Statistical Reliability in Nanoscale Devices: The Bias Temperature Instability

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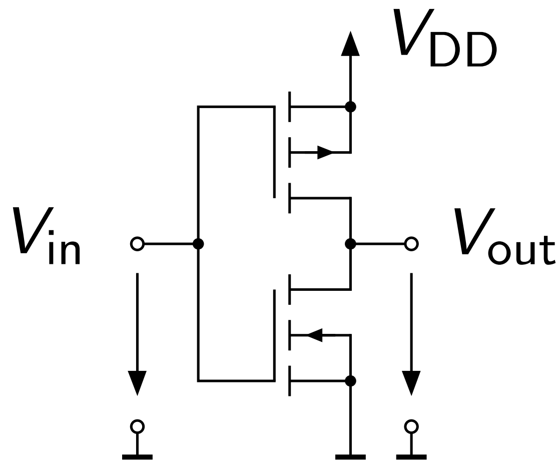
The Negative Bias Temperature Instability

When does the NBTI scenario occur?

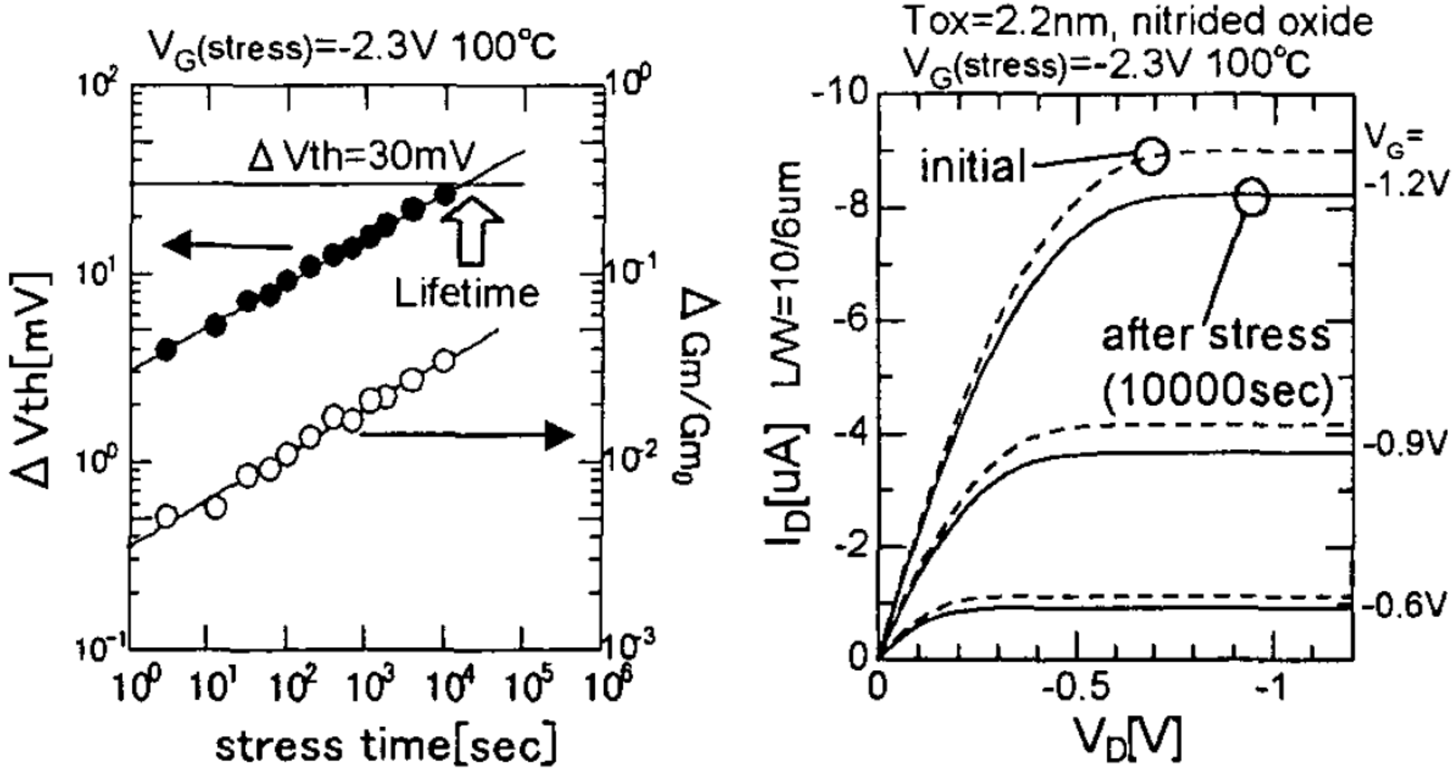
NBTI: $V_G \ll 0\,\mathrm{V}$, $V_S = V_D = 0\,\mathrm{V}$

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

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



What happens to the pMOS transistor?



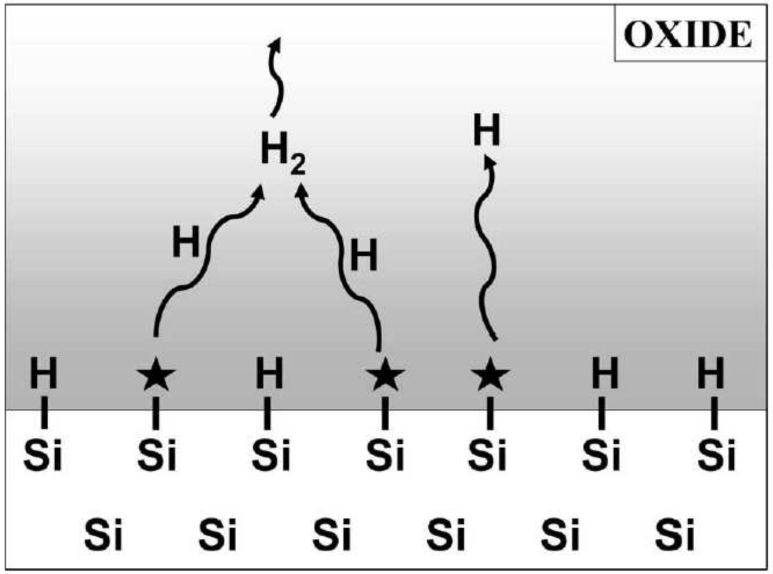
Kimizuka *et al.*, VLSI Symp. '00

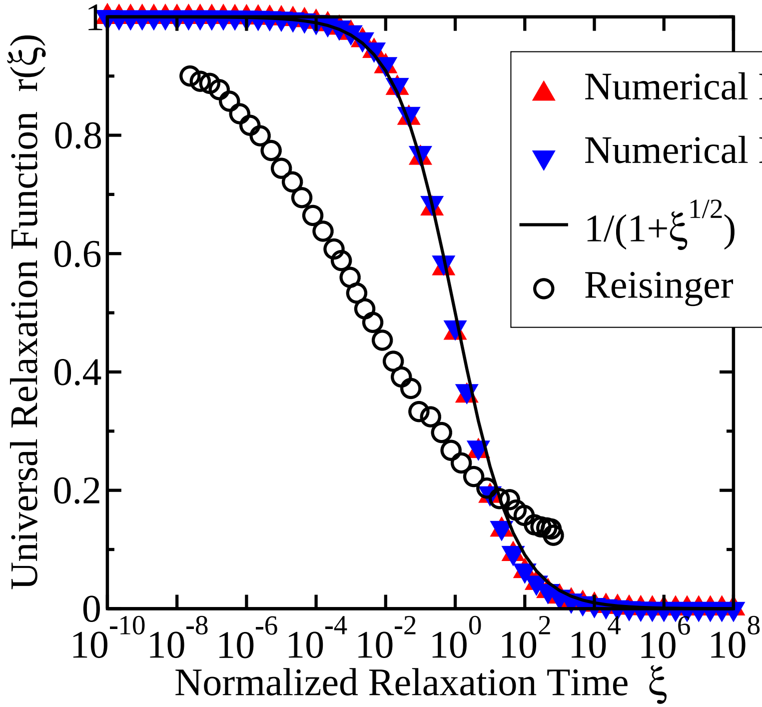
Standard Model: Reaction-Diffusion Model

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] Jeppson and Svensson, JAP '77 [2] Alam *et al.*, MR '06 [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

Implications

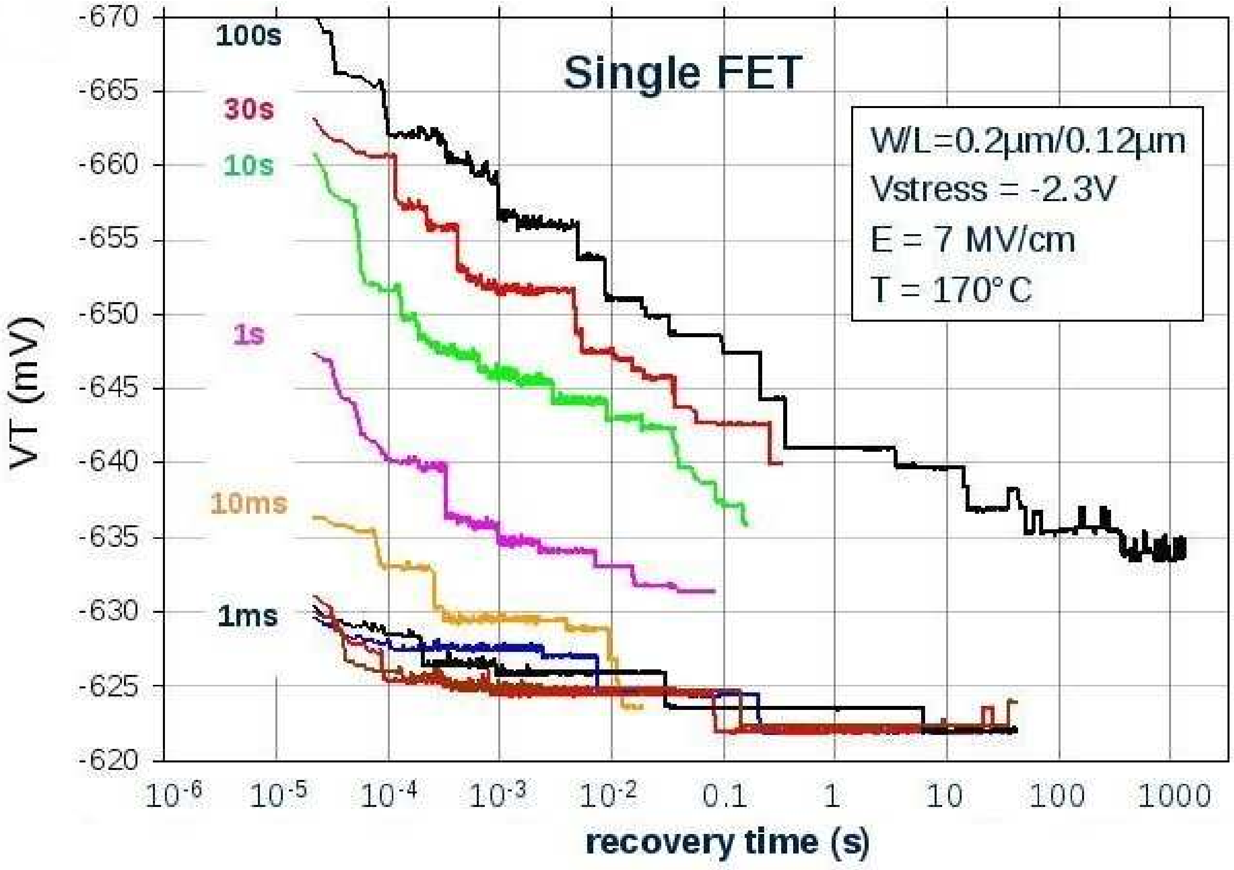
Lifetime of nanoscale MOSFETs

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:

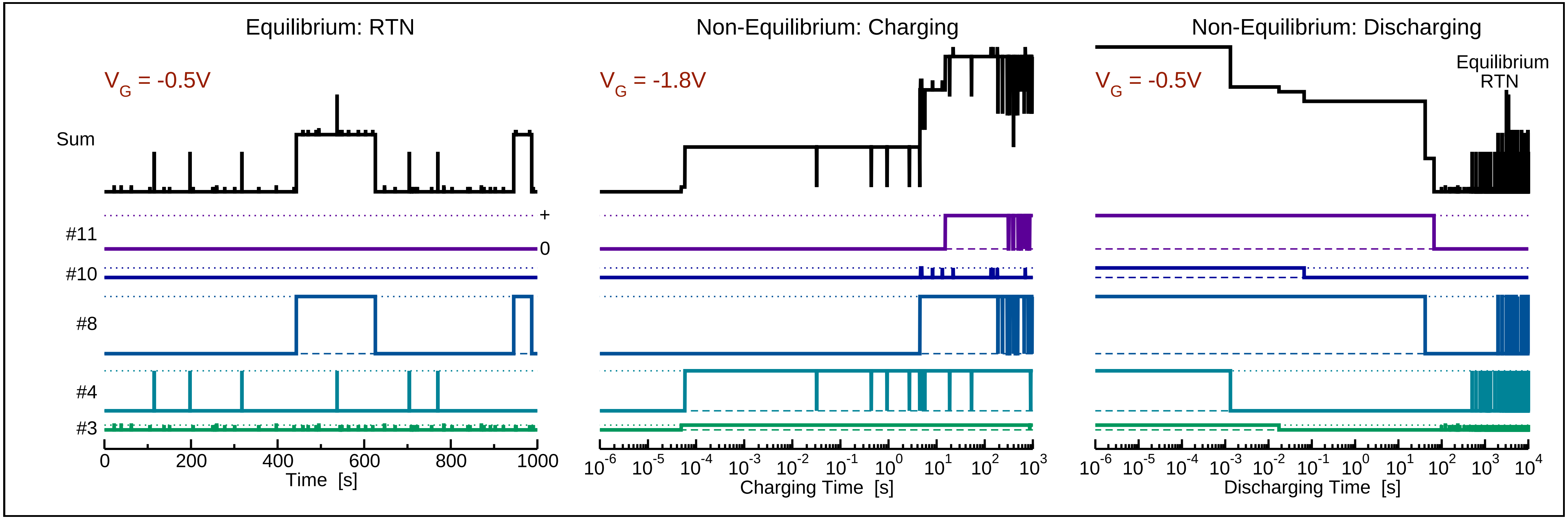
Some defects neutral, others positive, a few produce random telegraph noise (RTN)

Stress:

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

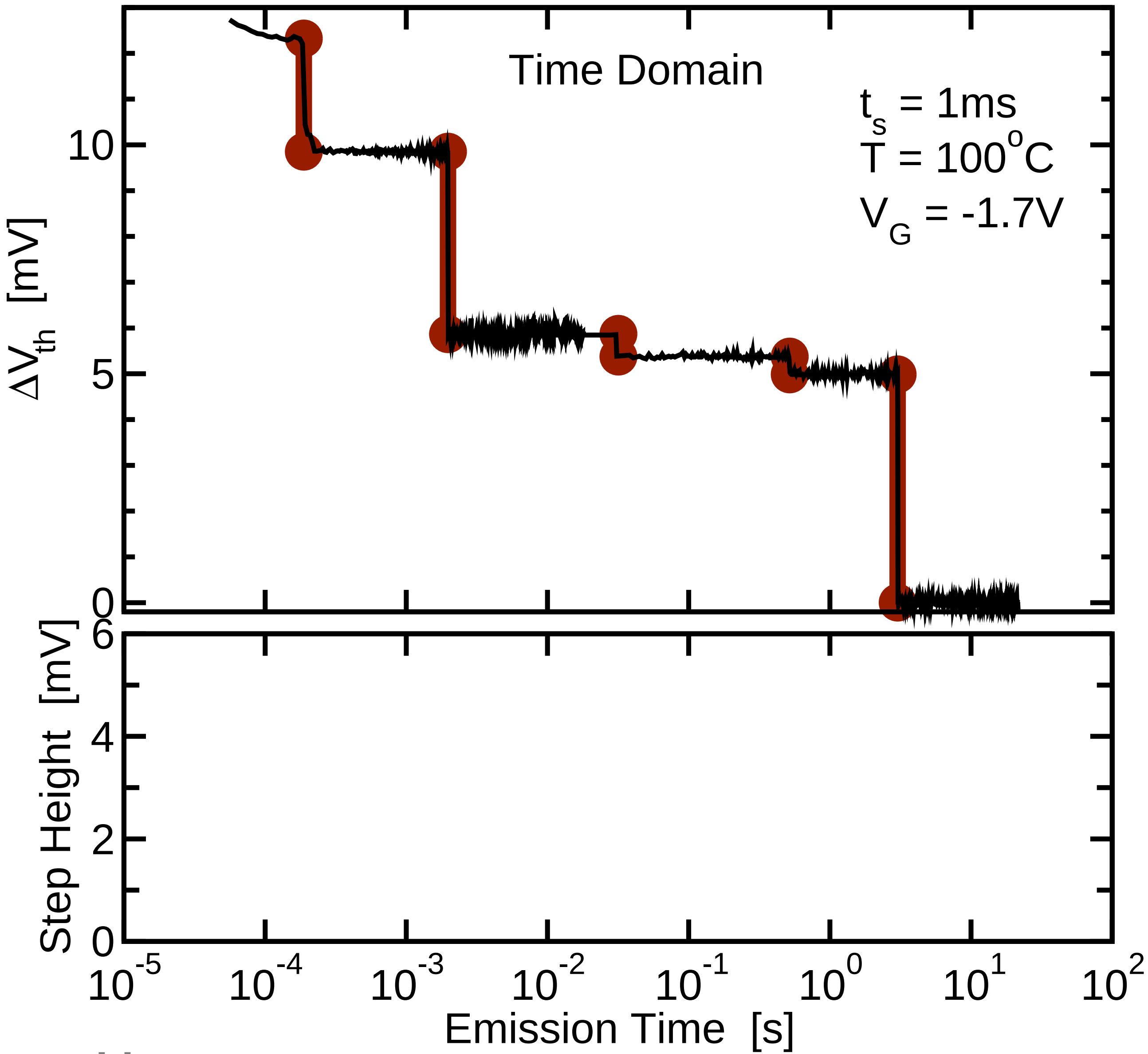
Recovery:

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



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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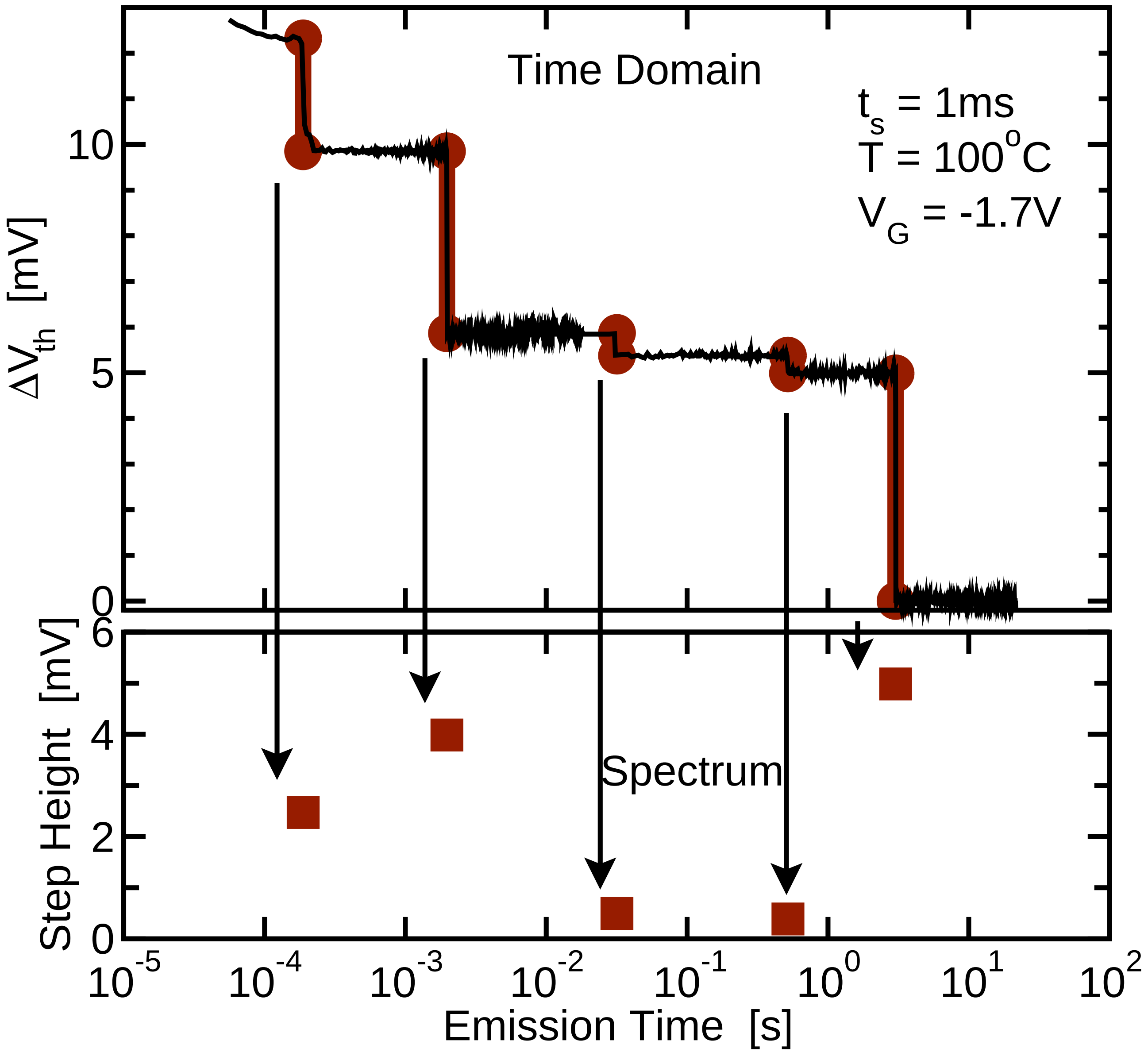

