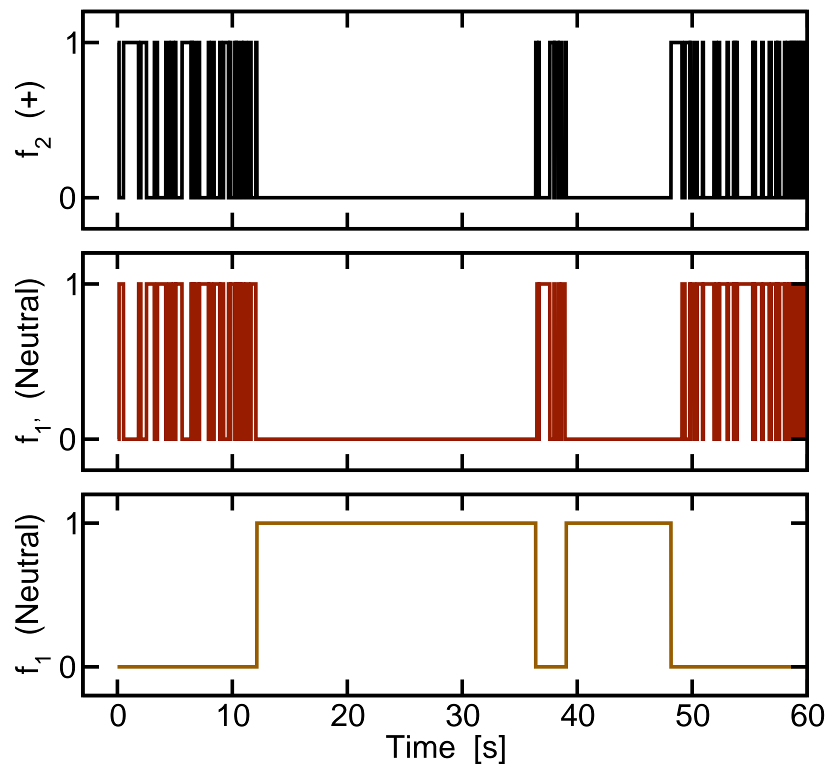


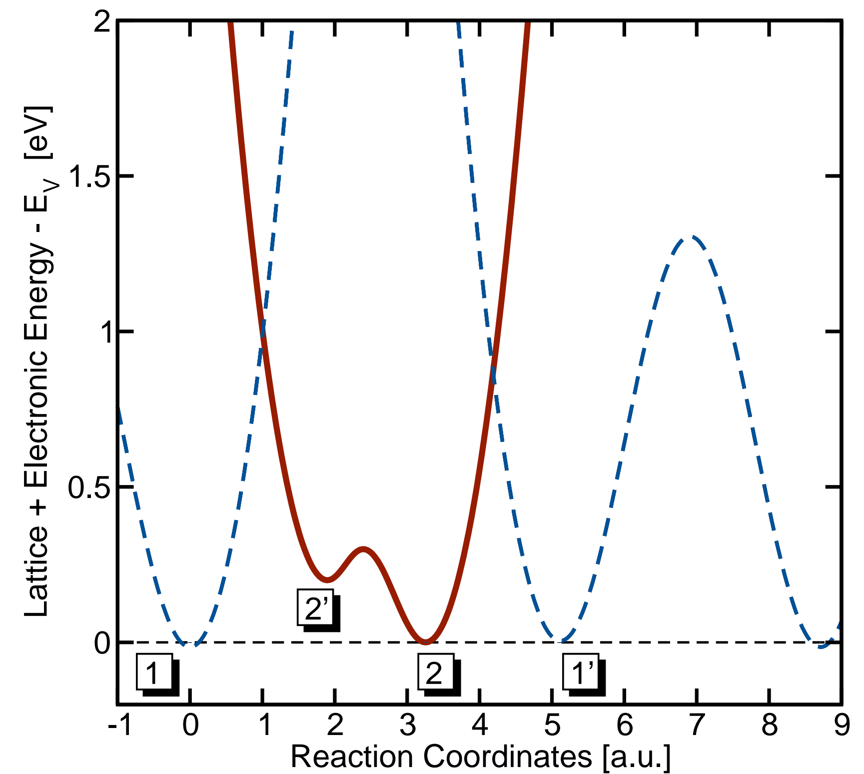
Kirton and Uren, Adv. Phys. '89

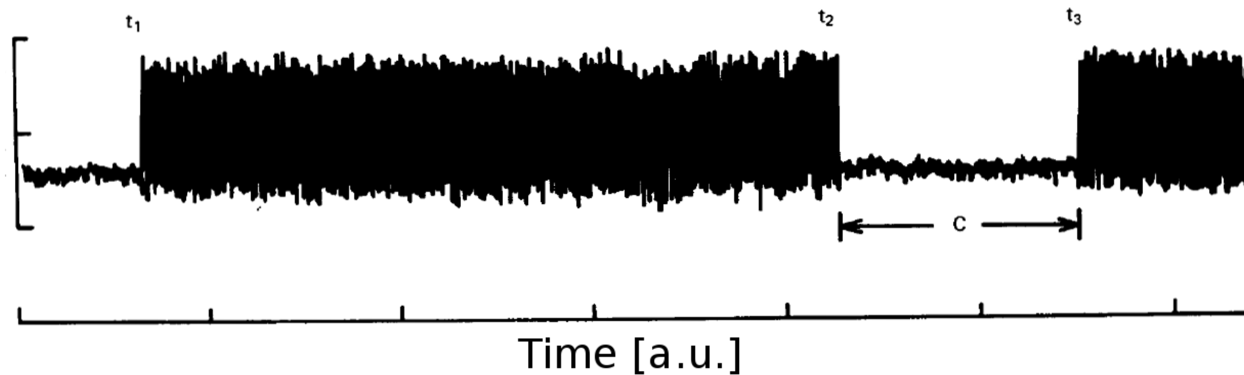
Qualitative Model Evaluation

Anomalous RTN

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





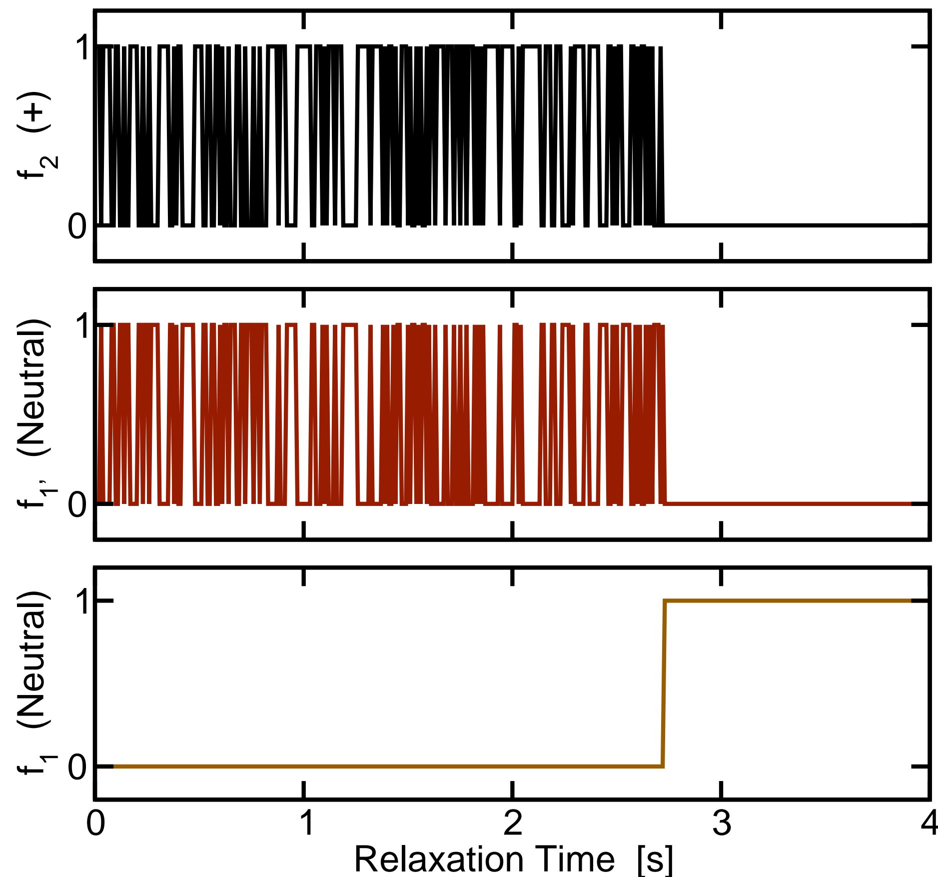


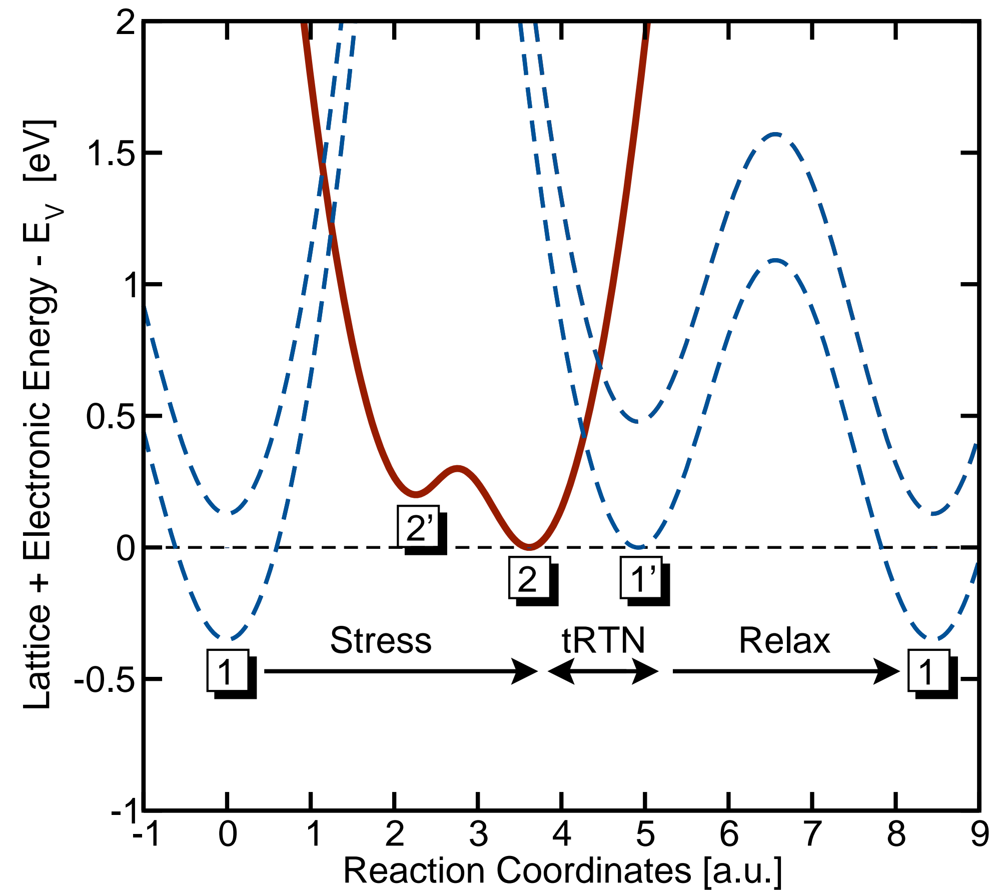
Uren *et al.*, PRB '88

Qualitative Model Evaluation

Temporary random telegraph noise (tRTN)

Very similar energetical position of the minima 2 and 1'