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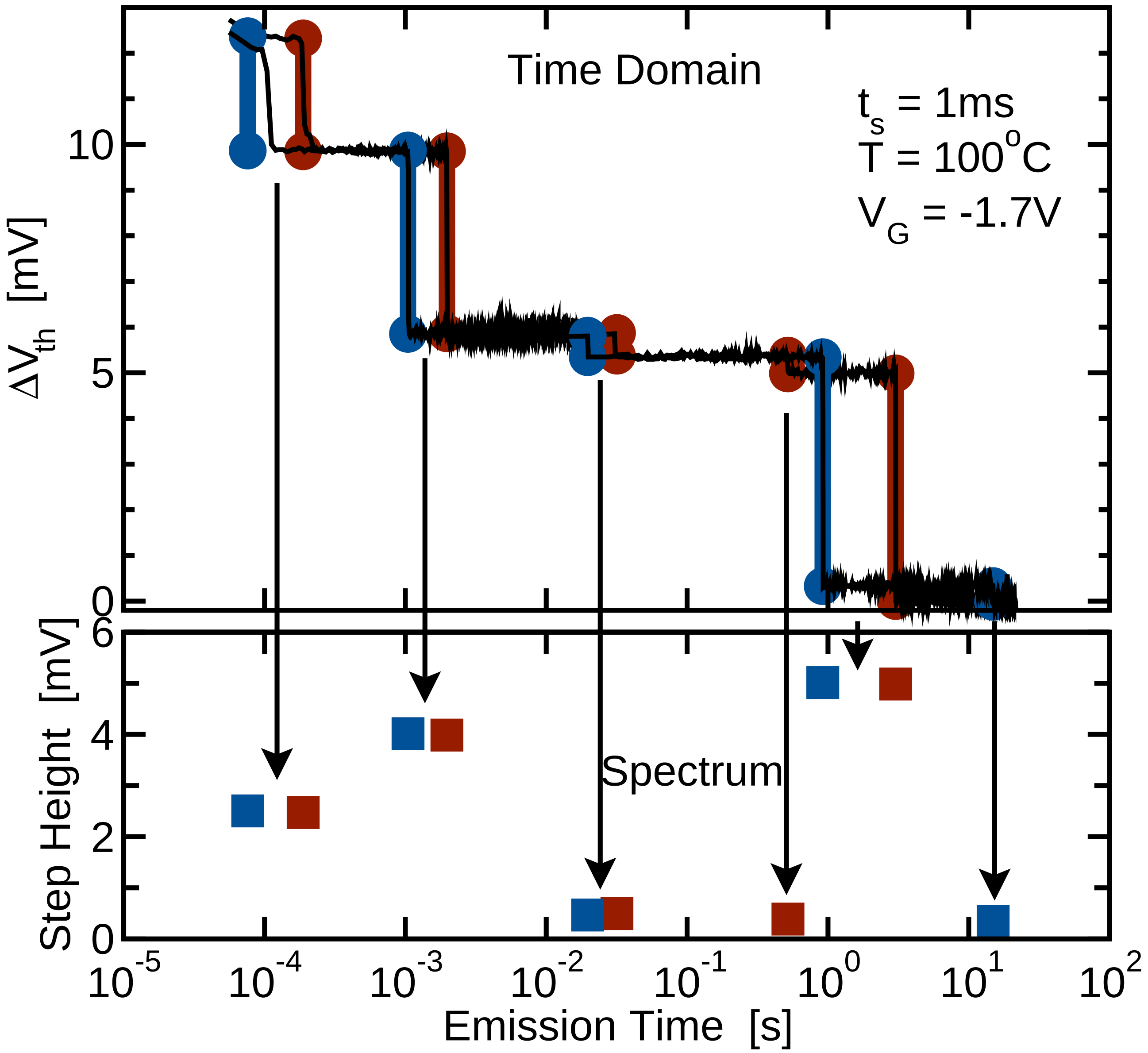

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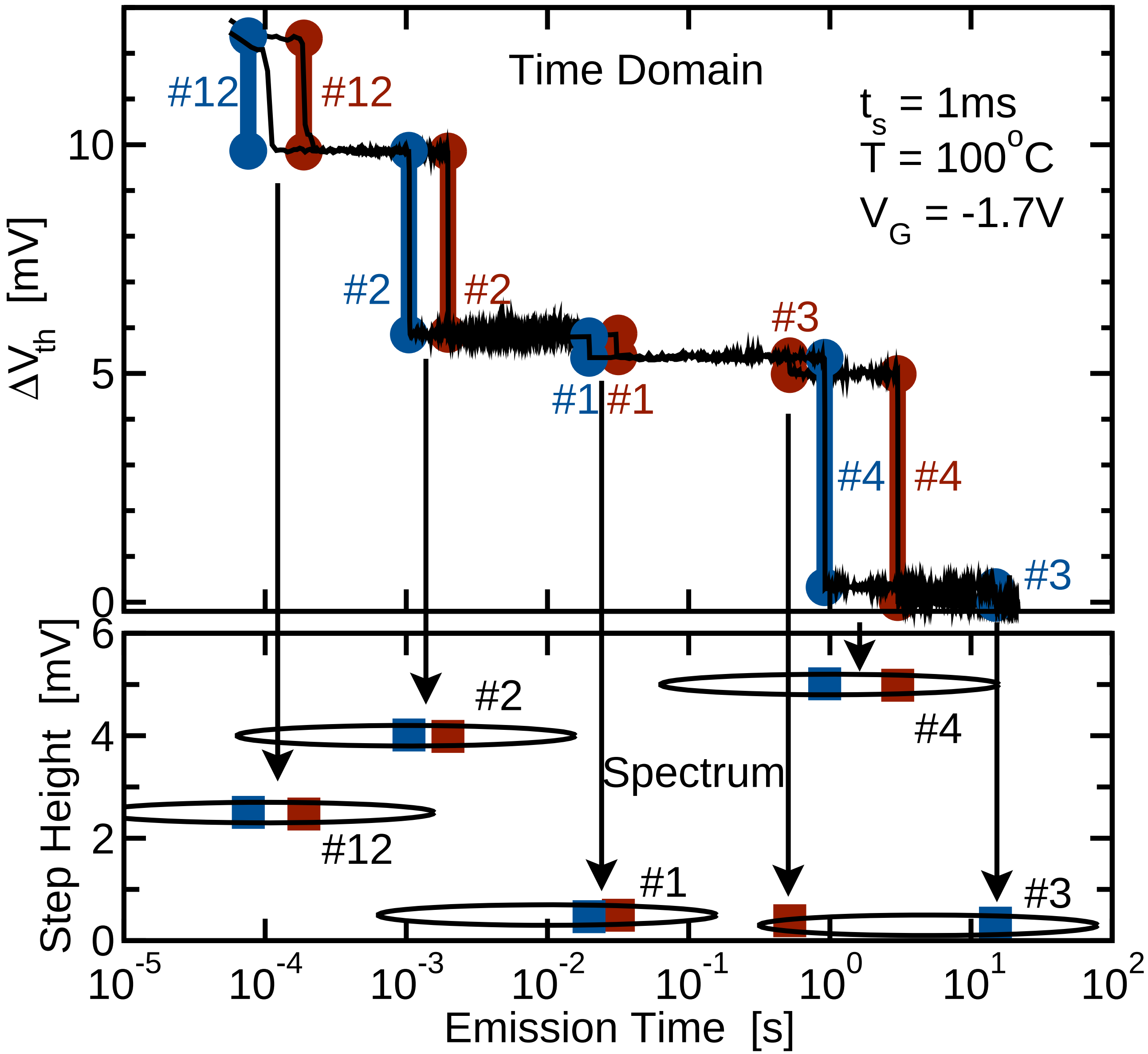
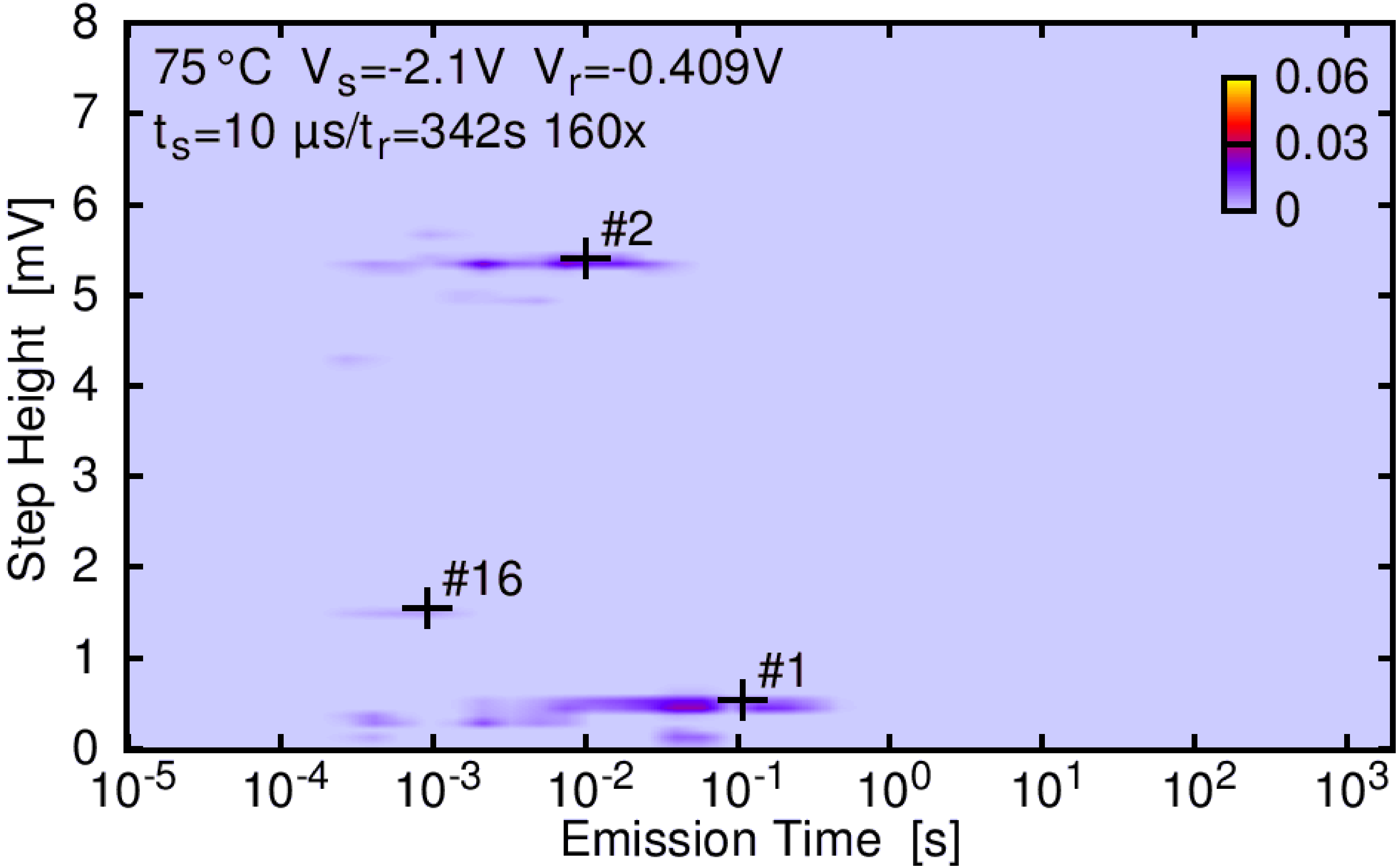


Function of stress time t_s



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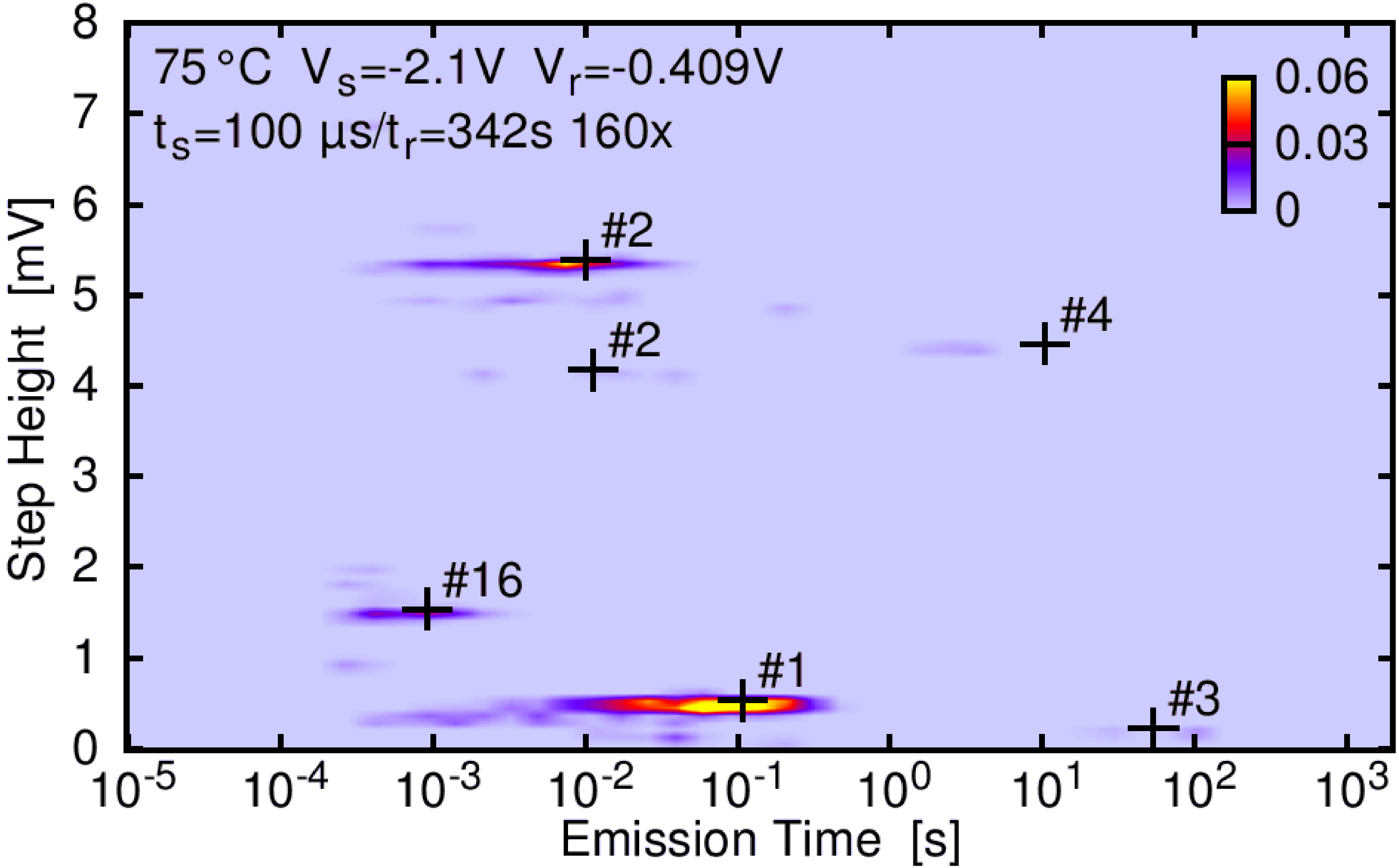

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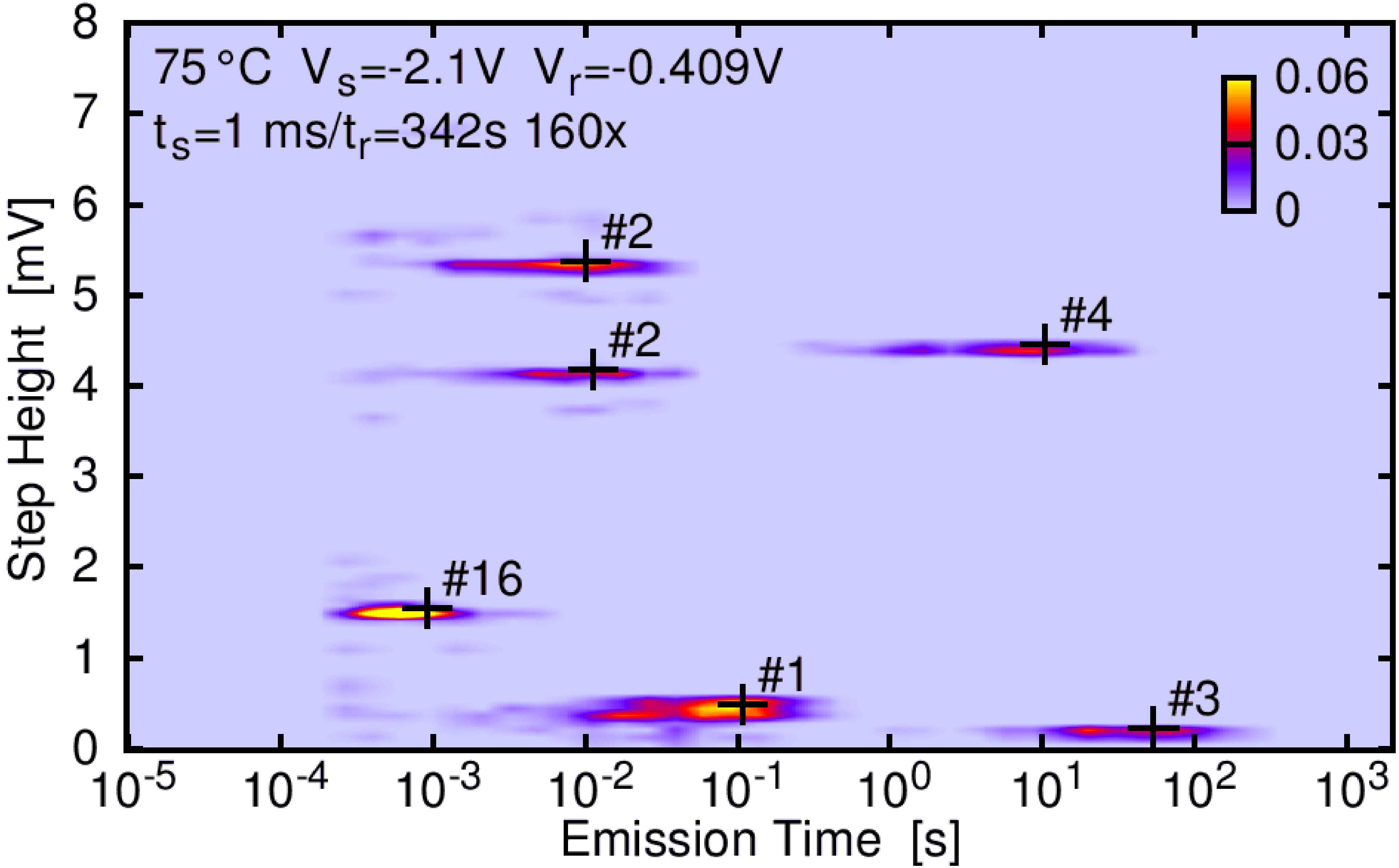

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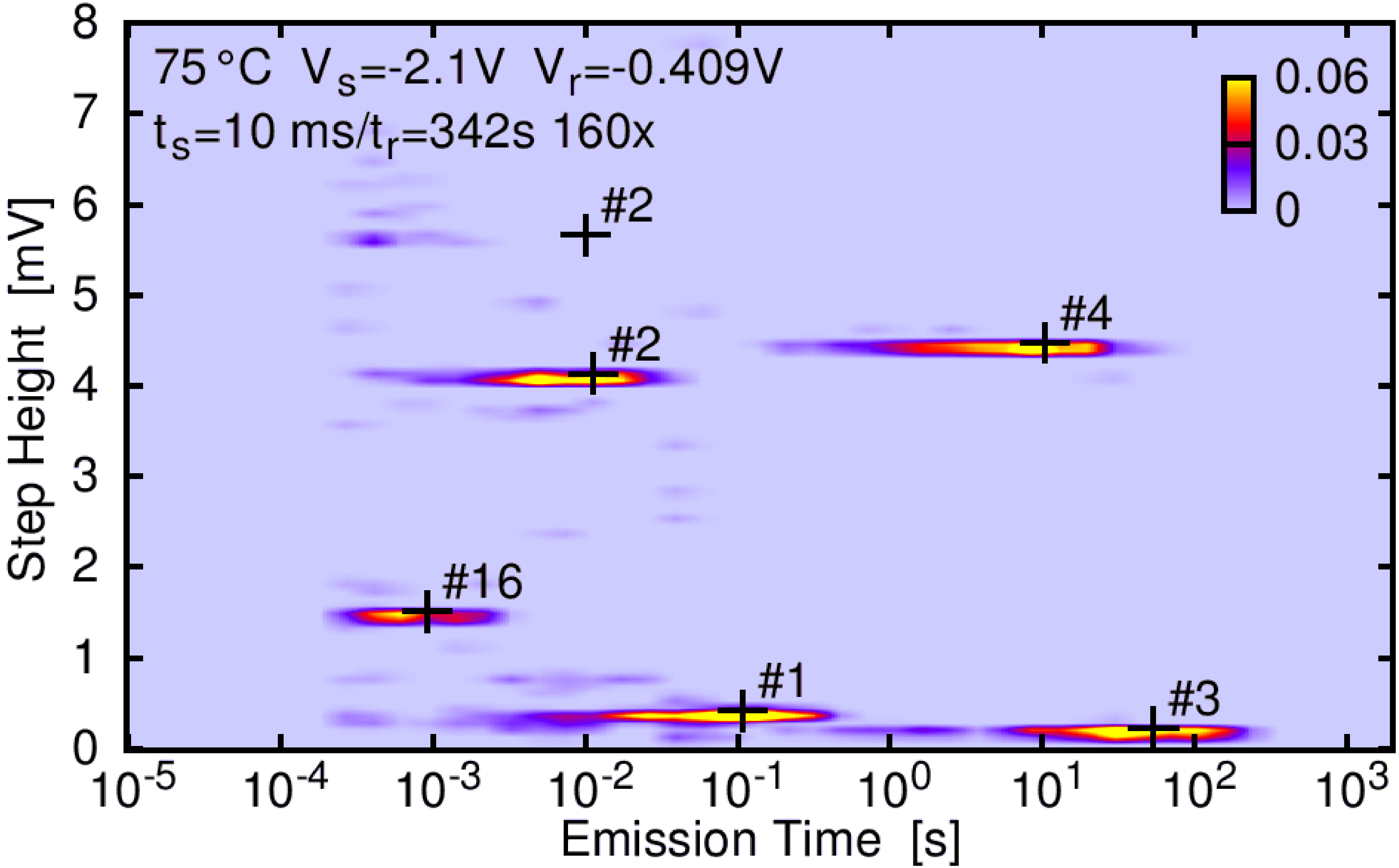
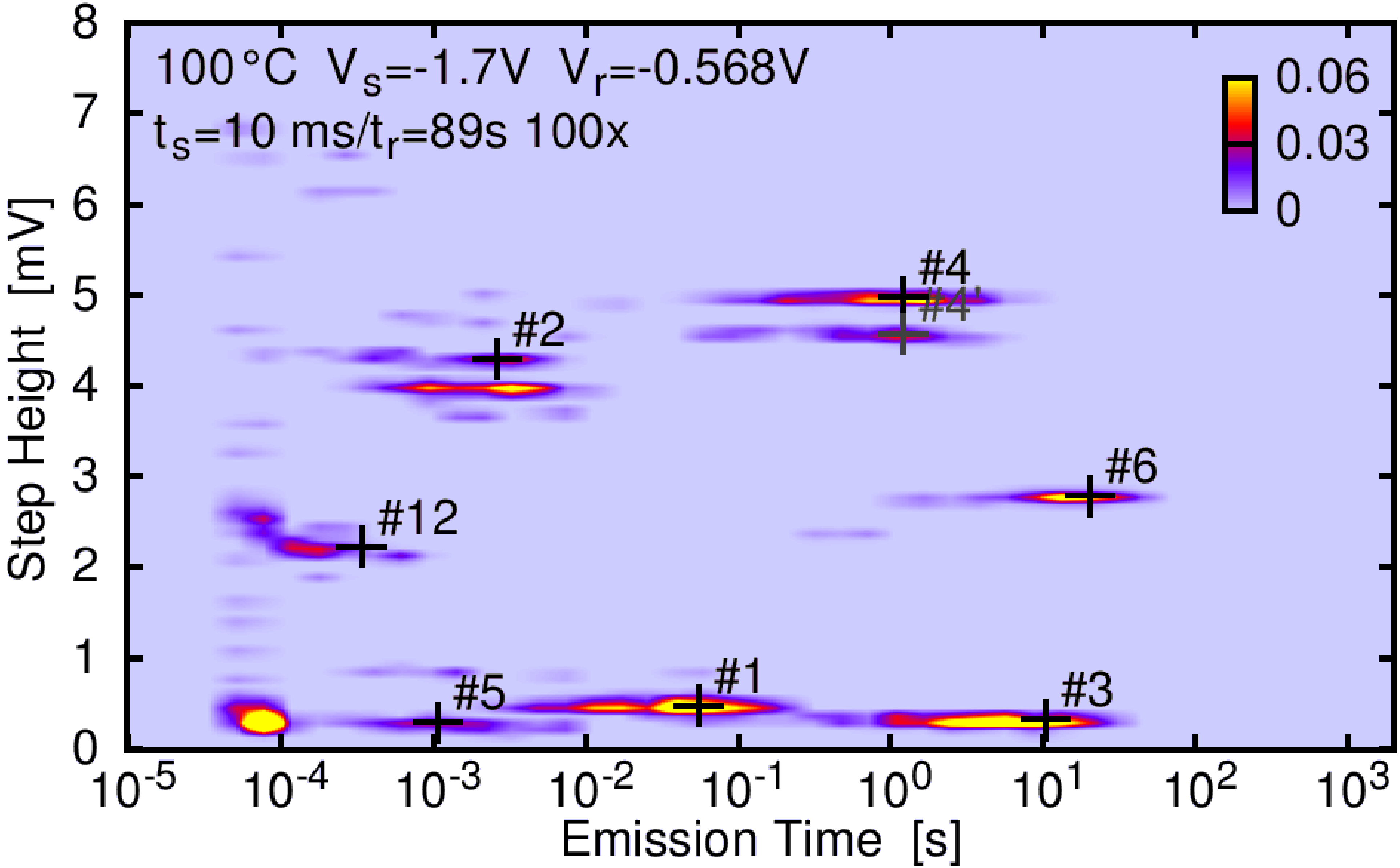