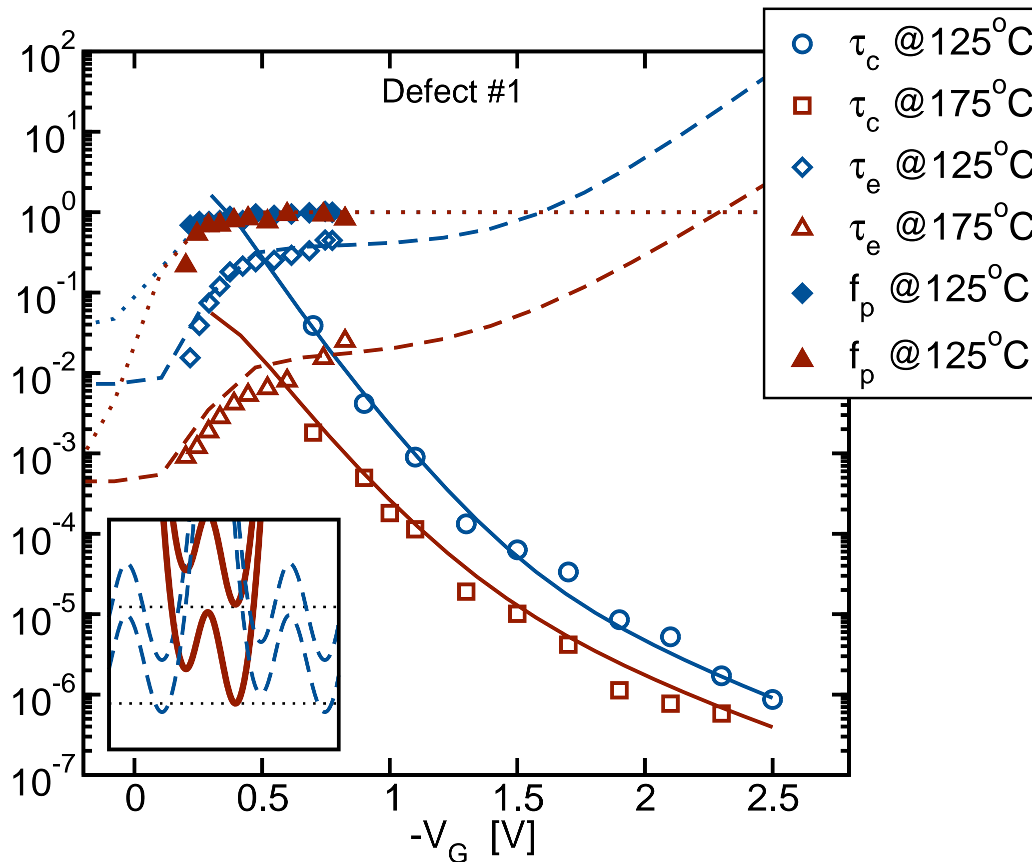
Quantitative Model Evaluation

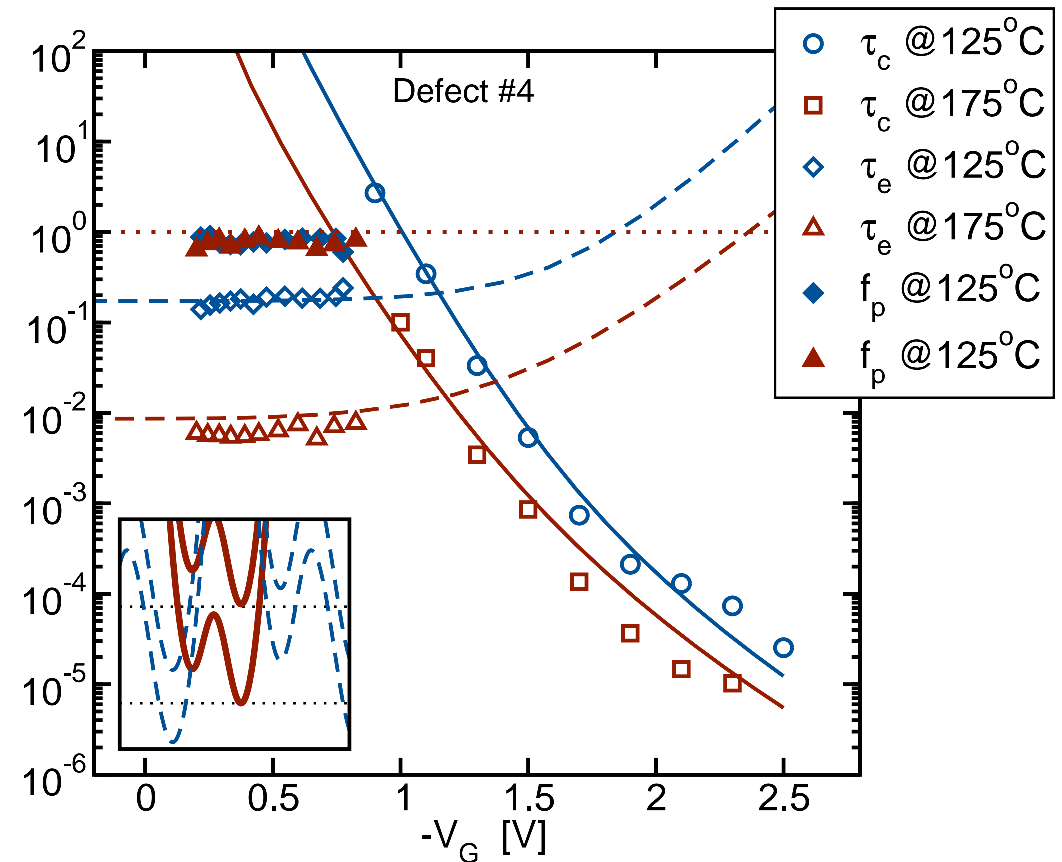
Excellent agreement for both capture and emission time constants

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

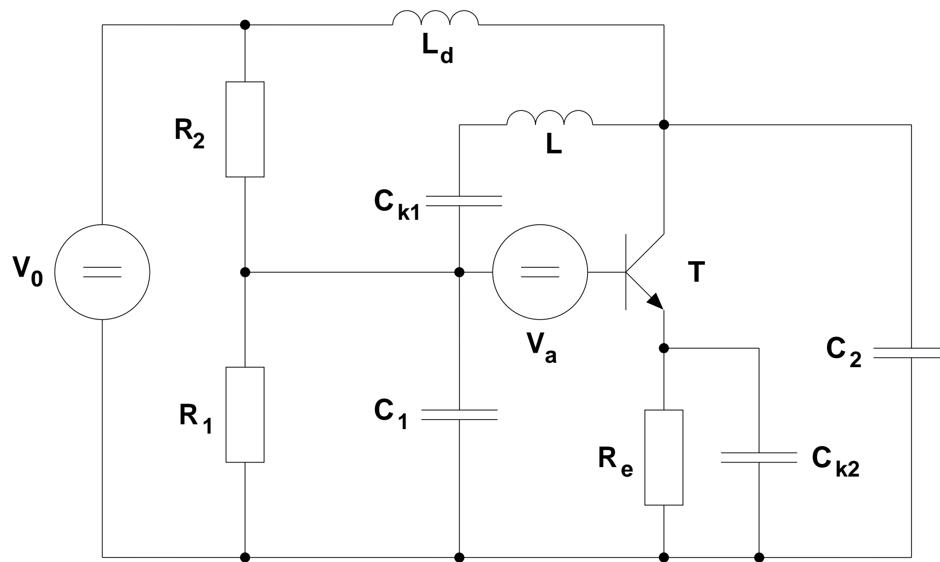
Does the defect act like a switching trap?

- Depends on the defect configuration





How to Model This with SPICE?