The Time Dependent Defect Spectroscopy

Function of temperature



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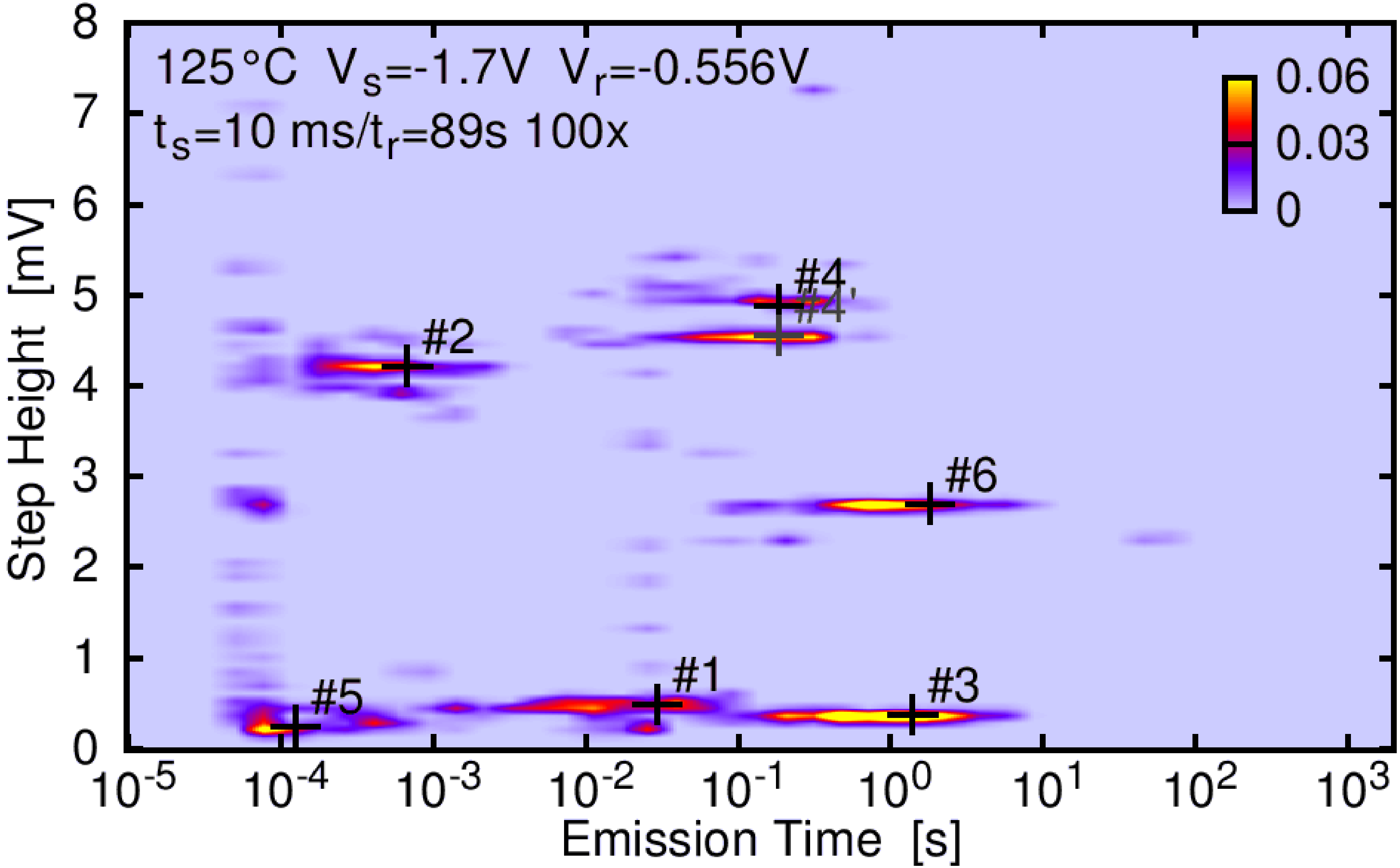

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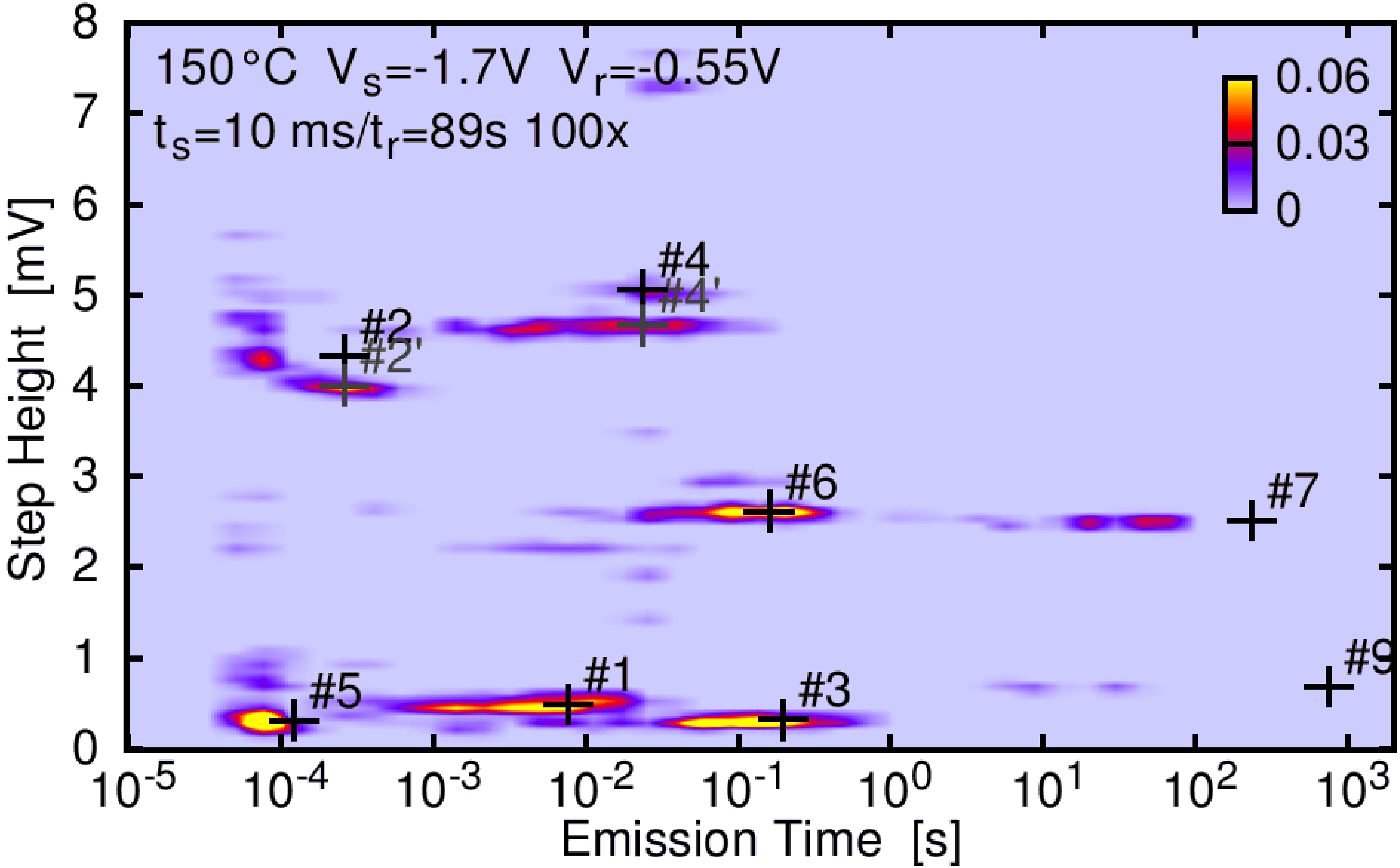

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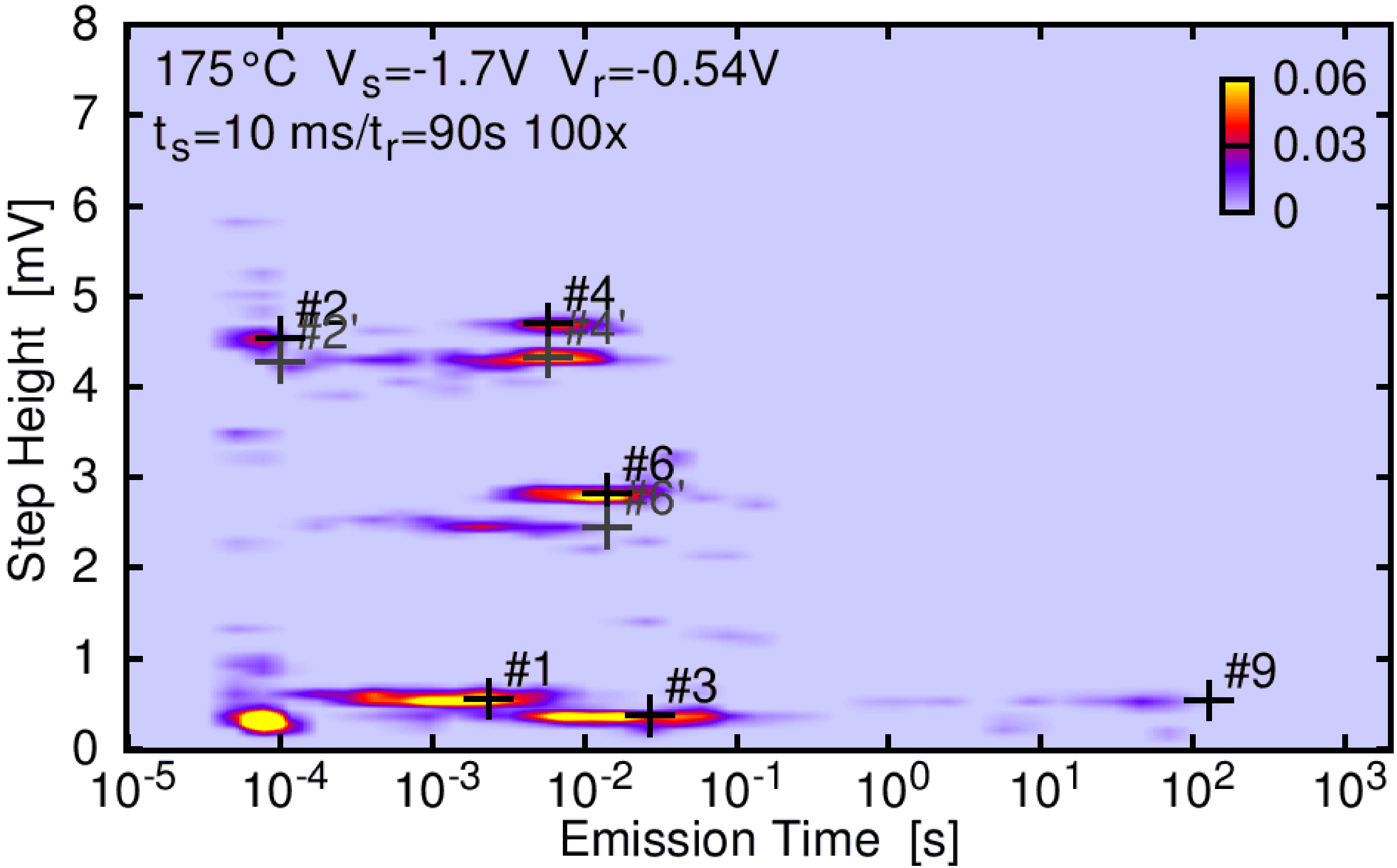
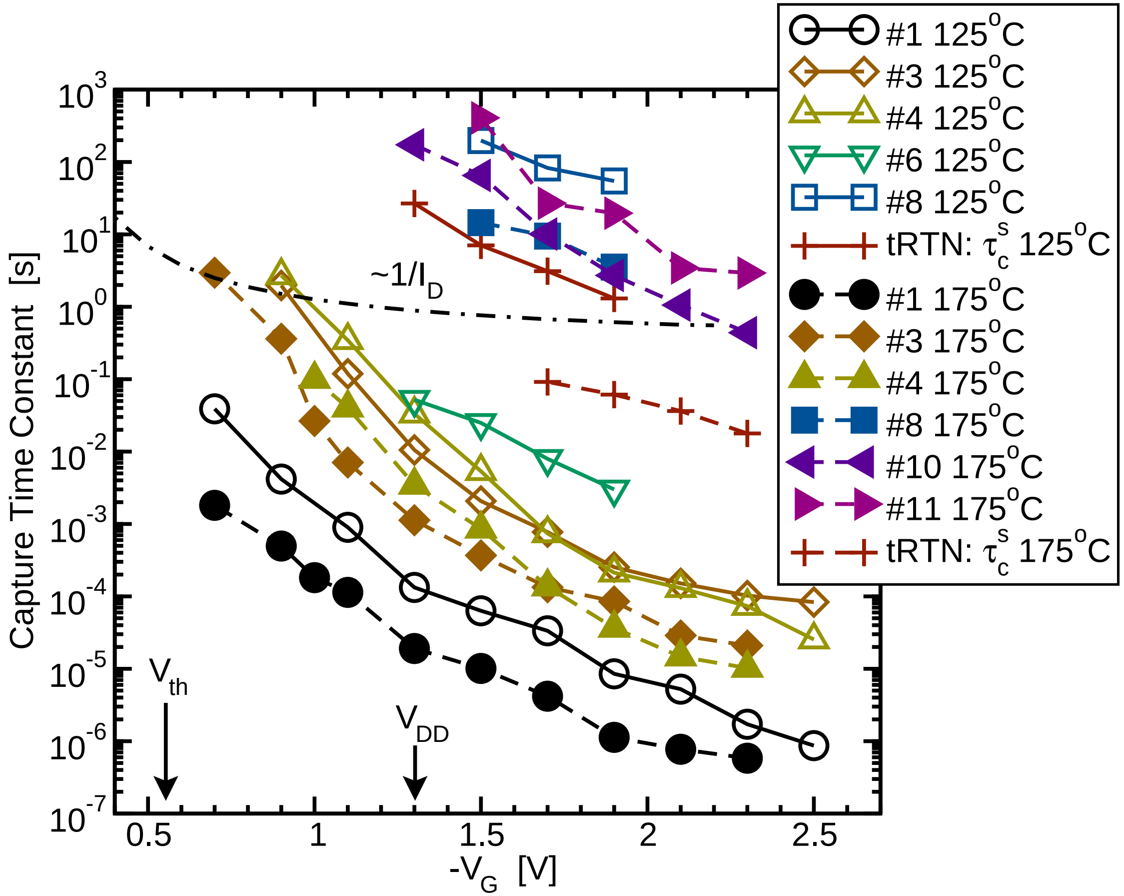
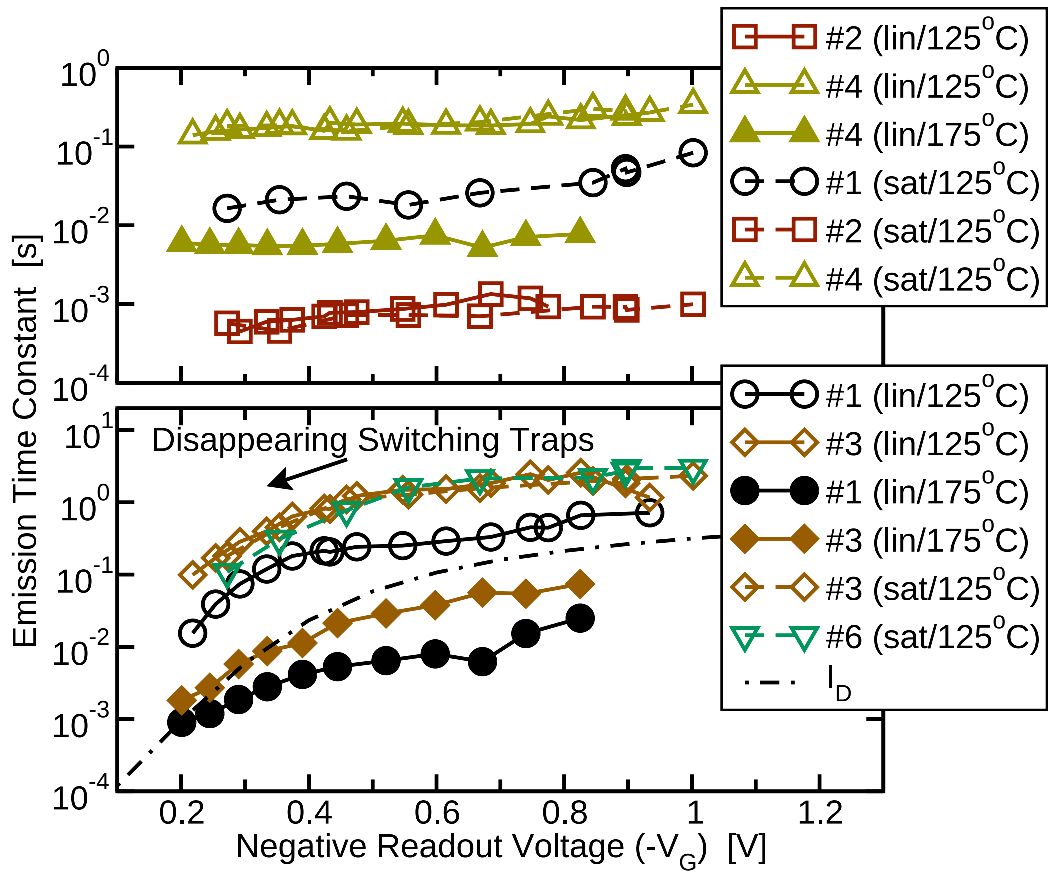