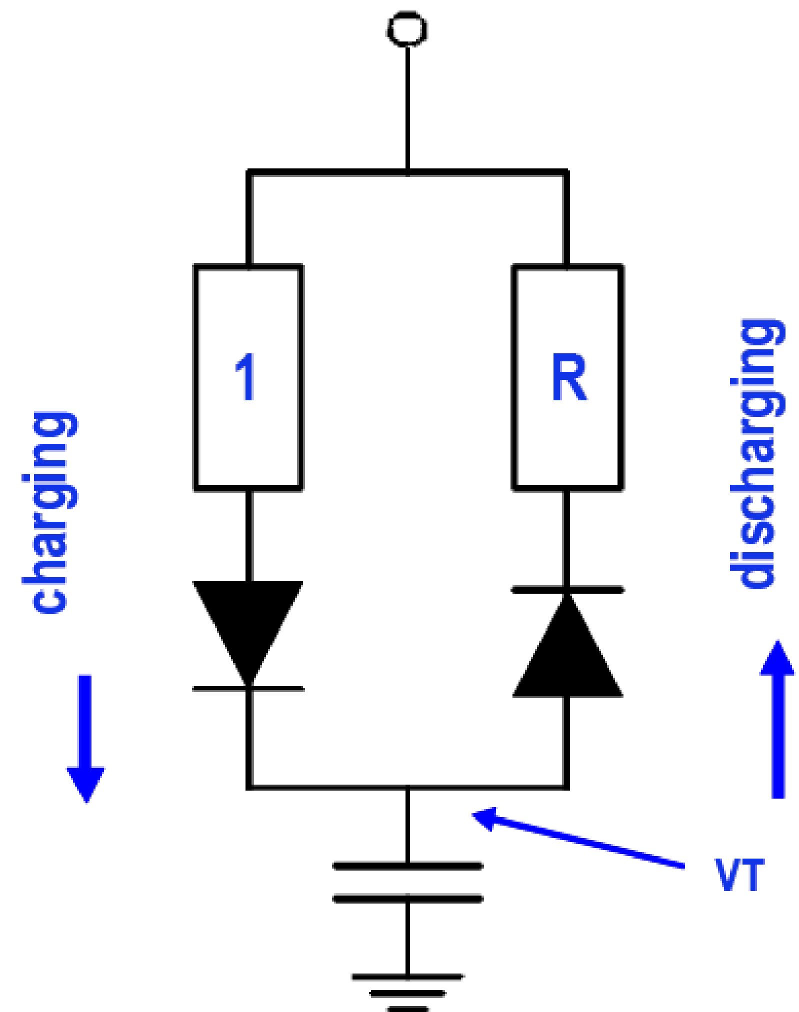
Compact Modeling

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

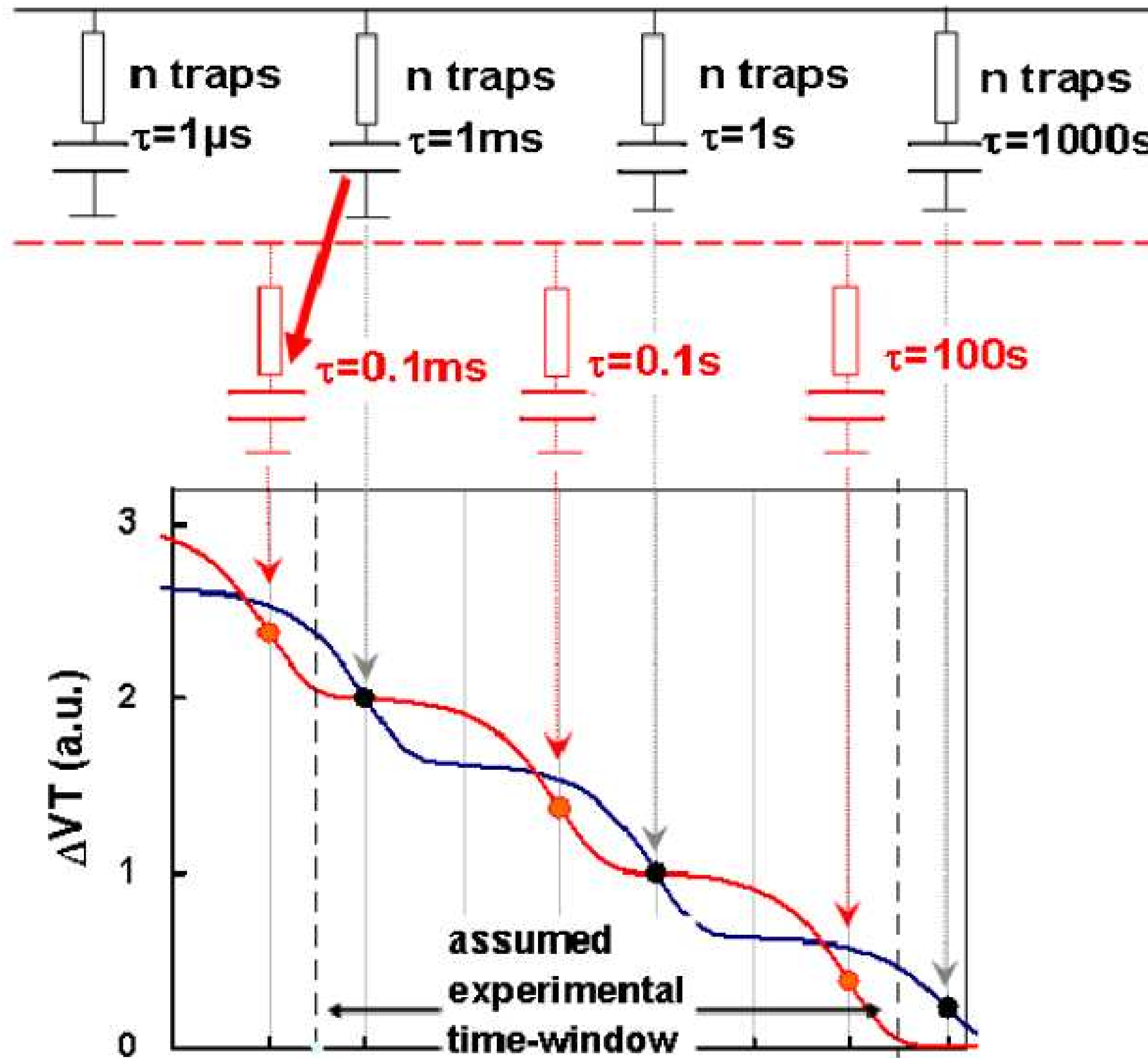


[1] Kaczer *et al.*, IRPS '10 [2] Reisinger *et al.*, IRPS '10

Compact Modeling

Example: modeling of recovery[1]

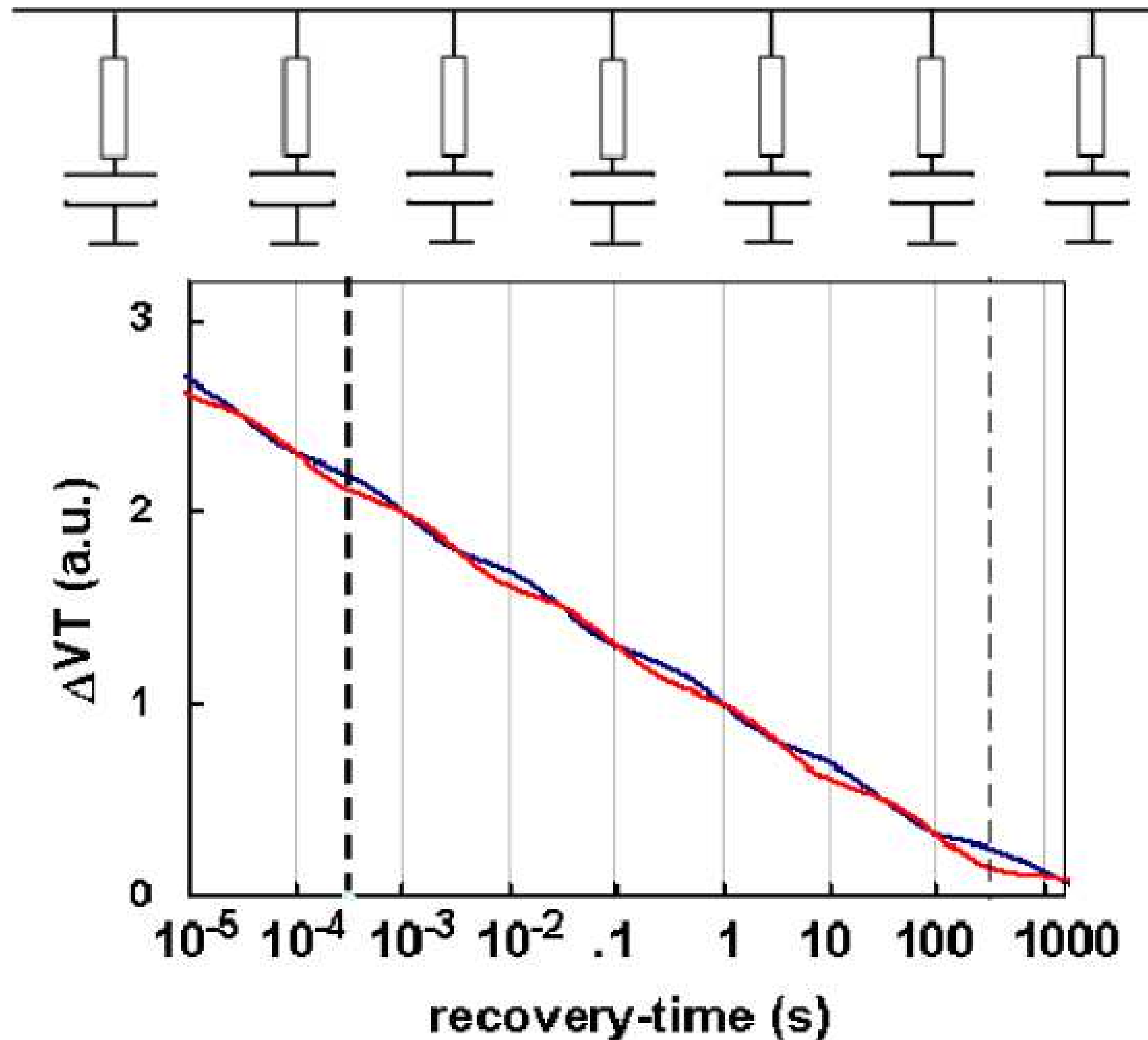
Crude approximation: 1 RC element every 3 decades