The Time Dependent Defect Spectroscopy

Different non-linear field dependence of the capture time constants

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

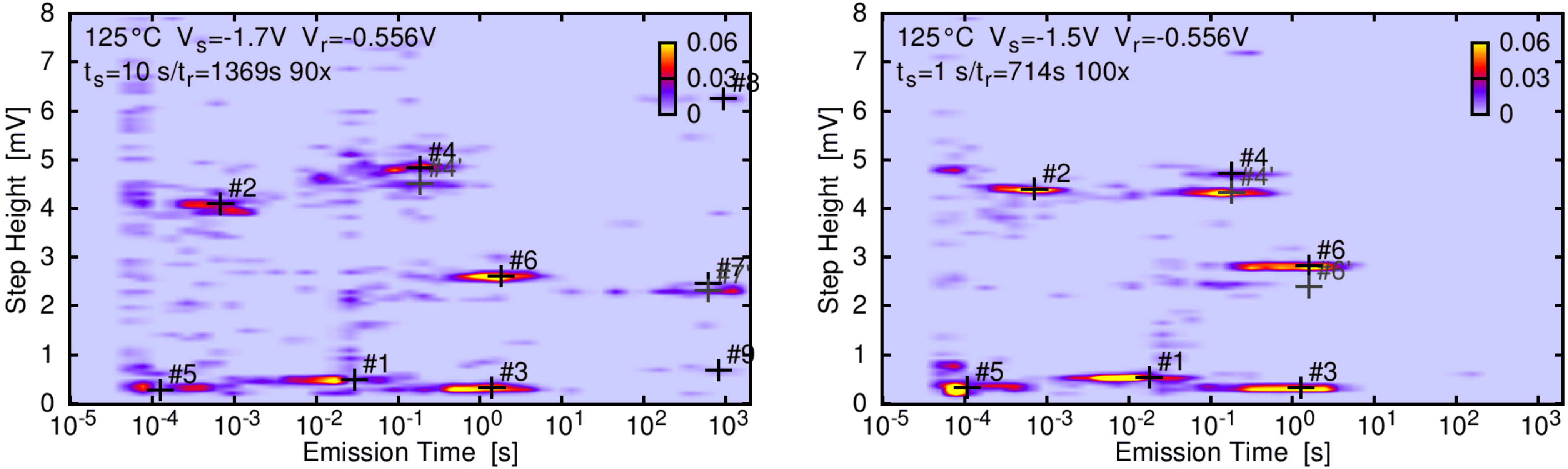




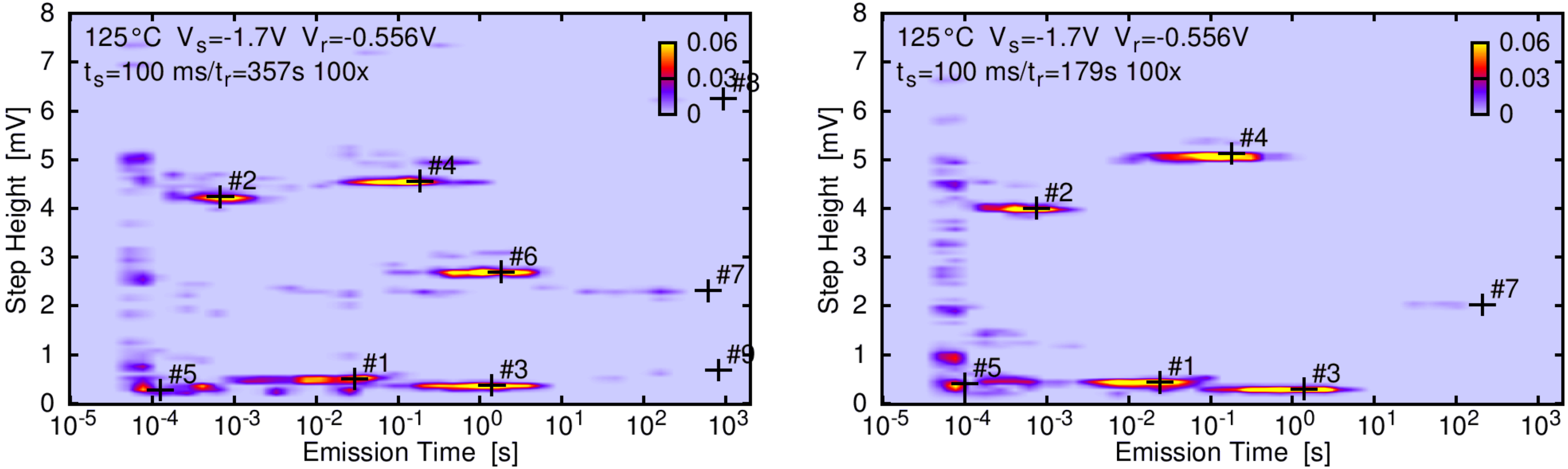
Compare SRH-like model: $\tau_c = \tau_0 \, e^{\beta \Delta E_B} \, \frac{N_v}{p}$ $\qquad \tau_e = \tau_0 \, e^{\beta \Delta E_B} \, e^{\beta \Delta E_T} \, e^{x F / V_T}$

Anomalous Defect Behavior

Defects disappear temporarily from the map (#7)

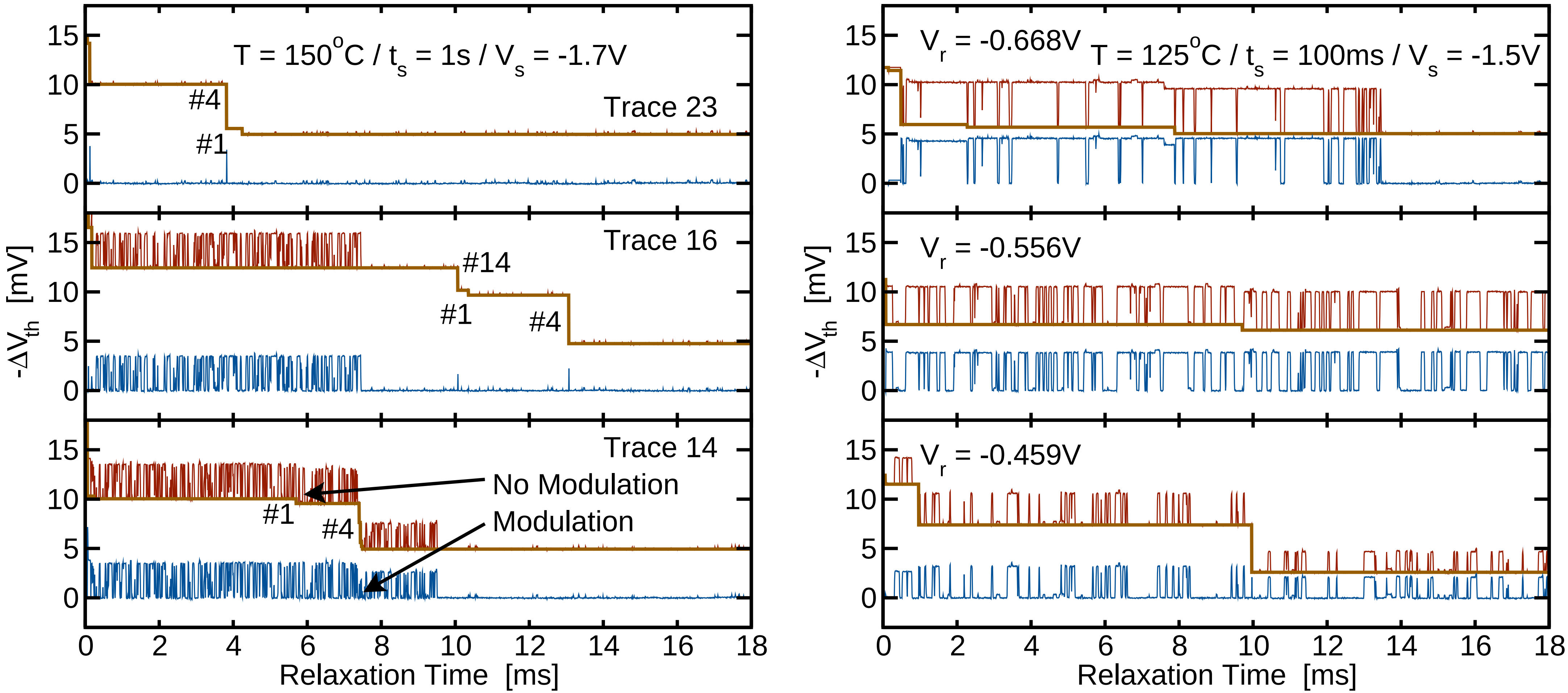


Long term stability: defect #6 missing for a few months now



Anomalous Defect Behavior

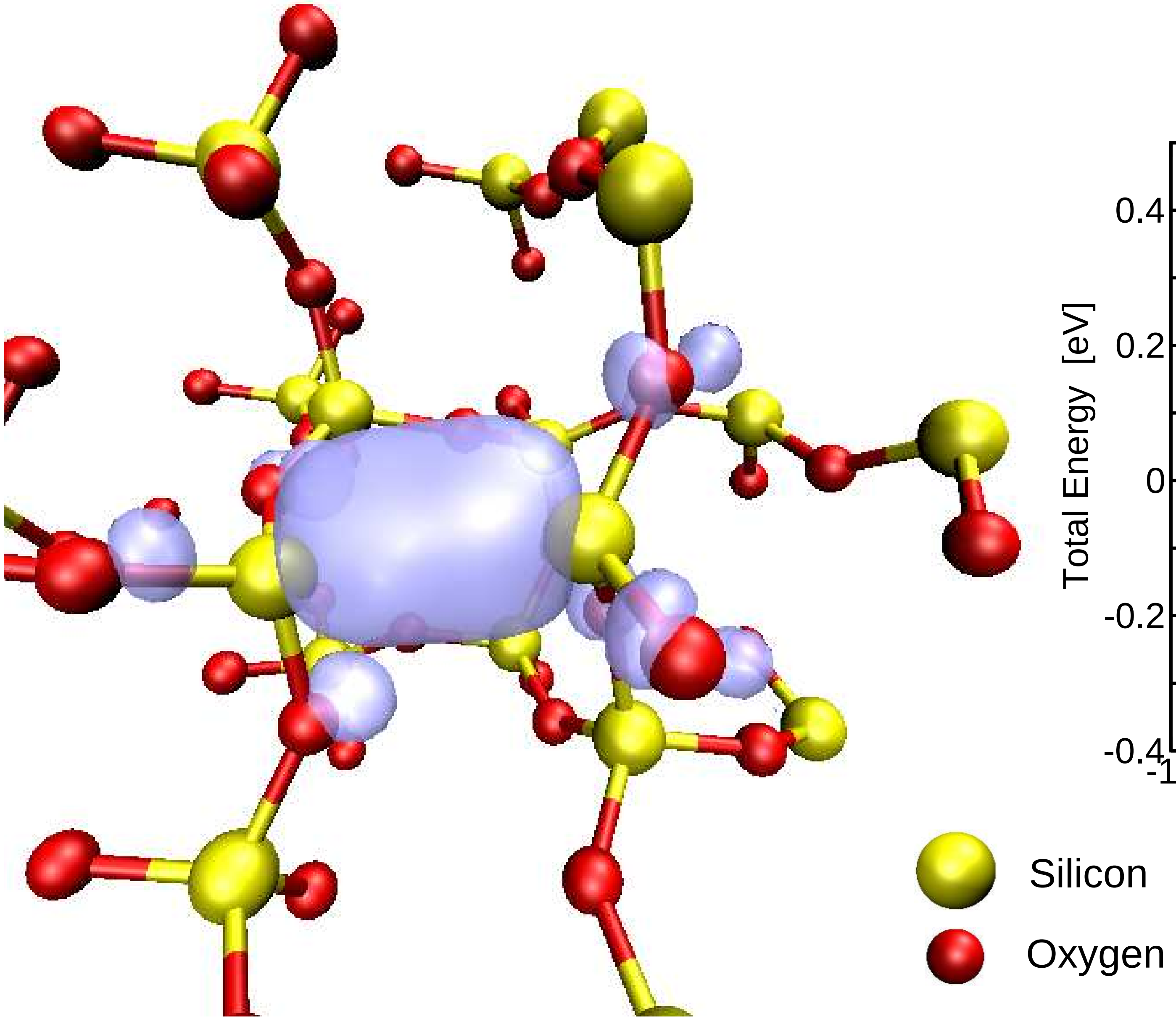
Temporary random telegraph noise (tRTN)

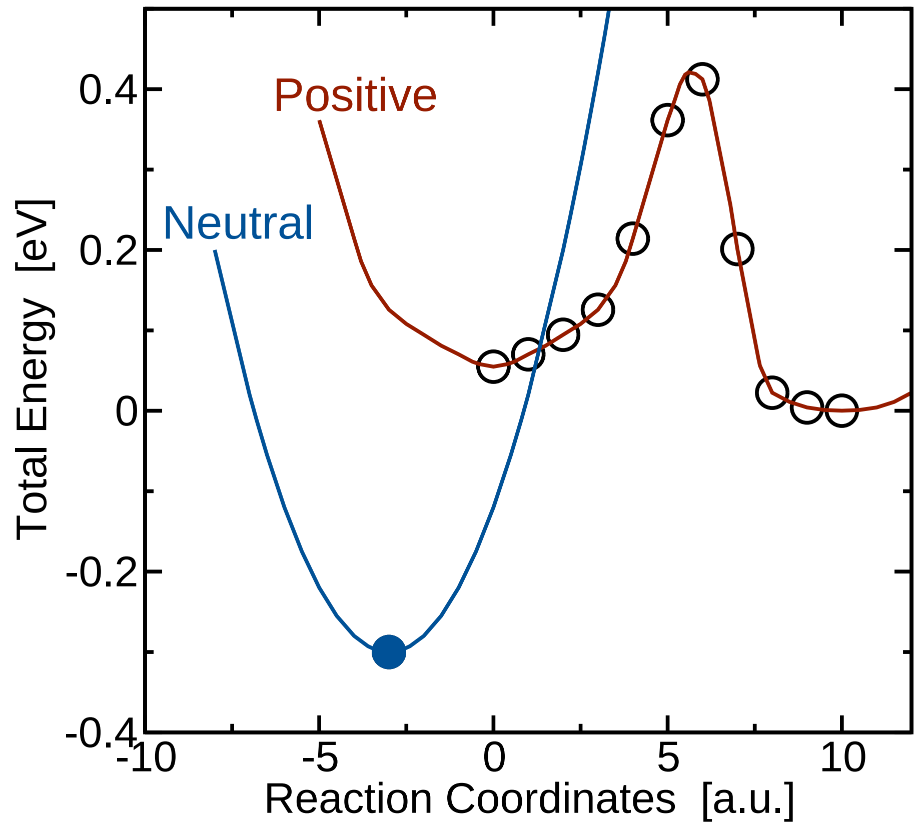


How Can We Model All That?

Lattice Relaxation and Metastability

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





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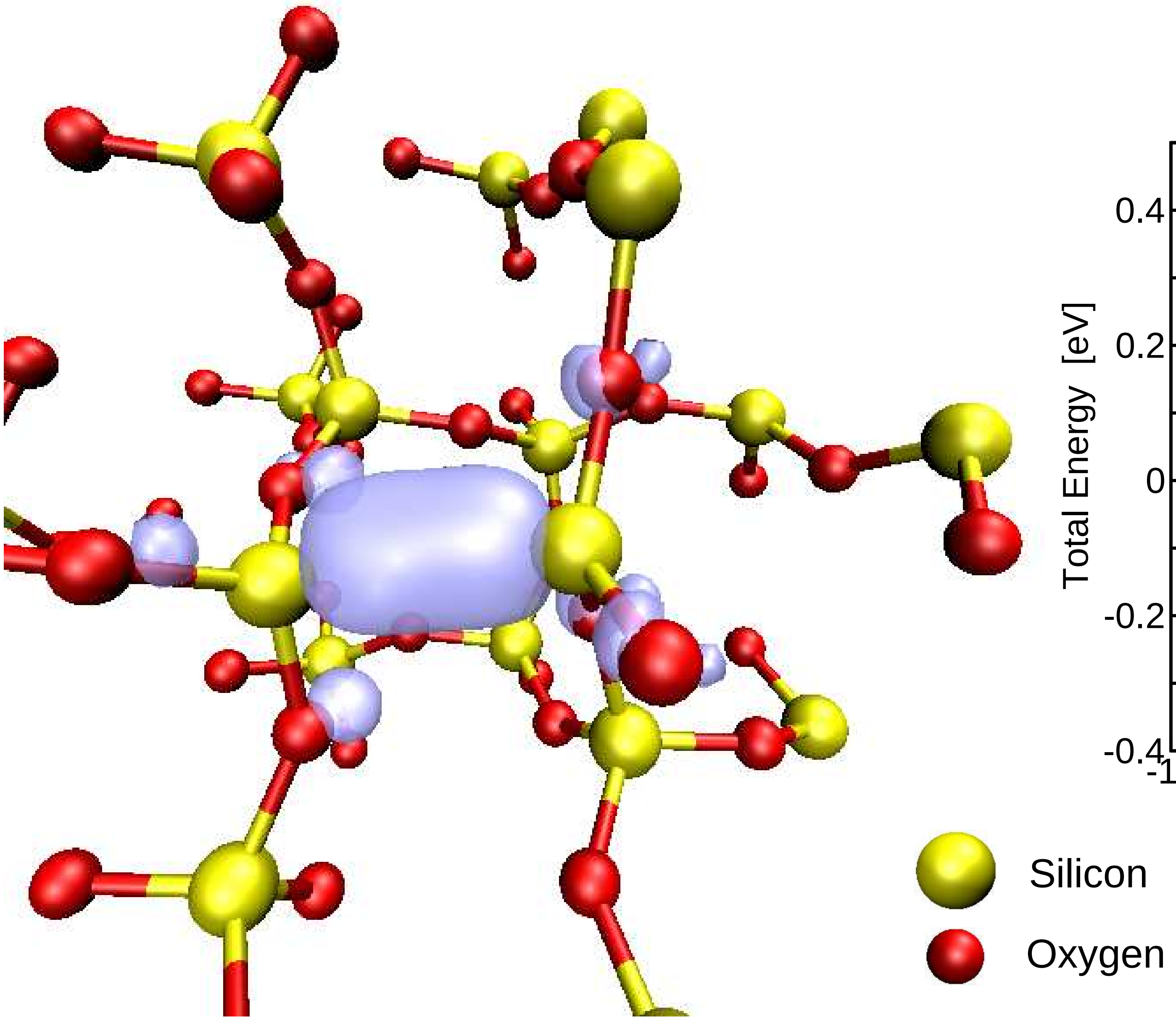

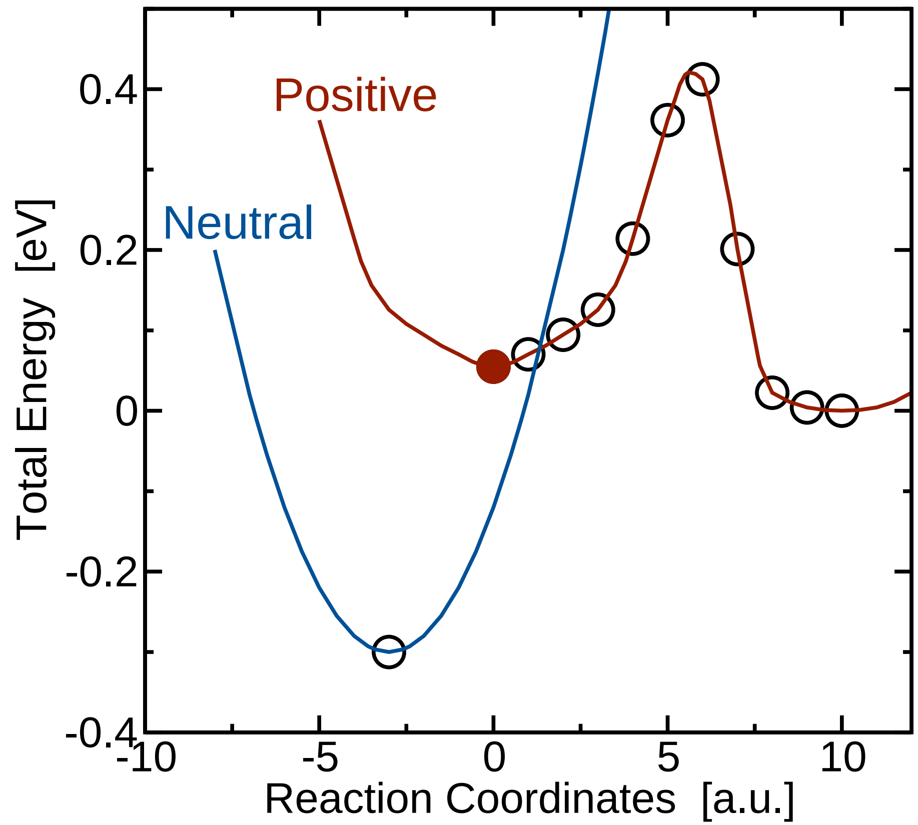

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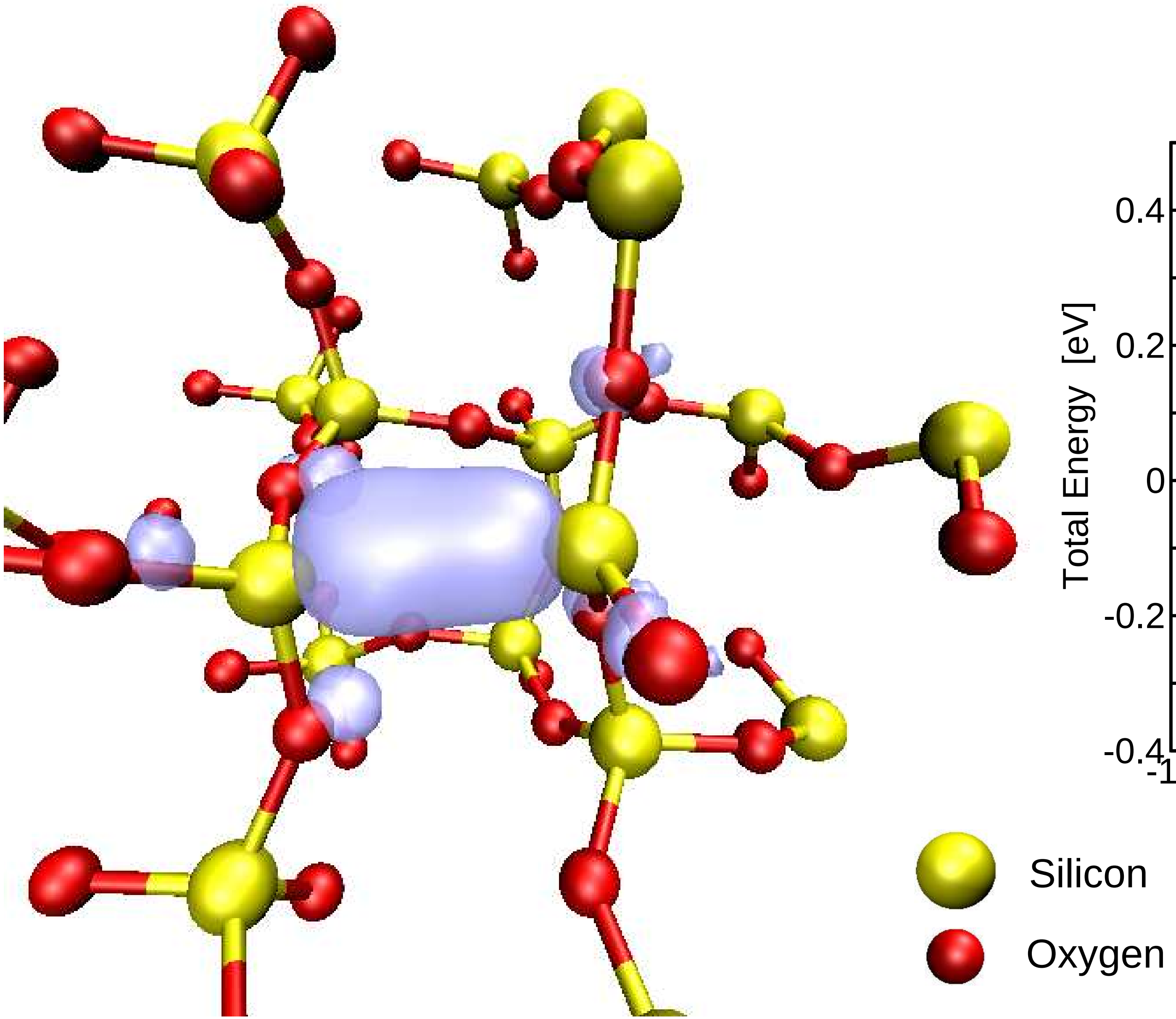