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

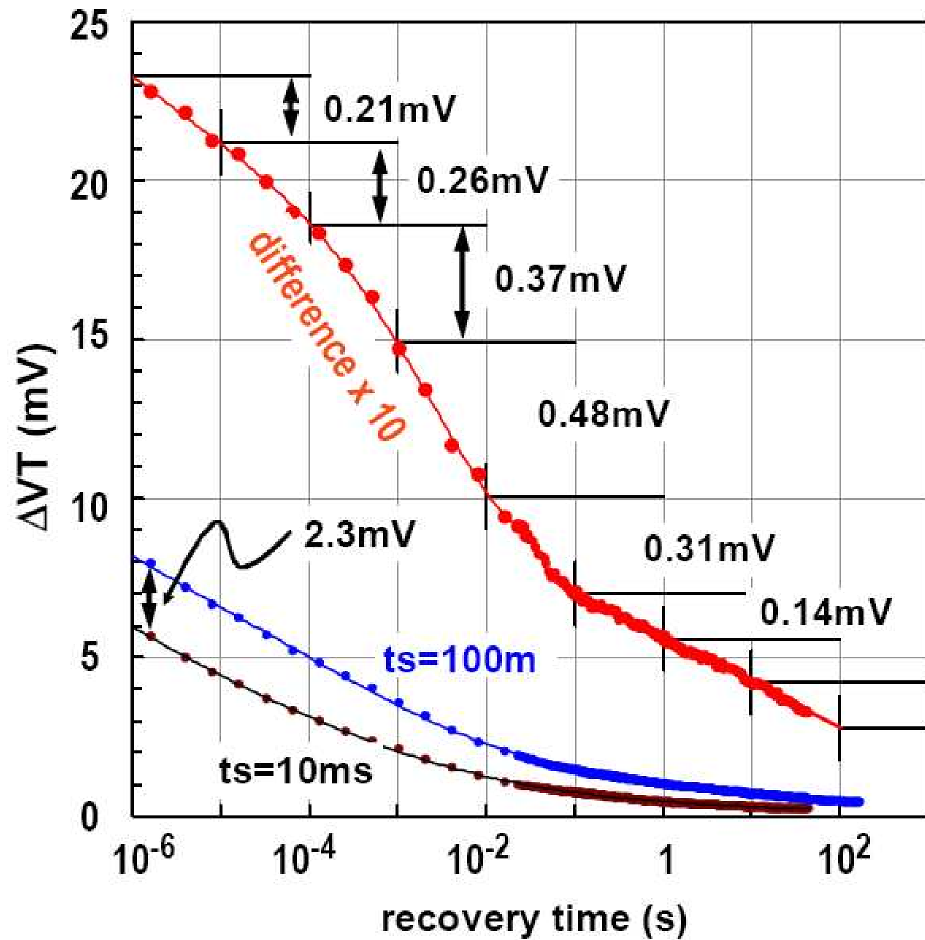
Example: modeling of recovery[1]

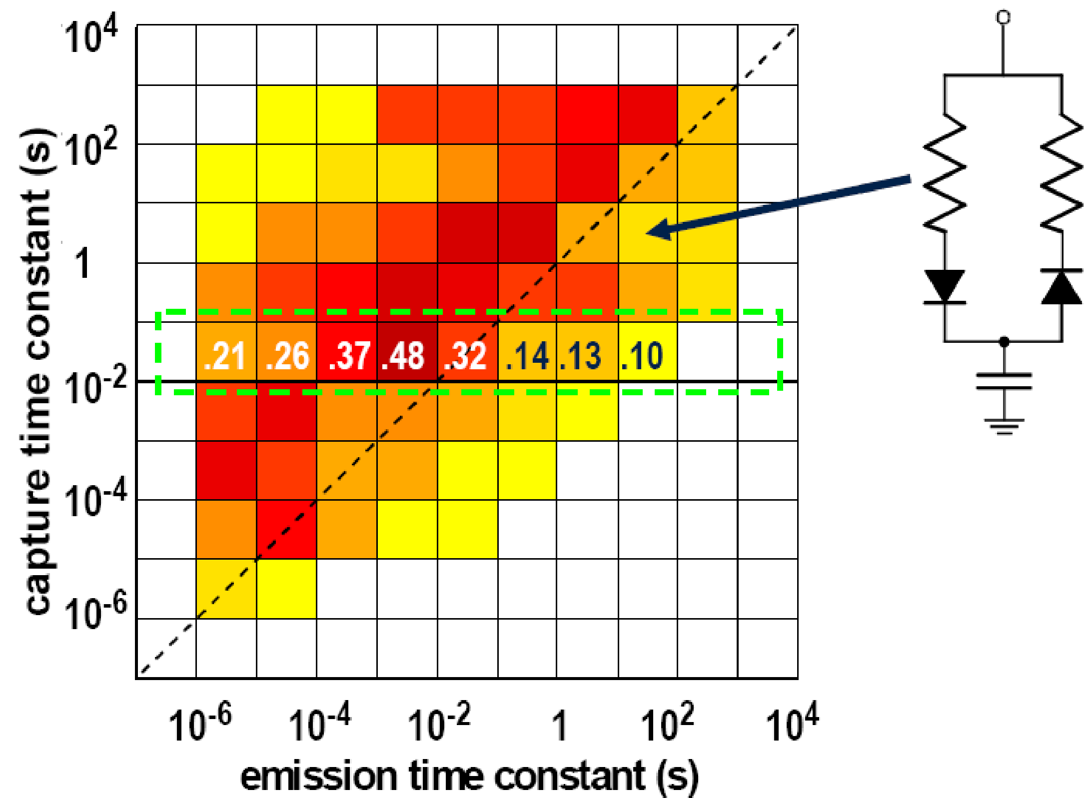
Finer approximation: 2 RC elements every 3 decades