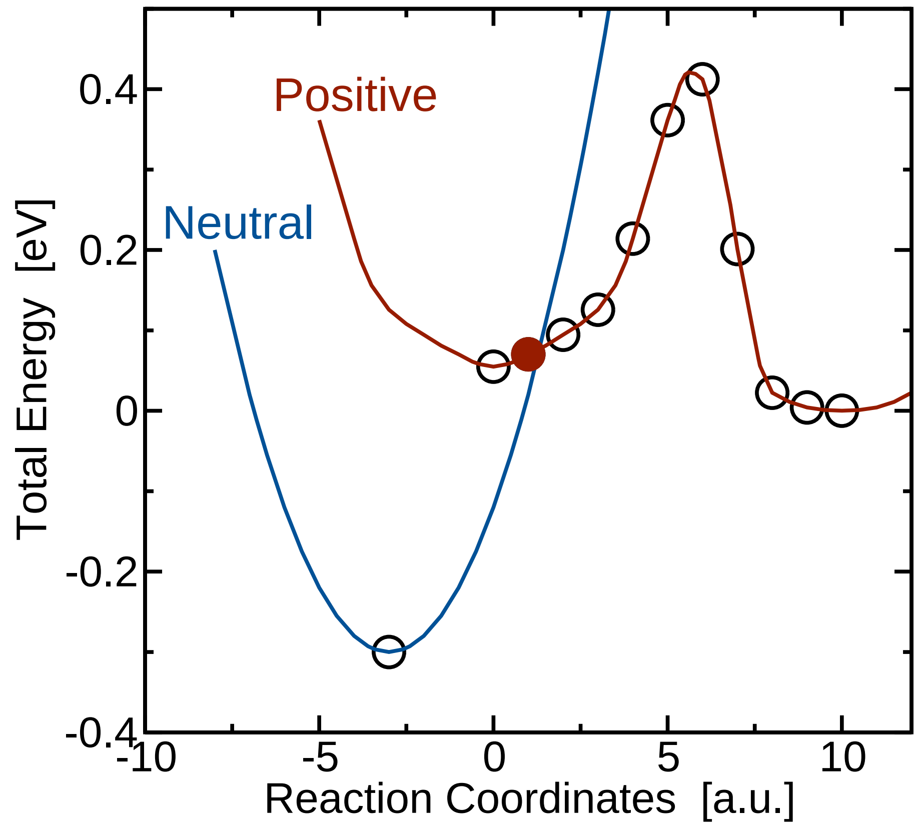

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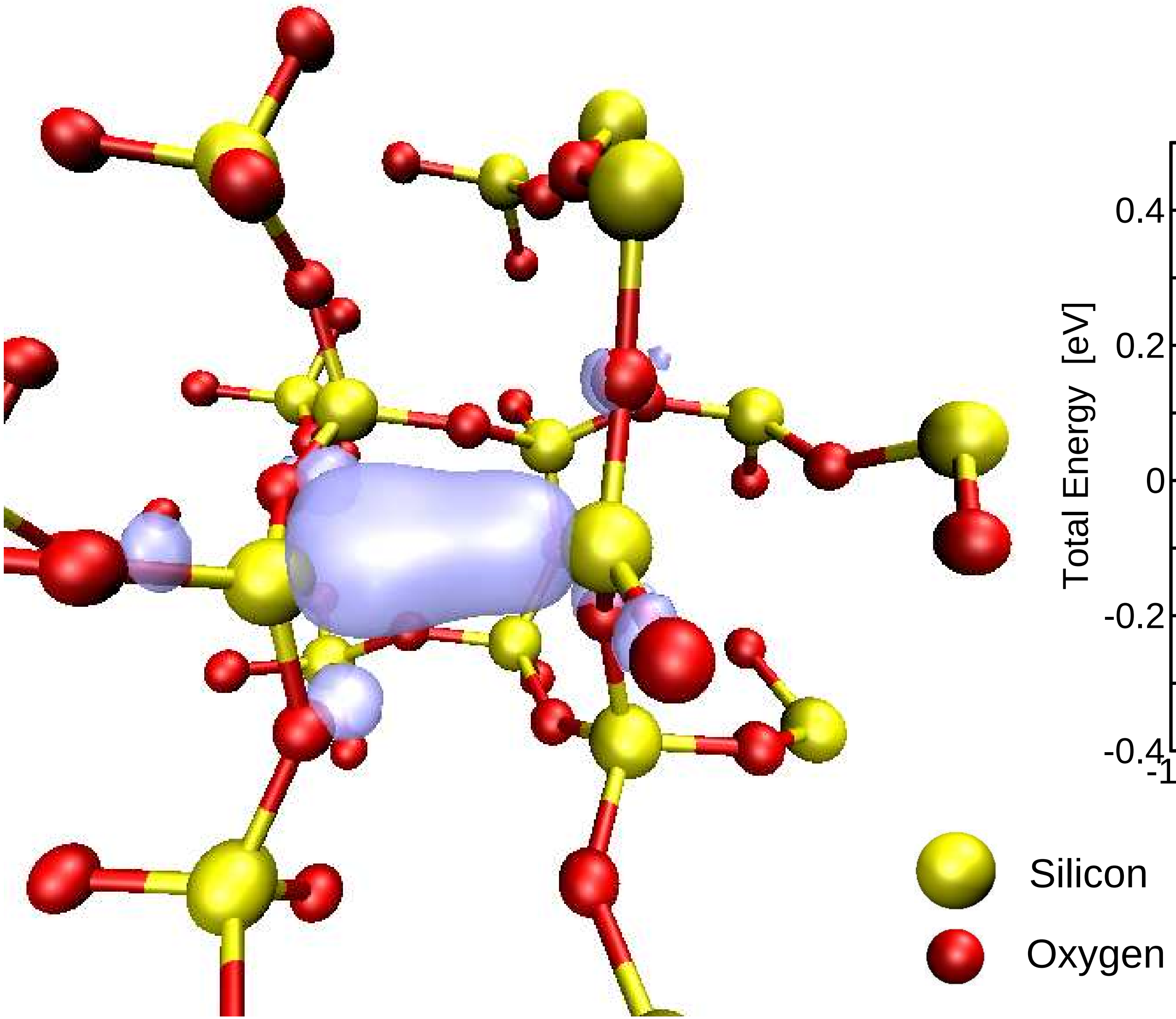

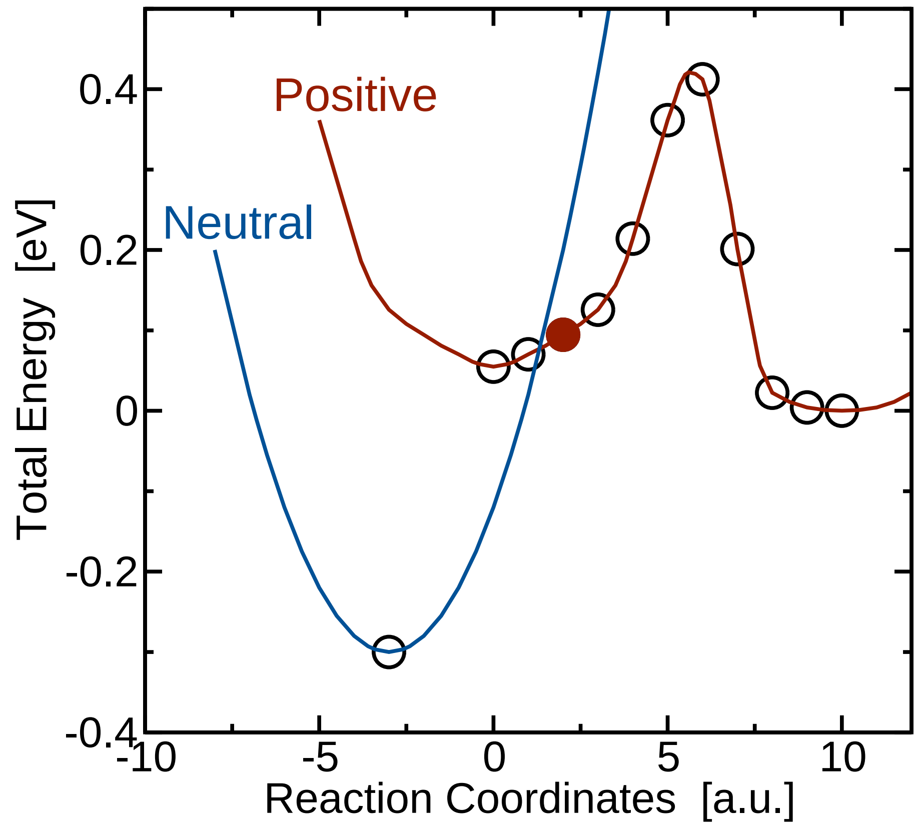

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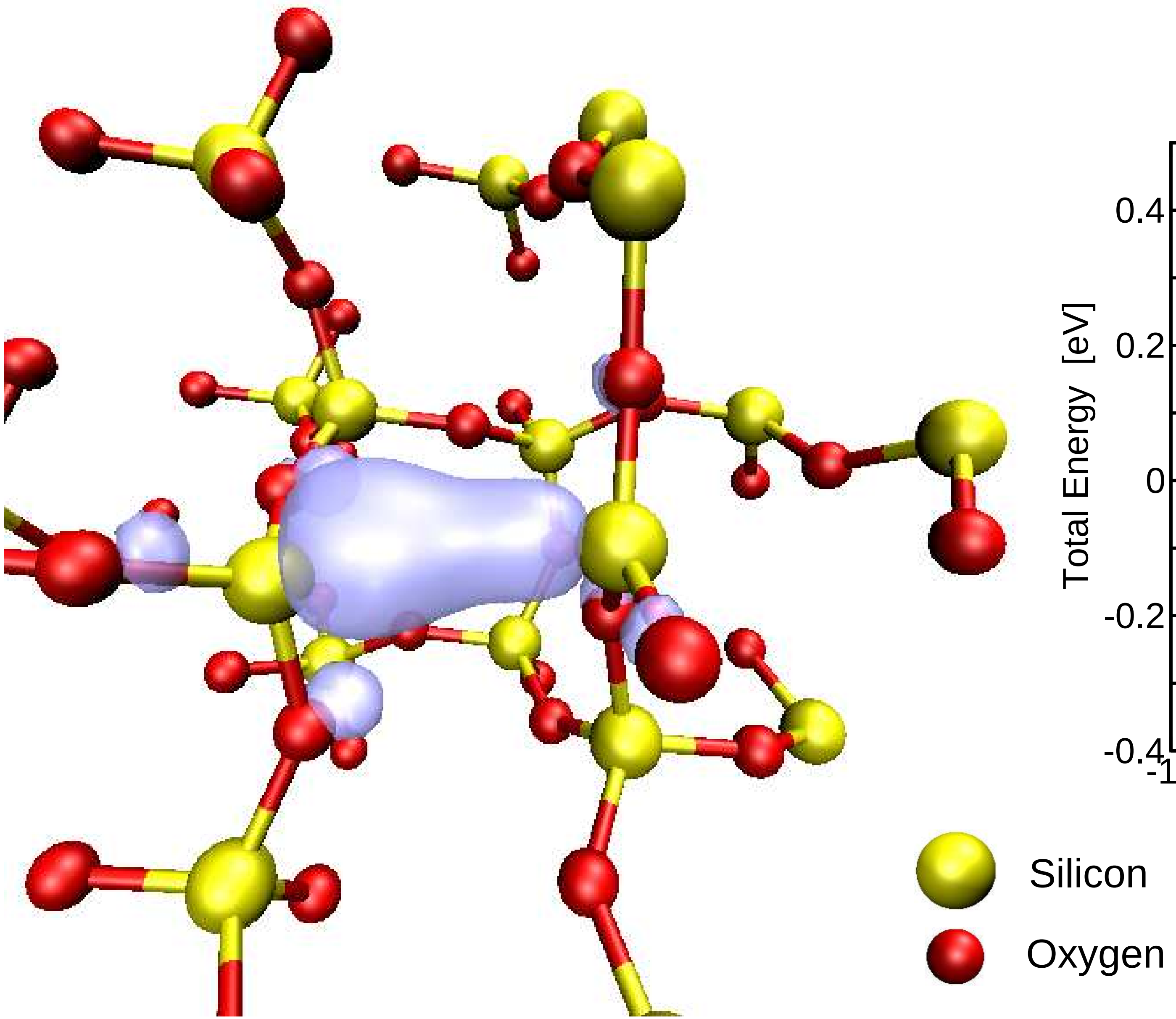

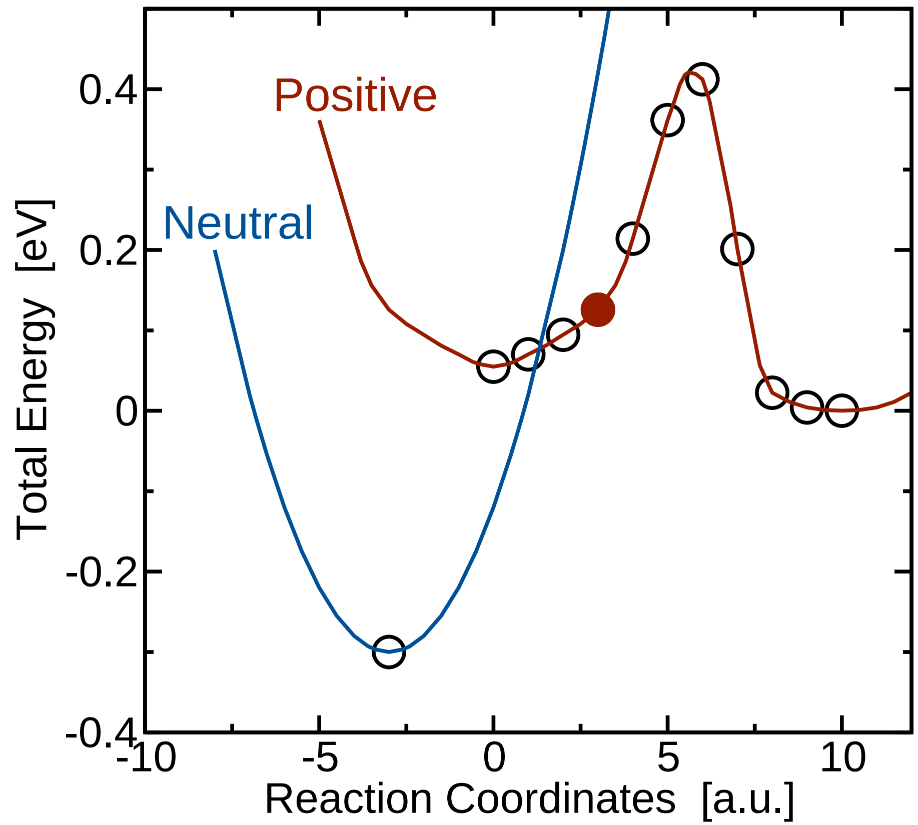

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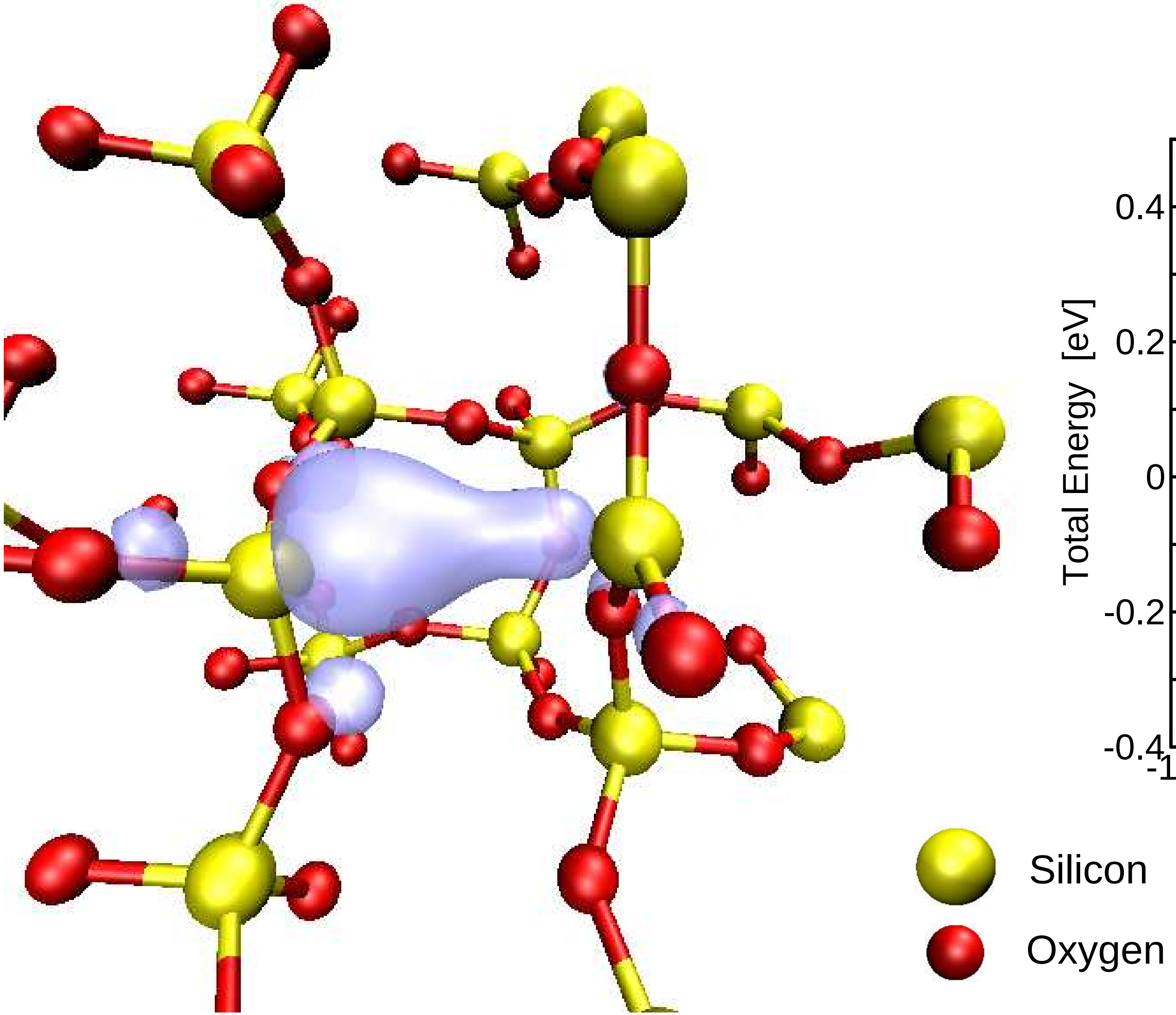

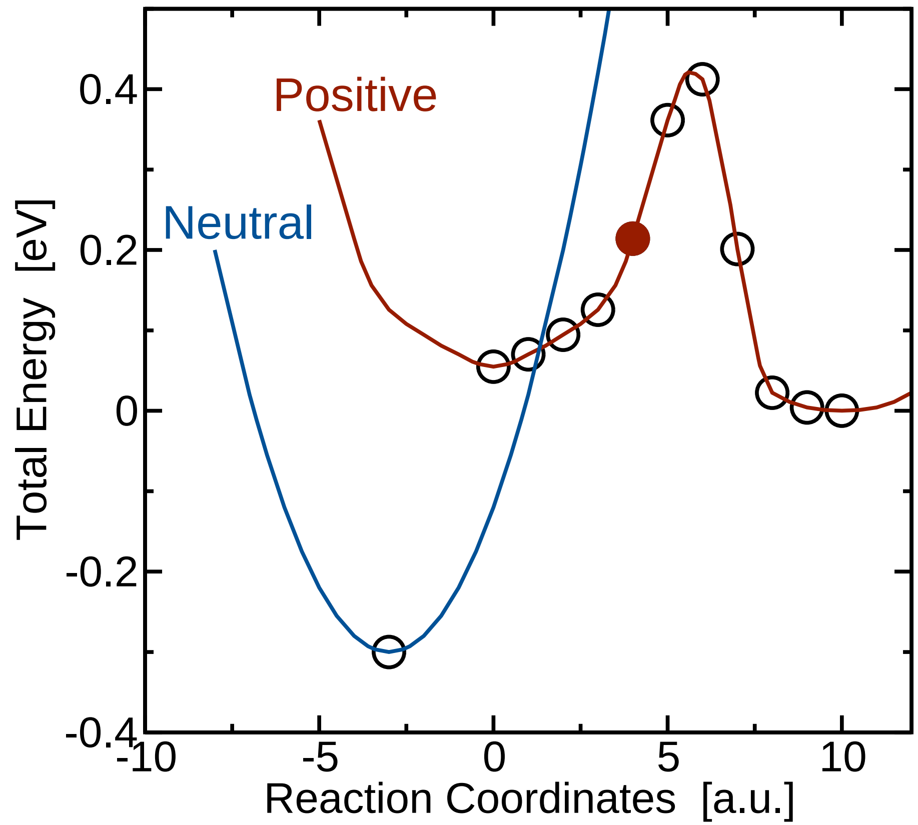

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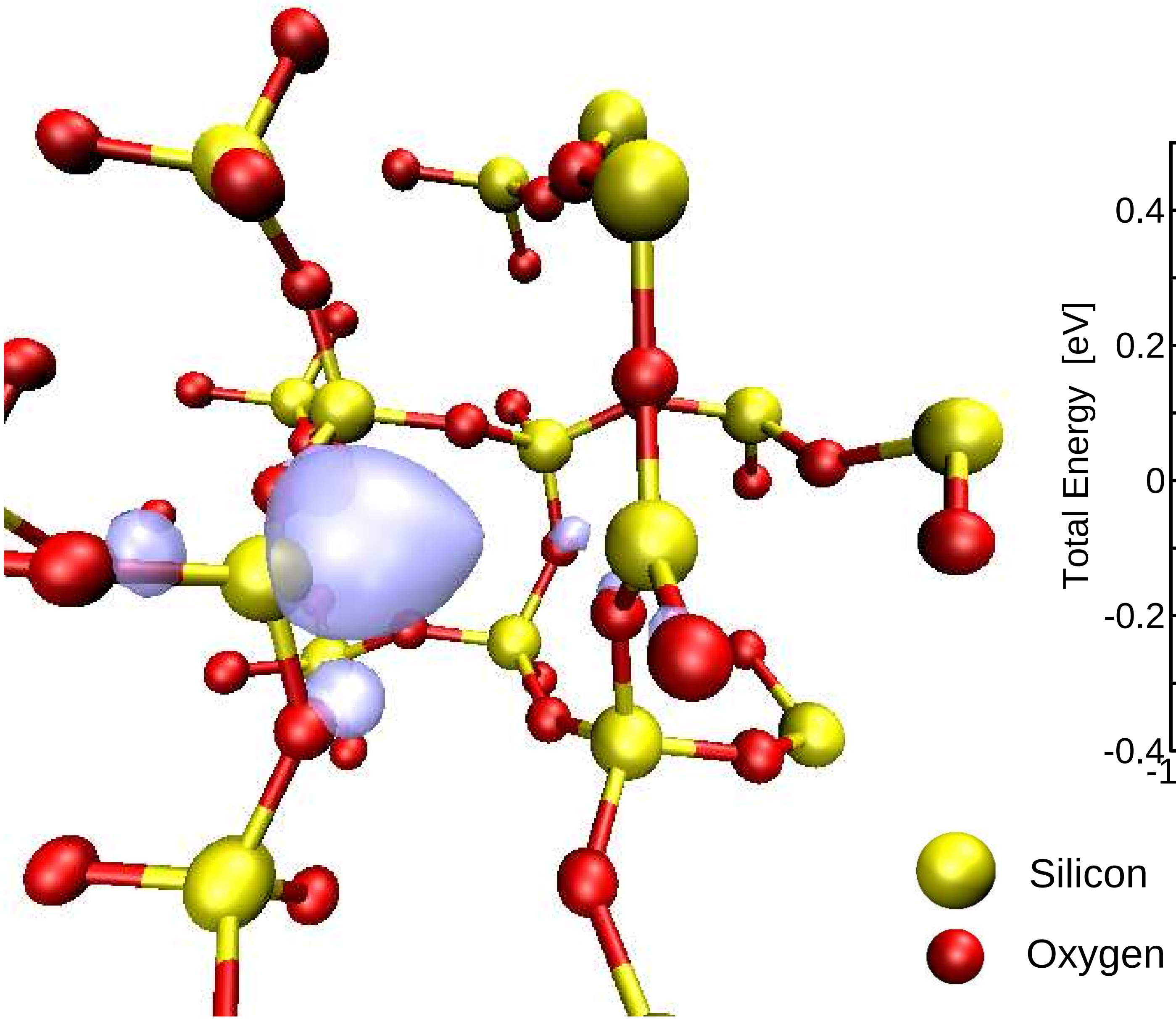

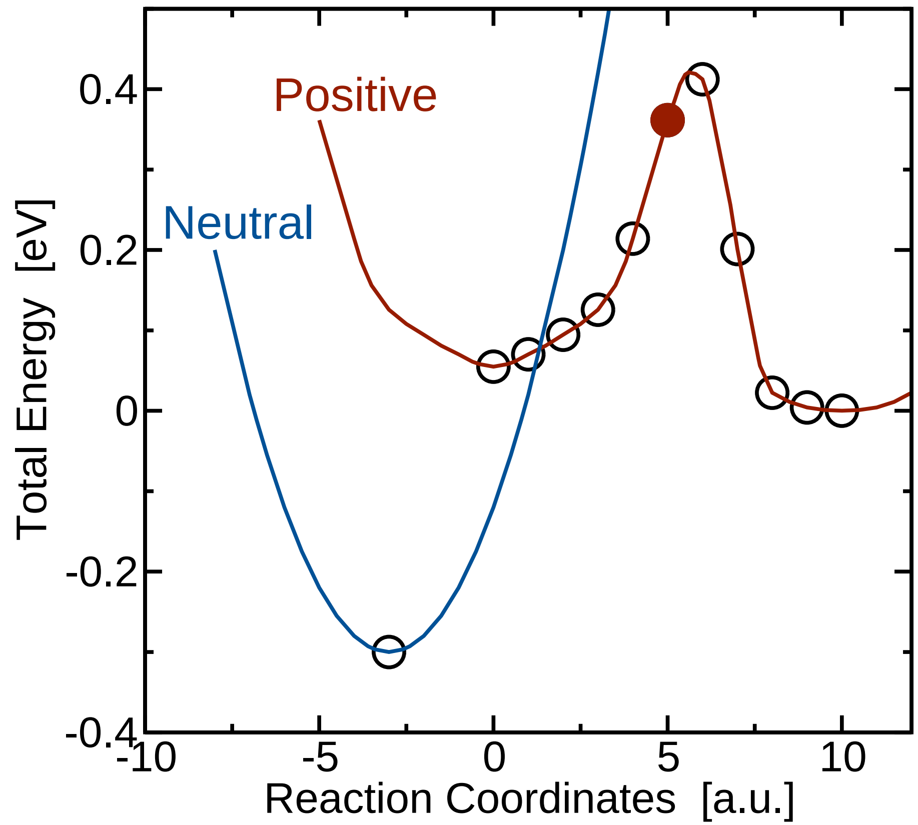

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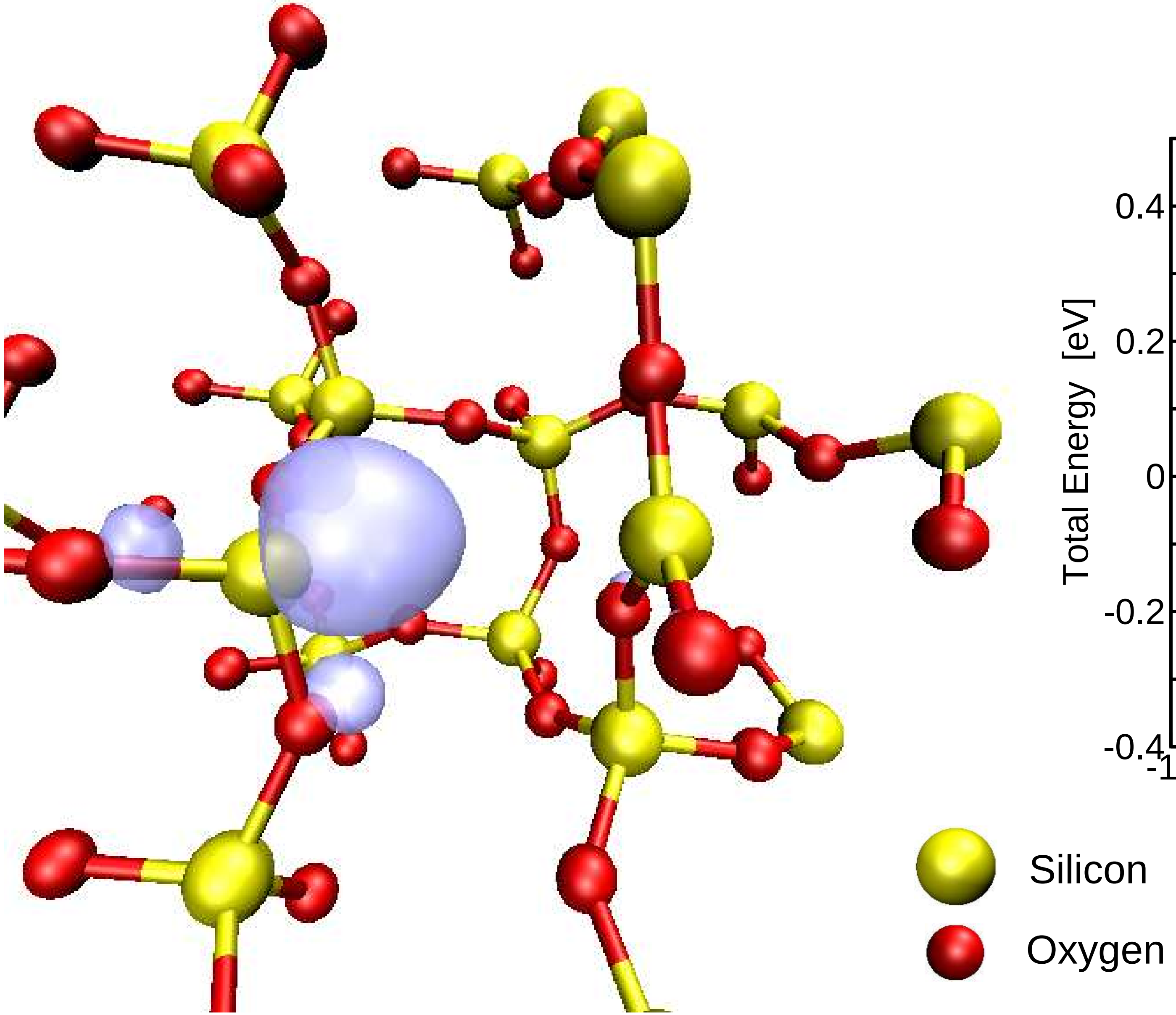

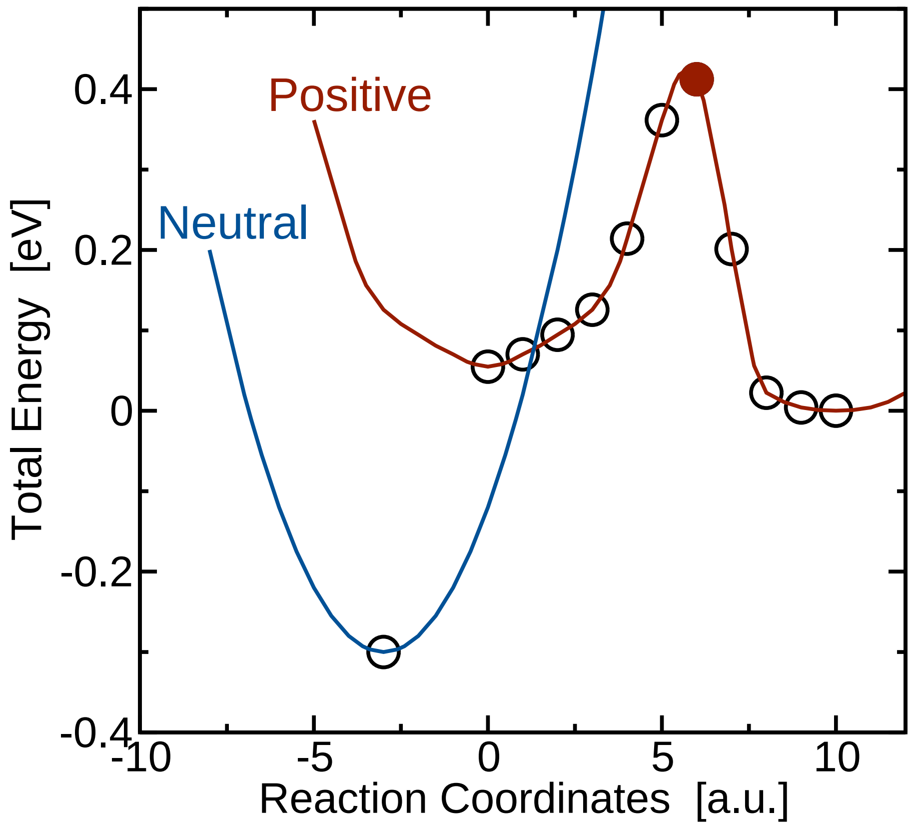

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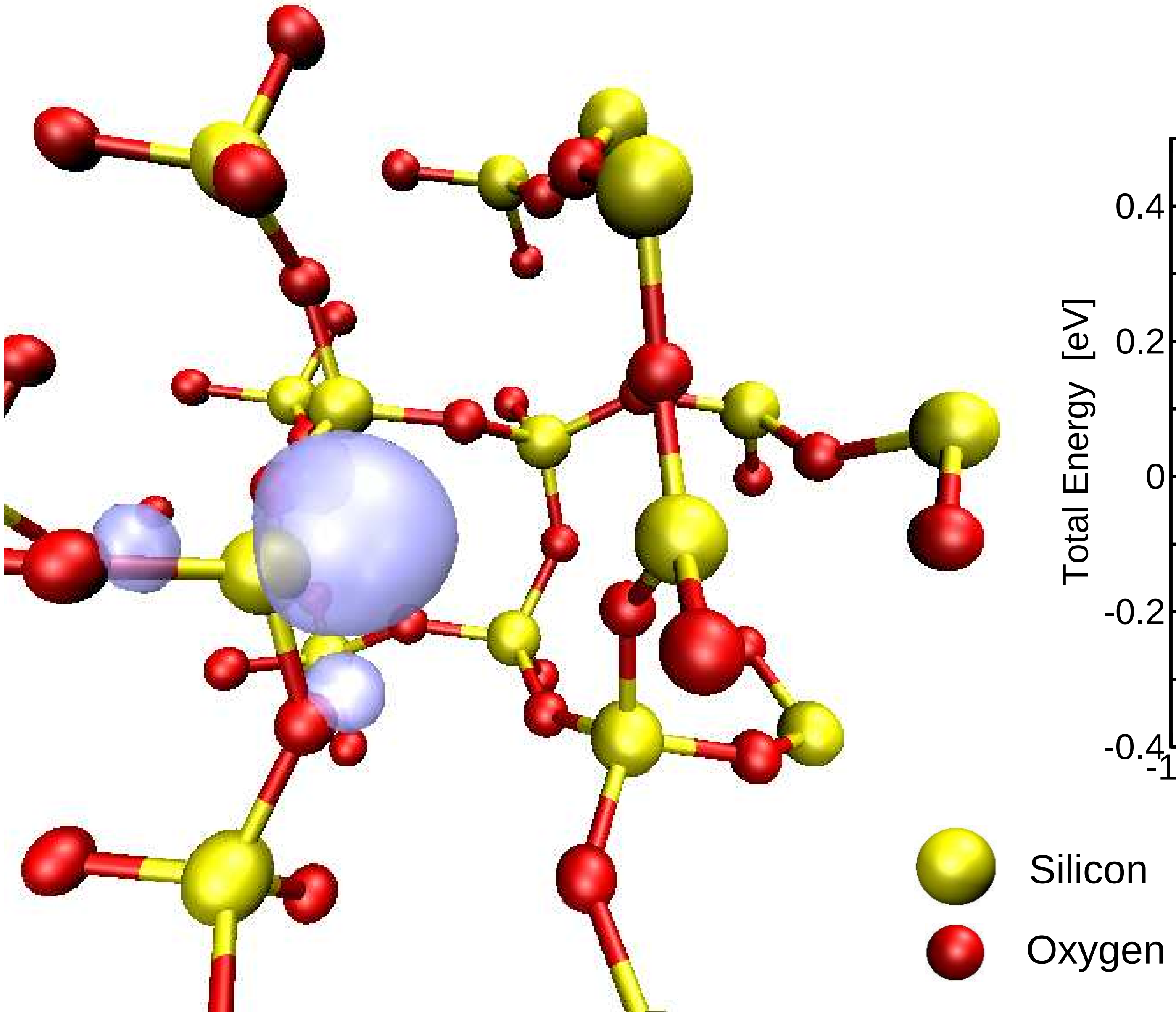

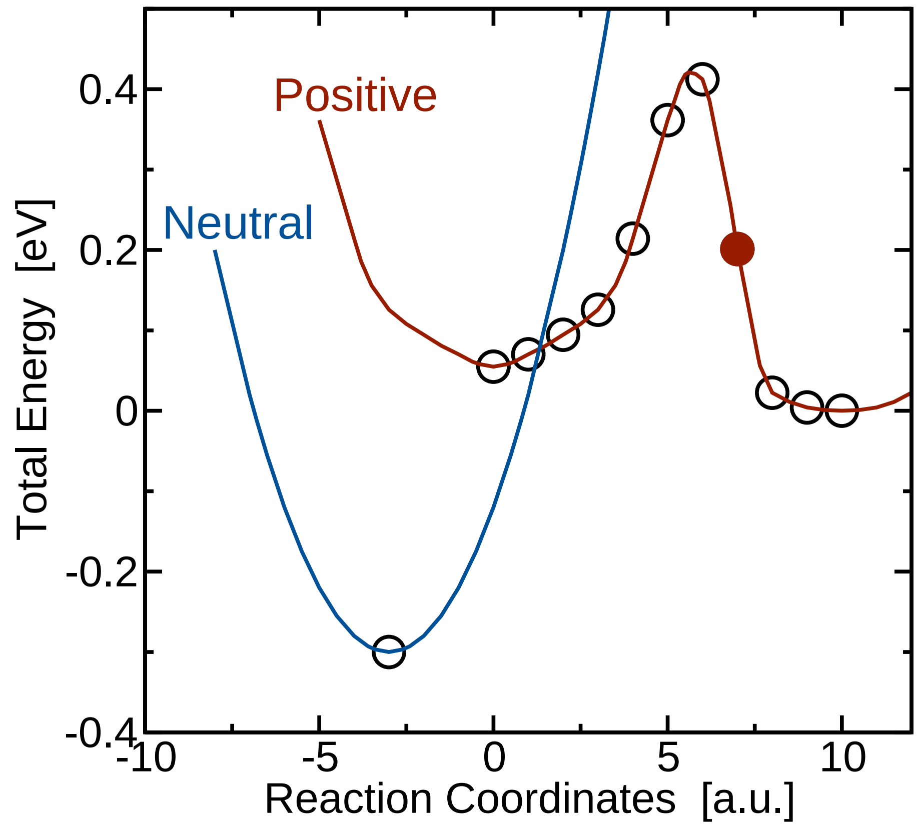

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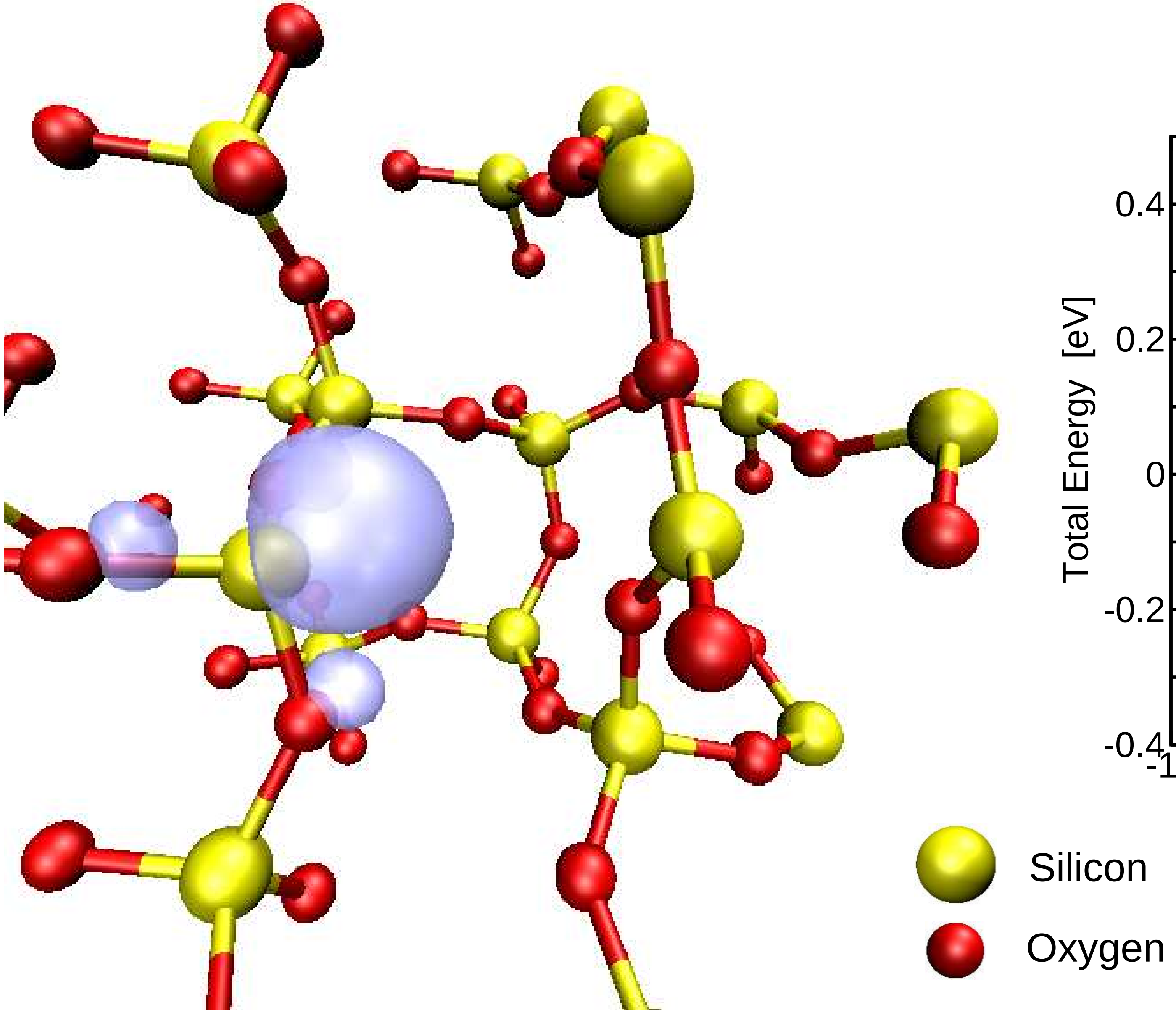