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

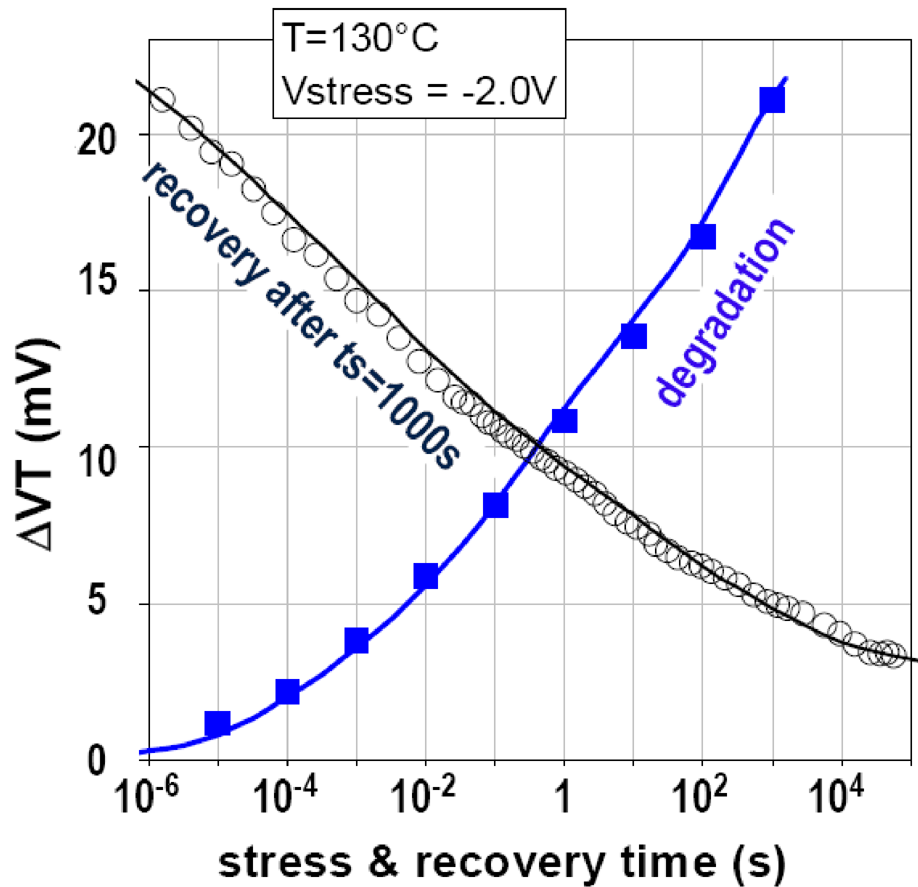
Extraction of the time constants[1]