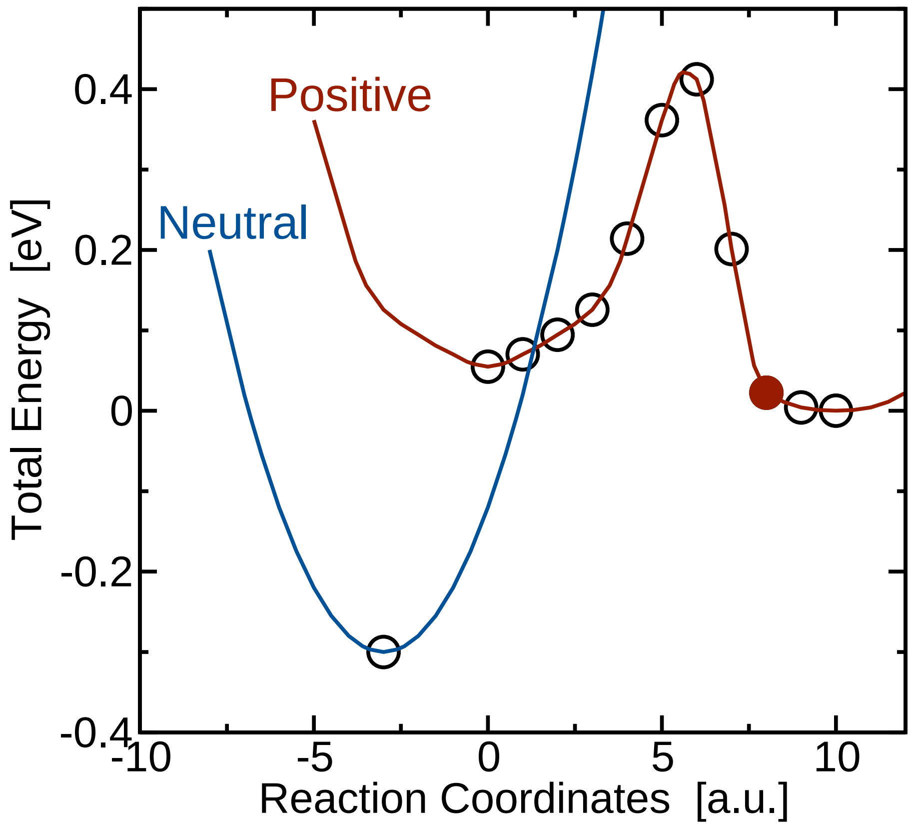

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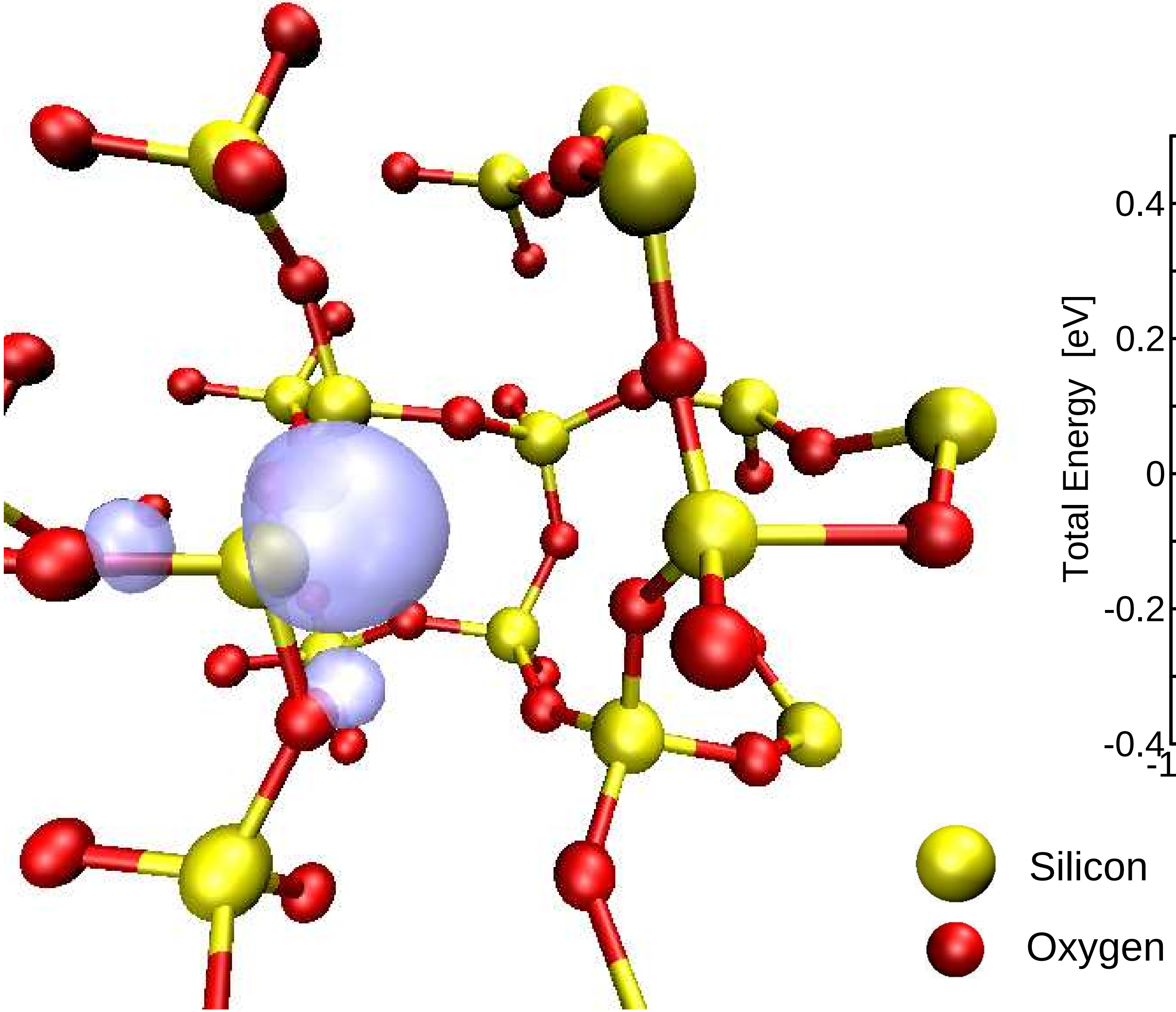

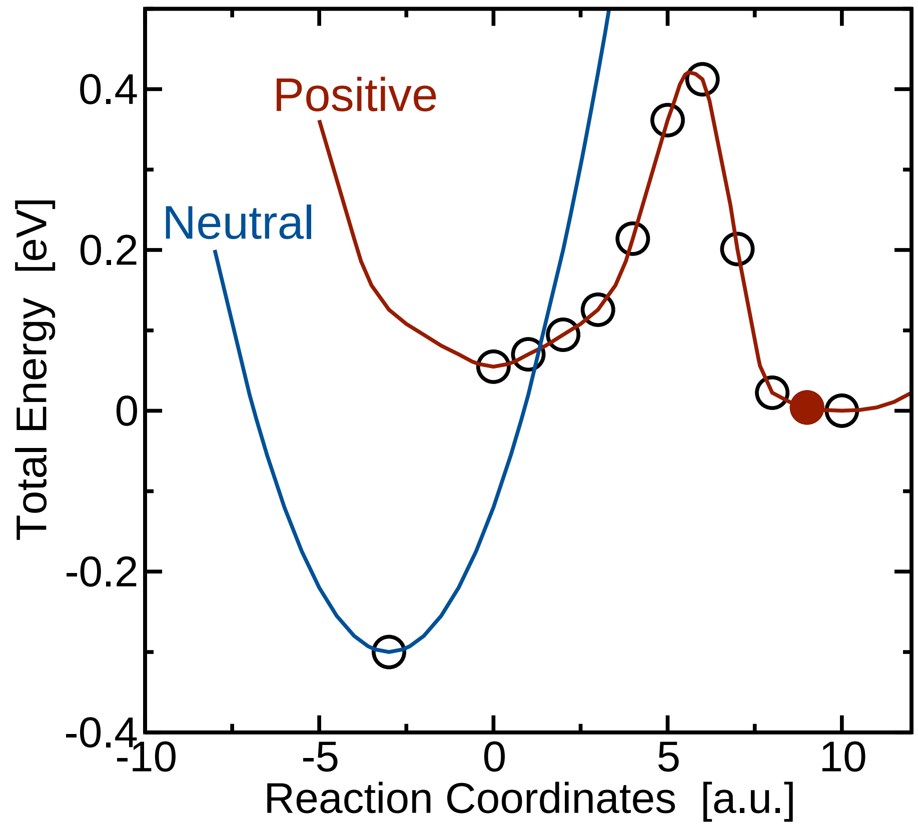

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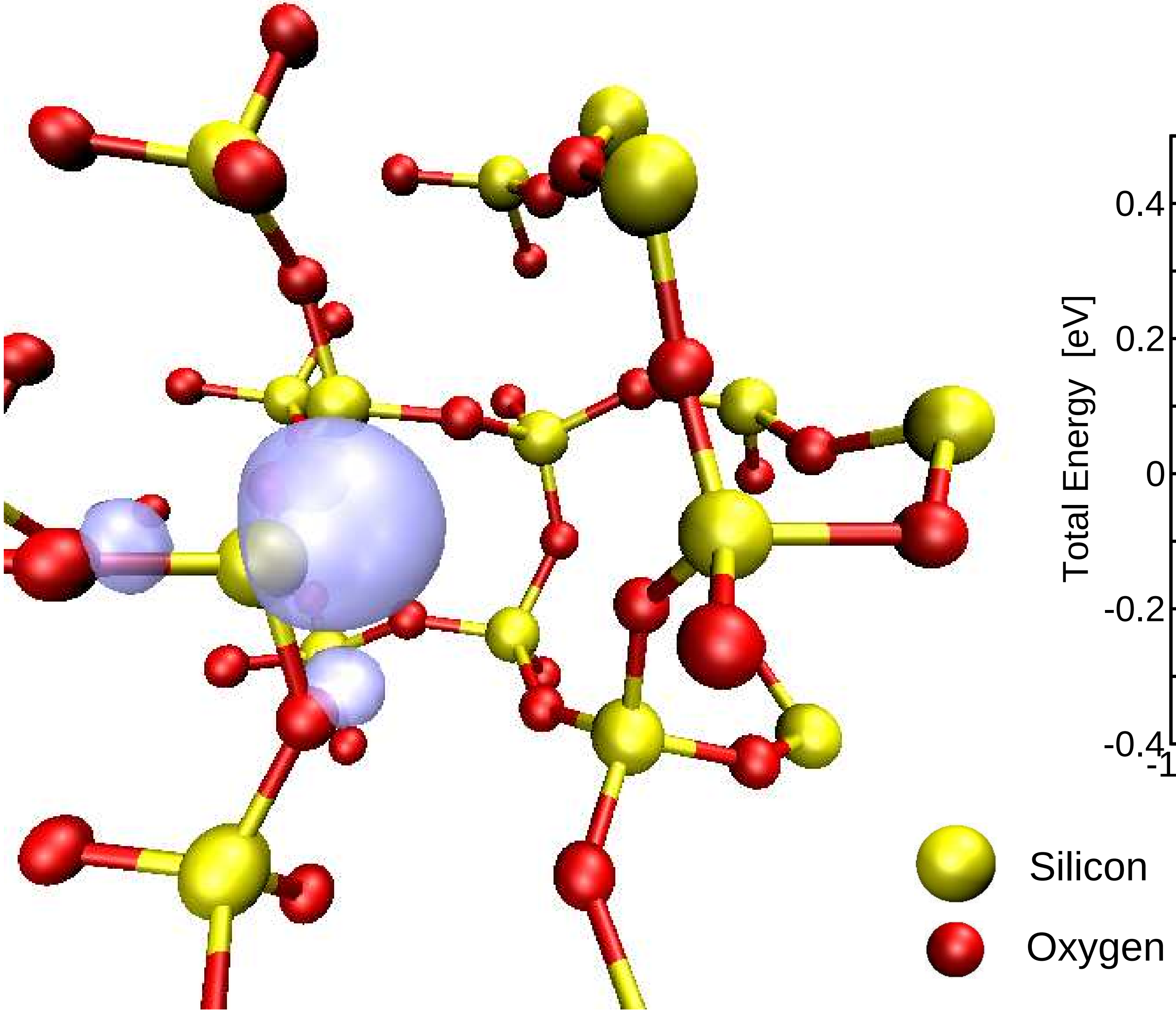
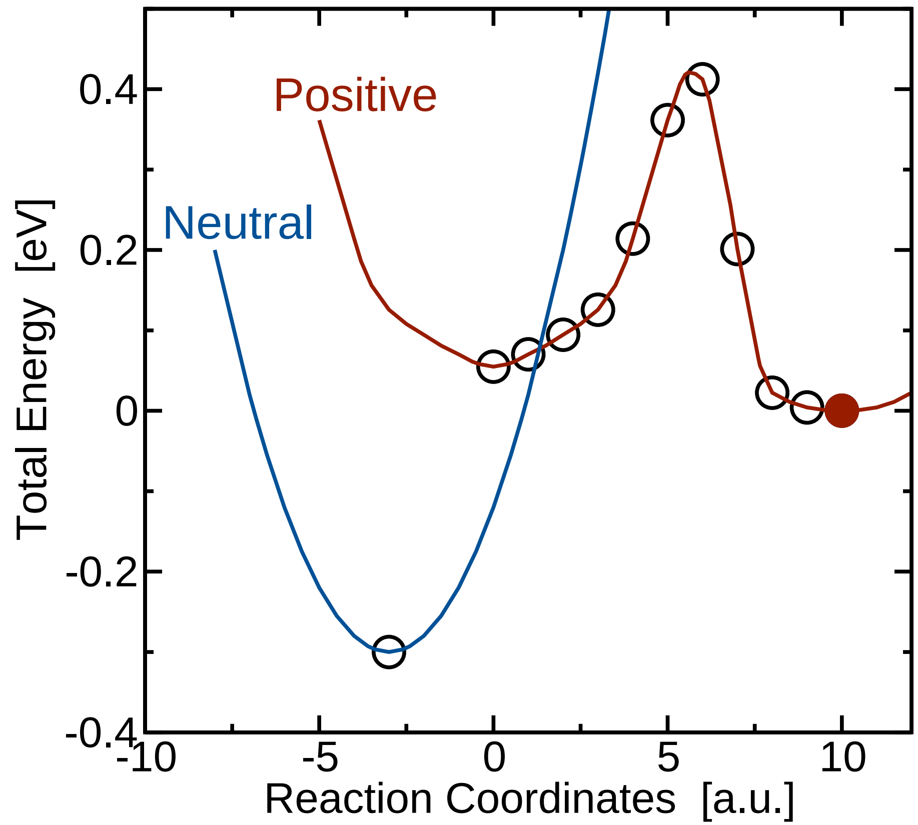
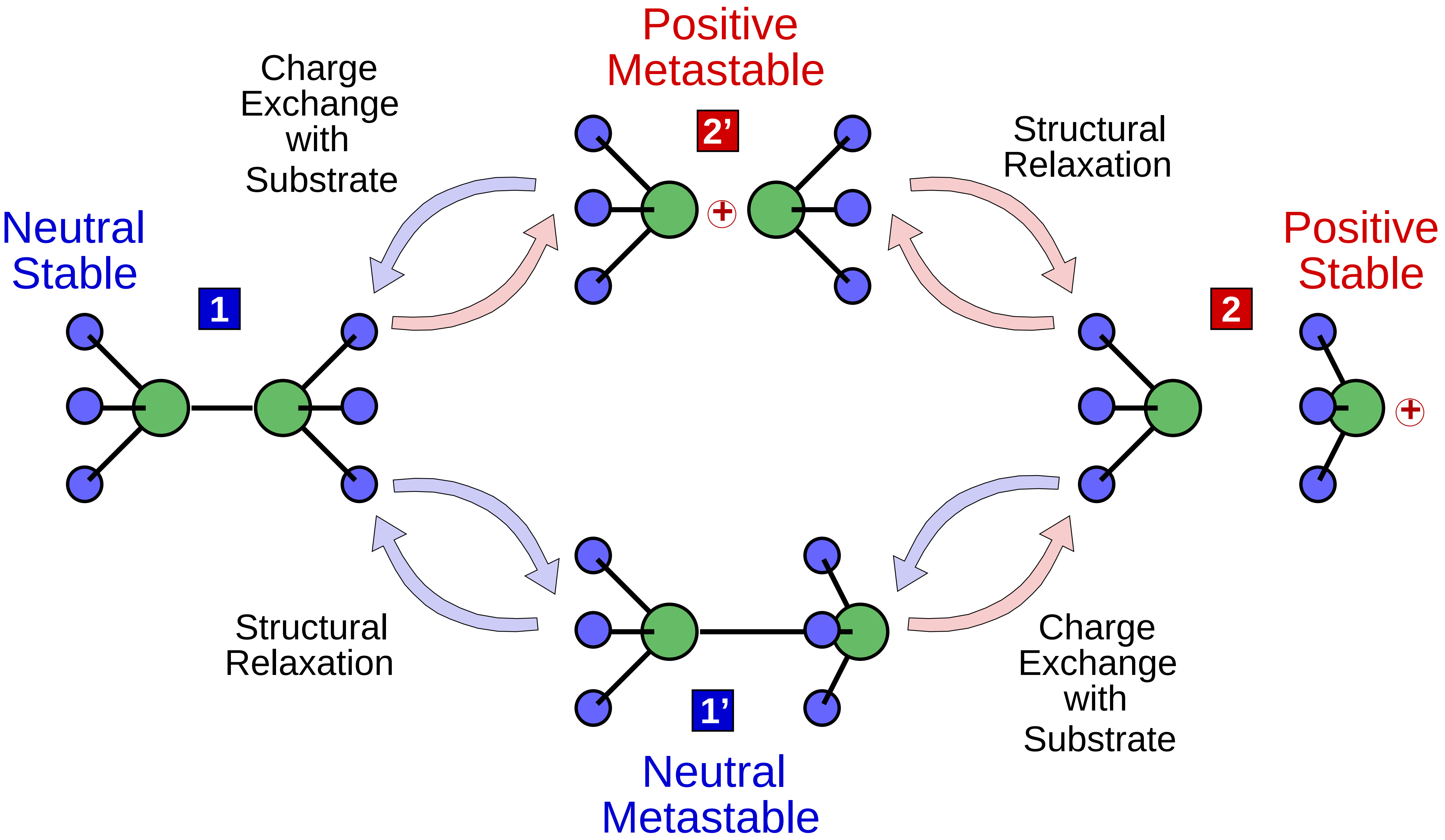




Detailed Defect Model Required



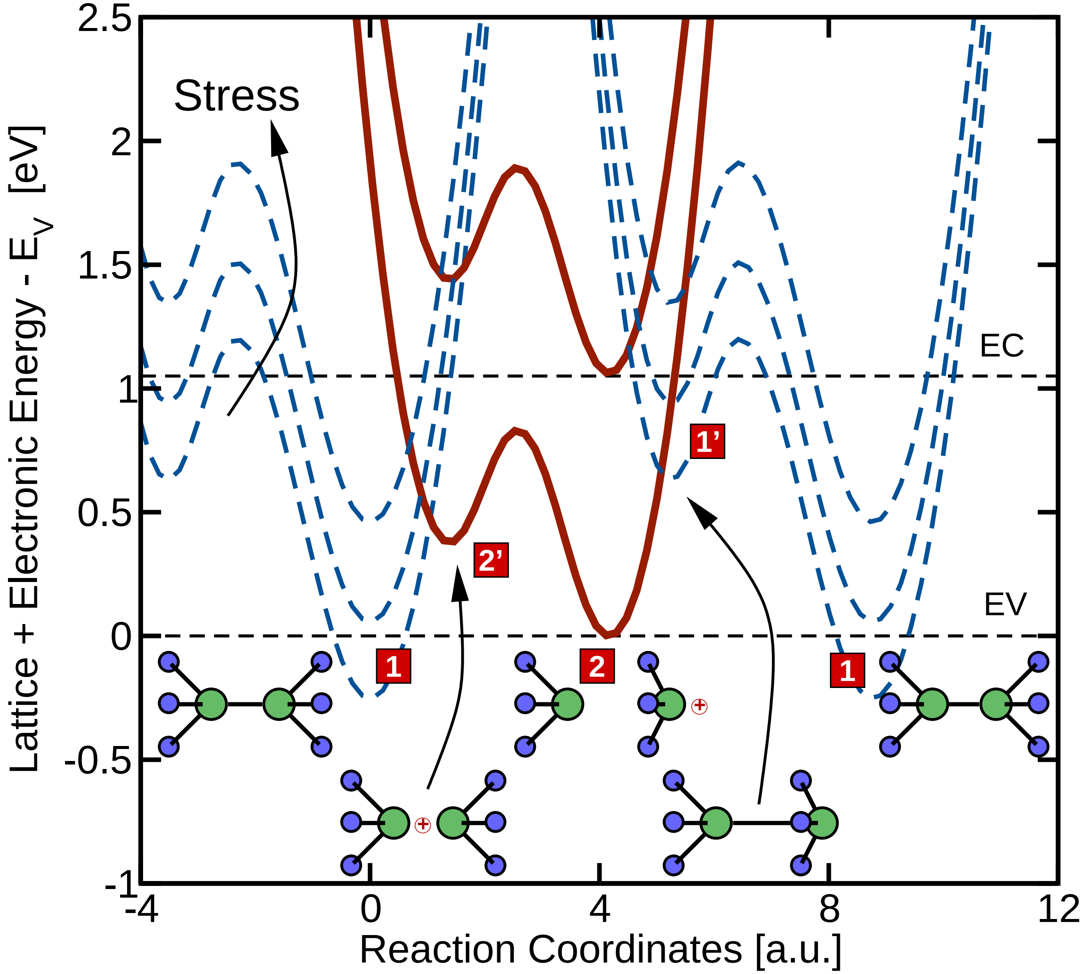
Model

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

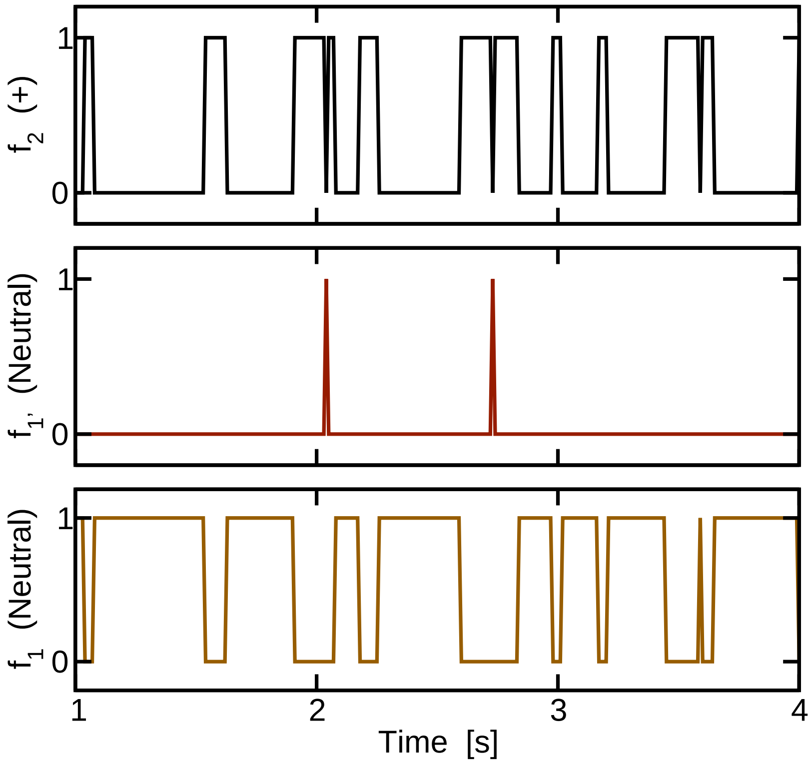
Stochastic Markov-model for defect kinetics based on multiphonon theory