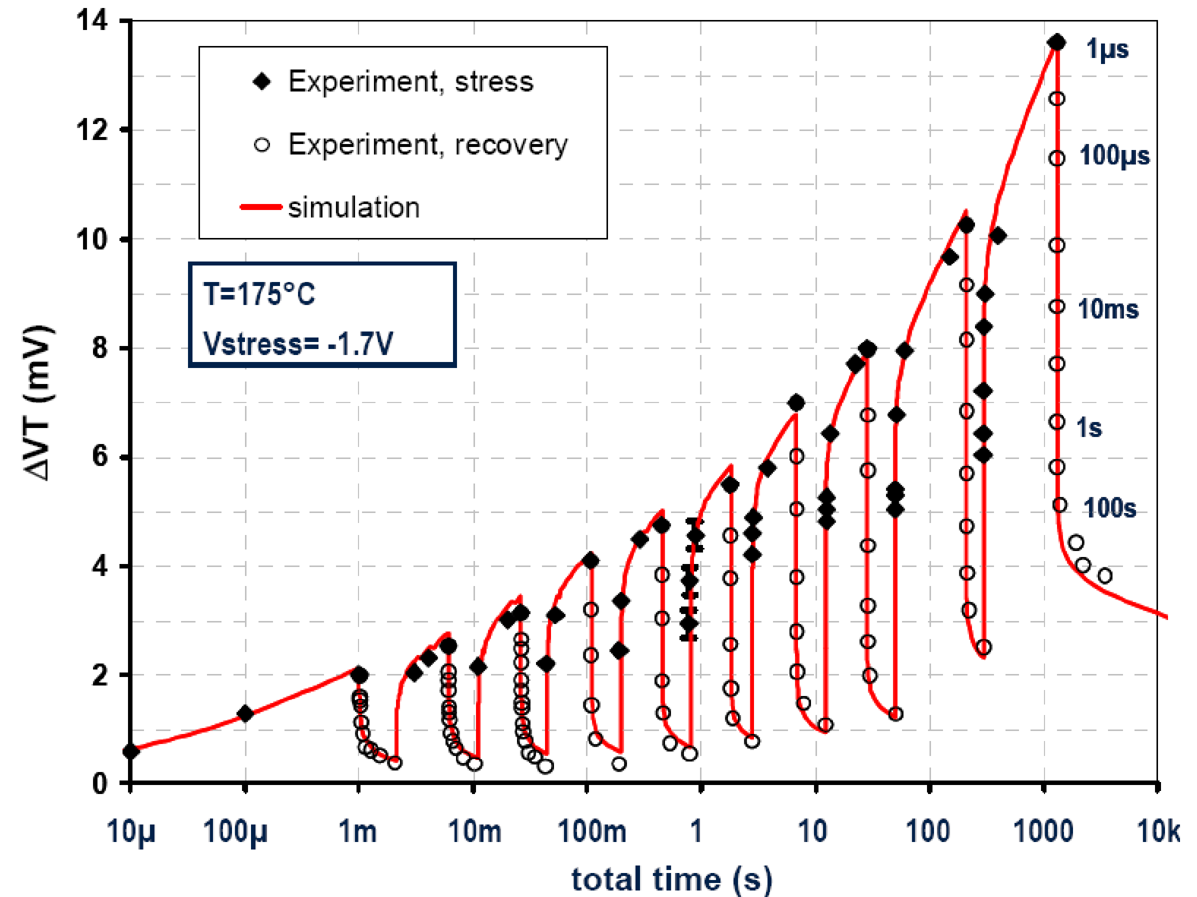




[1] Reisinger *et al.*, IRPS '10

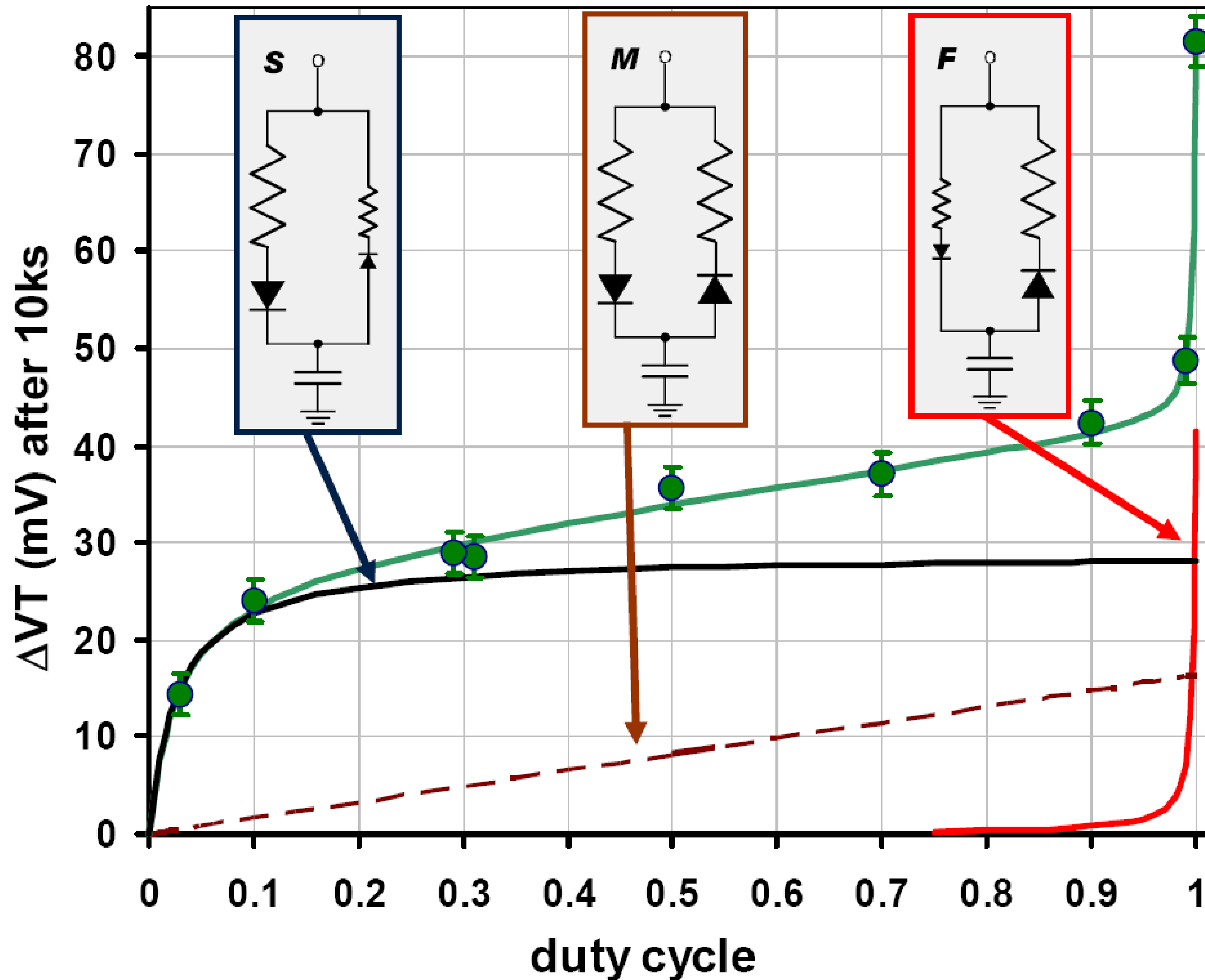
Application examples[1]





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

Notorious: duty factor dependence[1] [2] [3]



[1] Grasser *et al.*, IEDM '07 [2] Grasser *et al.*, IRPS Tutorial '08 [3] Reisinger *et al.*, IRPS '10

Why Would We Care?

Why Would We Care?

Defects determine the lifetime of the device

Statistics of individual defects become important in nanoscale MOSFETs

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

Fundamental implications on device reliability

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

How to Determine the Lifetime?

Small area devices: lifetime is a stochastic quantity [1] [2]

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

For details see Grasser *et al.* IEDM '10

[1] Kaczer *et al.* IRPS '09 [2] Grasser *et al.* IEDM '10

Conclusions

NBTI/PBTI is a challenging problem to understand and model

Dynamics are of utmost importance

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

Measurement method: time dependent defect spectroscopy (TDDS)

- Operates on nanoscale MOSFETs with a handful of defects
- Allows extraction of $\bar{\tau}_{\mathrm{e}}$, $\bar{\tau}_{\mathrm{c}}$, and step-height over very wide range
- Allows simultaneous analysis of multiple defects

New defect model

- Metastable defect states, nonradiative multiphonon theory, stochastic behavior

First attempts towards compact modeling

- Equivalent RC circuits which deliver ΔV_{th}
- Can capture the main features, e.g. DC vs. AC

Lifetime becomes a stochastic quantity

This work would have been impossible without the support of ...

The Institute for Microelectronics

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Financial support, measurement data, and discussion

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