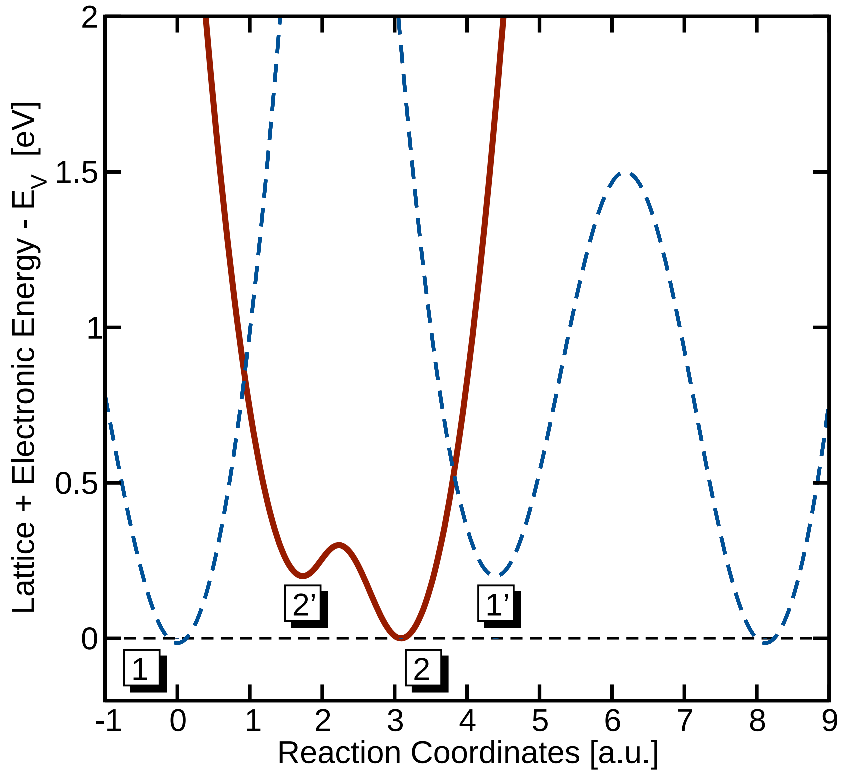


Qualitative Model Evaluation

Normal random telegraph noise (RTN)

Very similar energetical position of the minimas 1 and 2



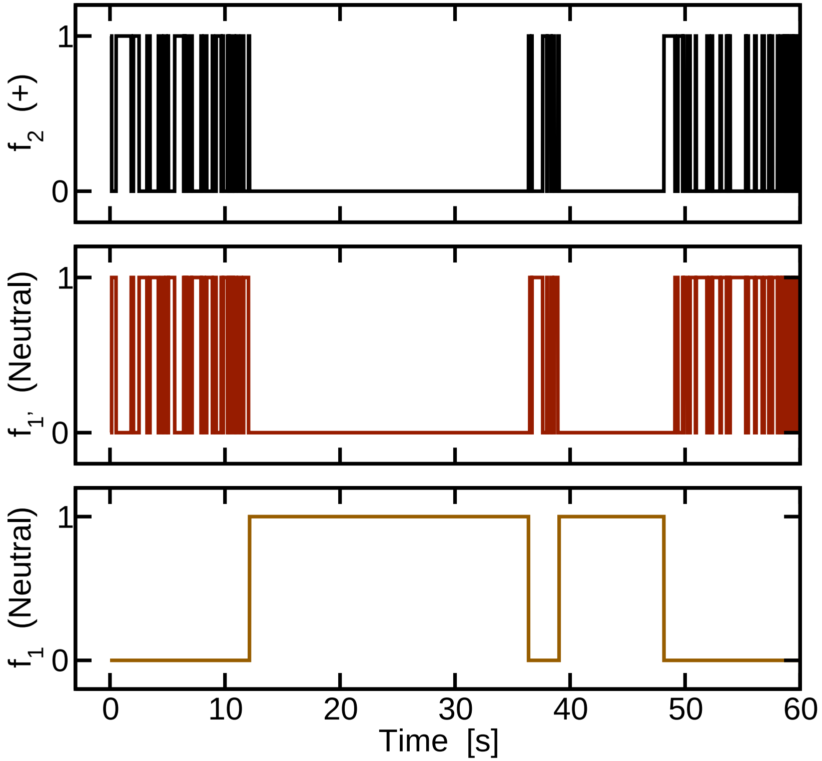


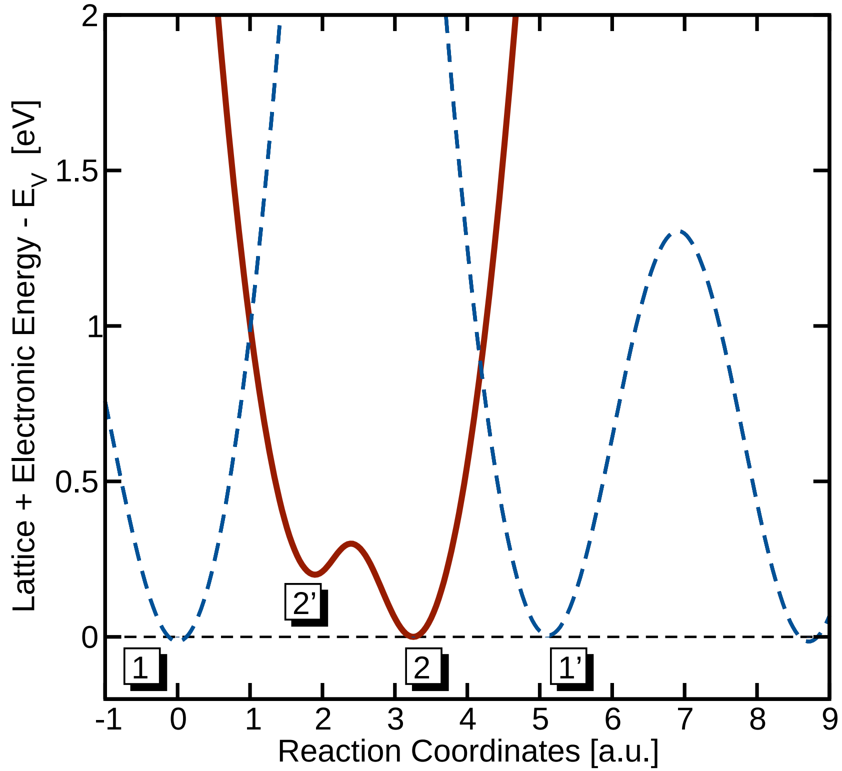
Kirton and Uren, Adv. Phys. '89

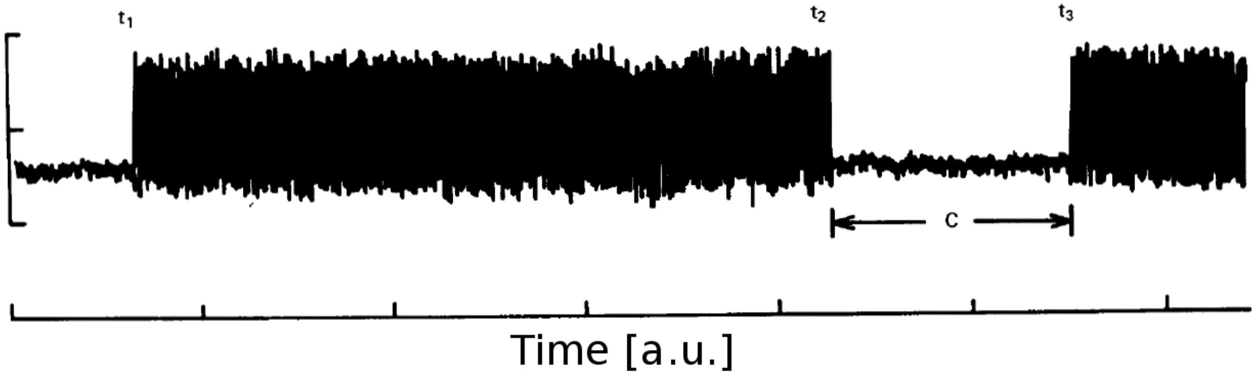
Qualitative Model Evaluation

Anomalous RTN

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





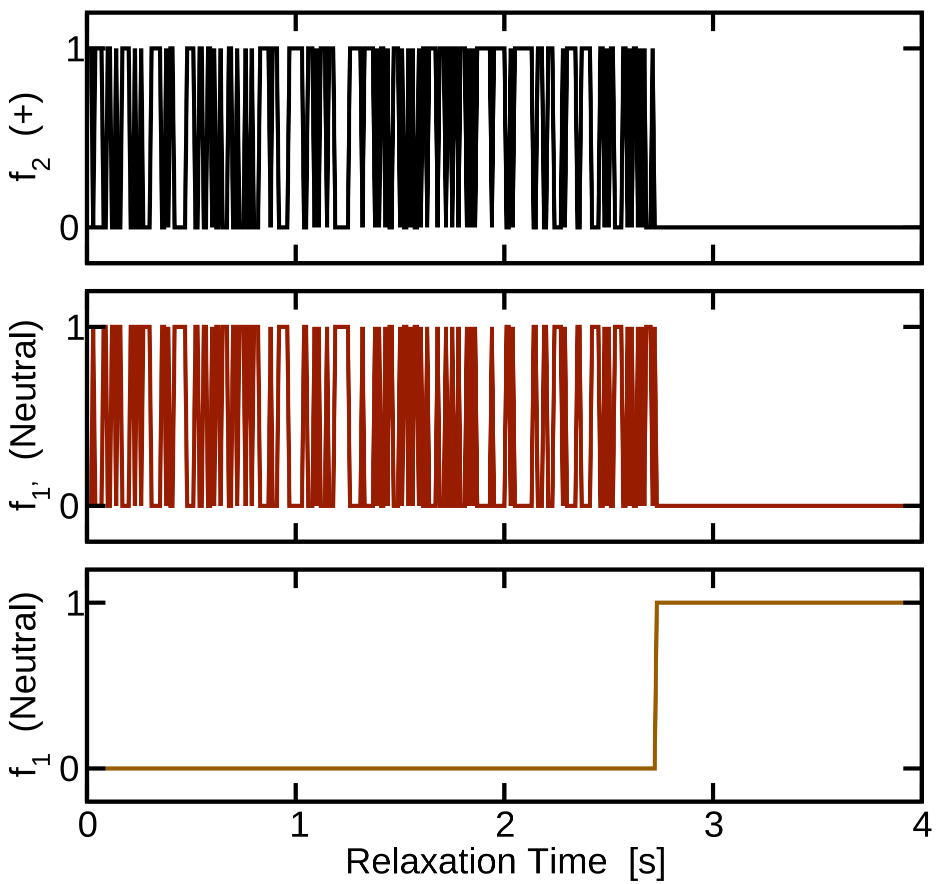


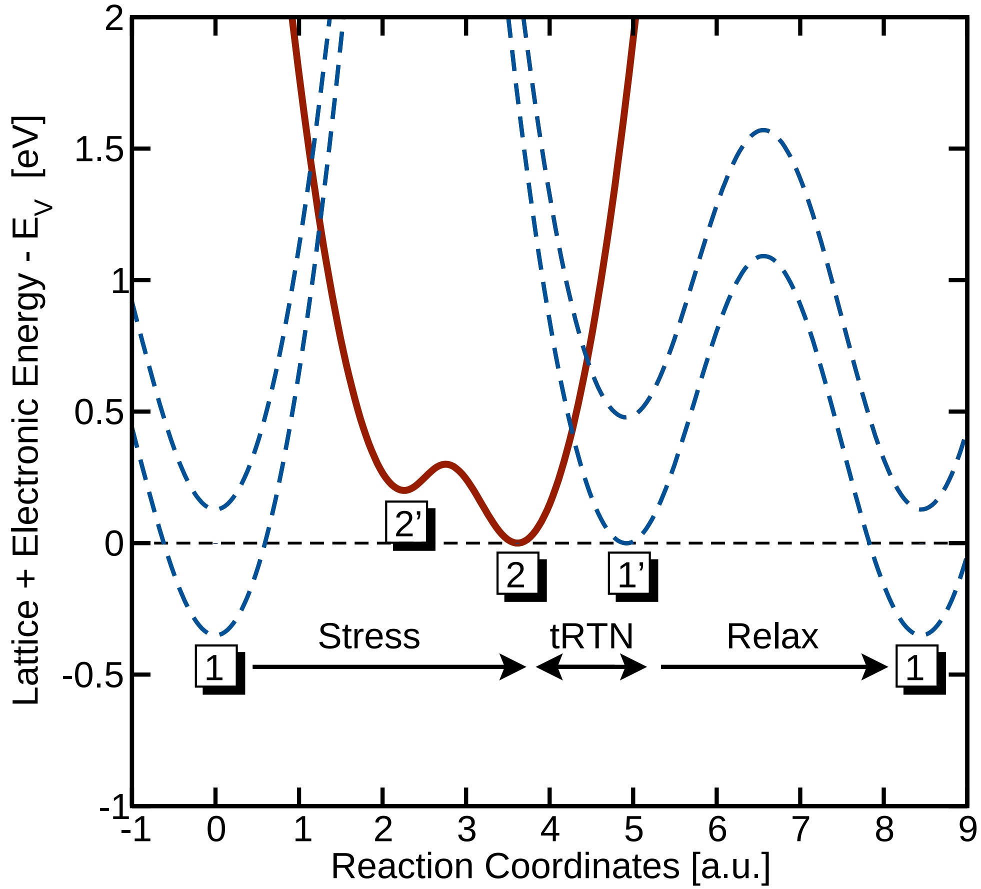
Uren *et al.*, PRB '88

Qualitative Model Evaluation

Temporary random telegraph noise (tRTN)

Very similar energetical position of the minima 2 and 1'





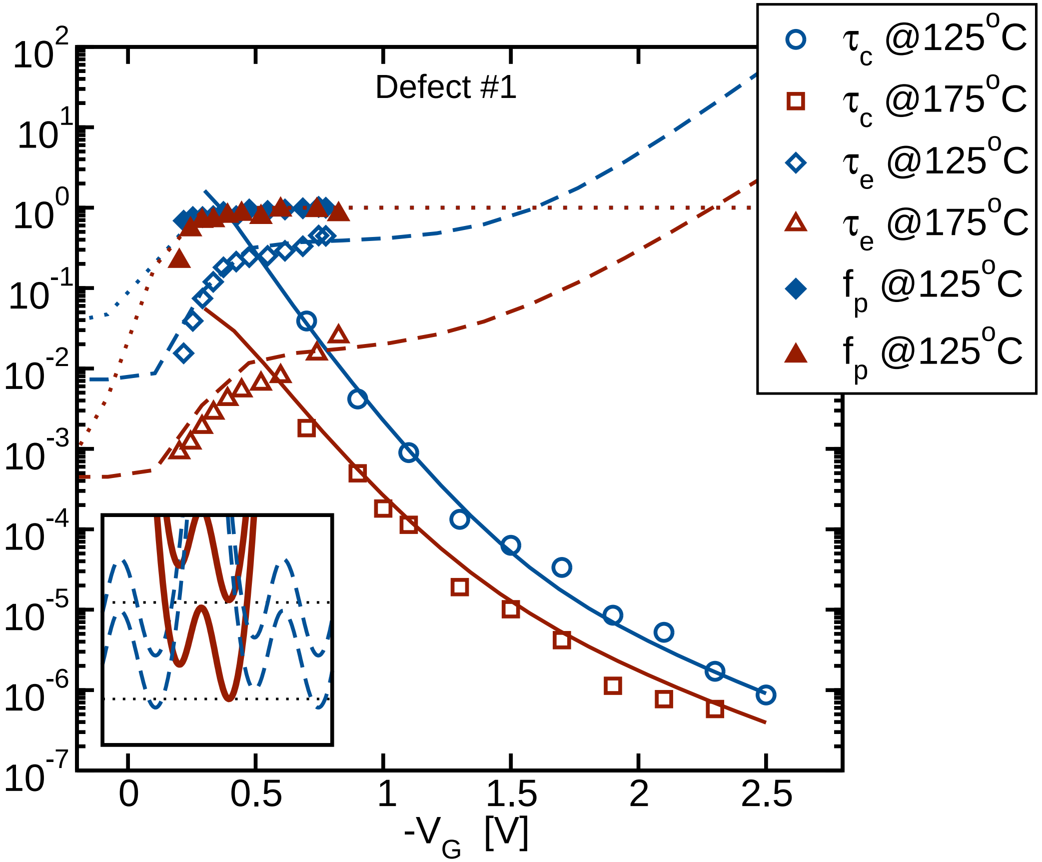
Quantitative Model Evaluation

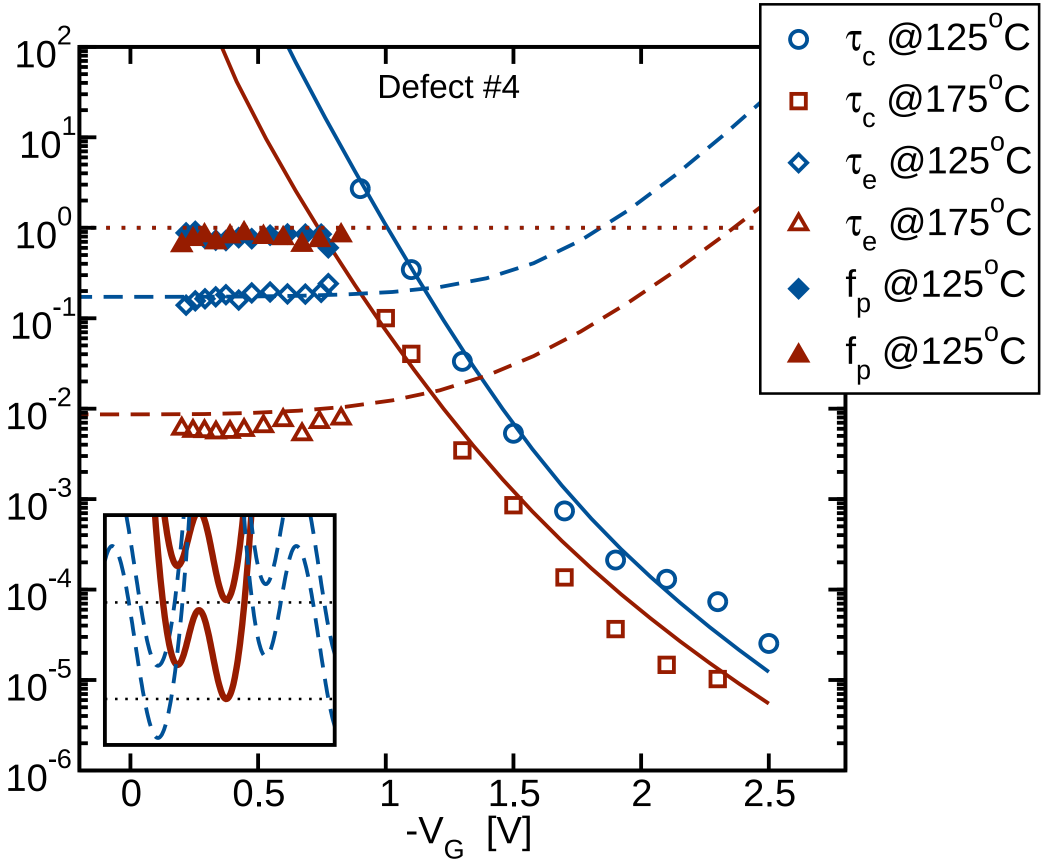
Excellent agreement for both capture and emission time constants

- 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

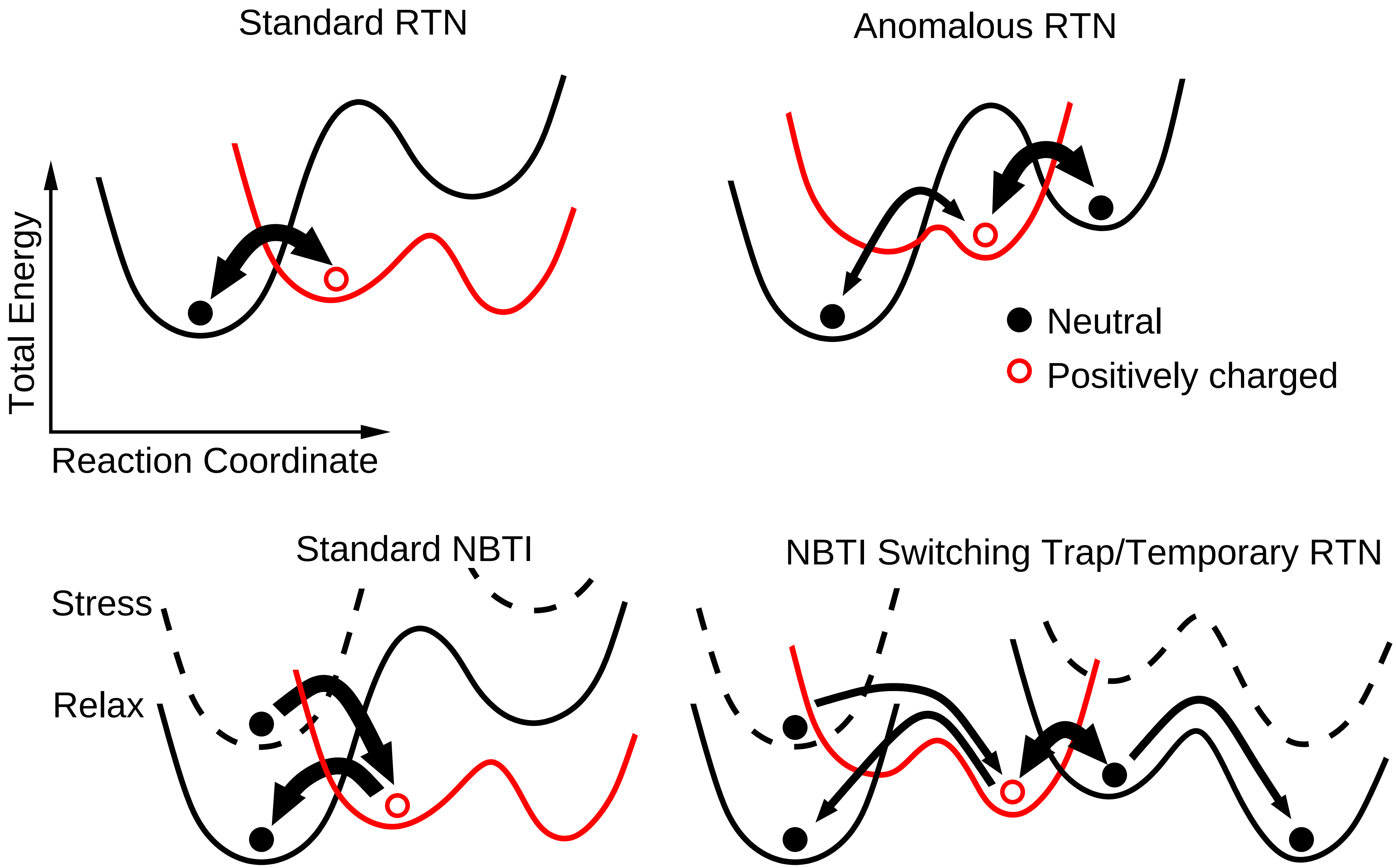




Model Summary

All features can be consistently explained with a general defect model

Differences simple consequences of defect potentials (amorphous oxide!)



How to Determine the Lifetime?

Small area devices: lifetime is a stochastic quantity

For details please refer to: Grasser *et al.* IEDM '10.

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 $\bar{\tau}_{\mathrm{e}}$, $\bar{\tau}_{\mathrm{c}}$, and step-height over very wide range
- Allows simultaneous analysis of multiple defects

New defect model

- Metastable defect states, nonradiative multiphonon theory, stochastic behavior

Fundamental implications on device reliability

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