Charge Trapping Phenomena in MOSFETS: From Noise to Bias Temperature Instability.

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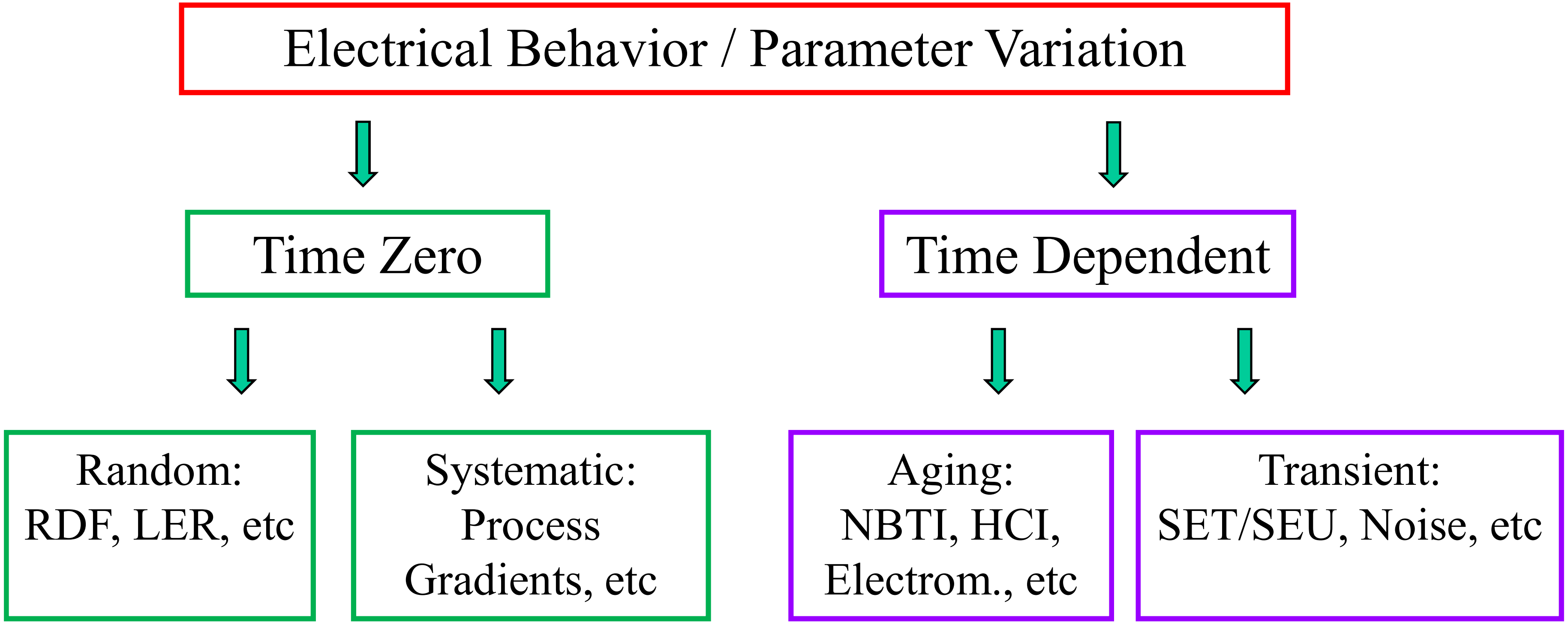
Variability in Nano-Scale Technologies



Electrical Behavior / Parameter Variation

Time Zero

Time Dependent

Random:
RDF, LER, etc

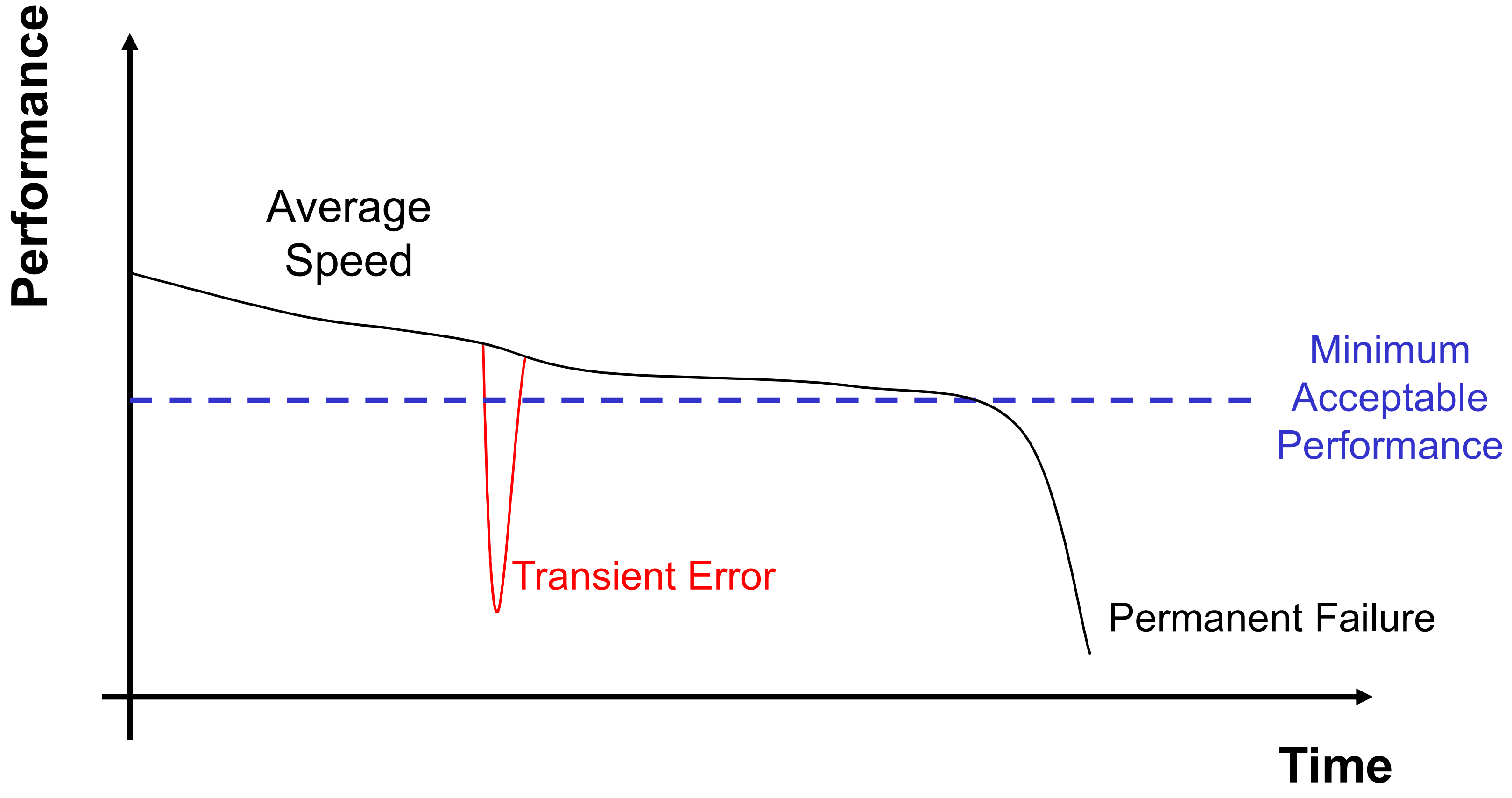
Systematic:
Process
Gradients, etc

Aging:
NBTI, HCI,
Electrom., etc

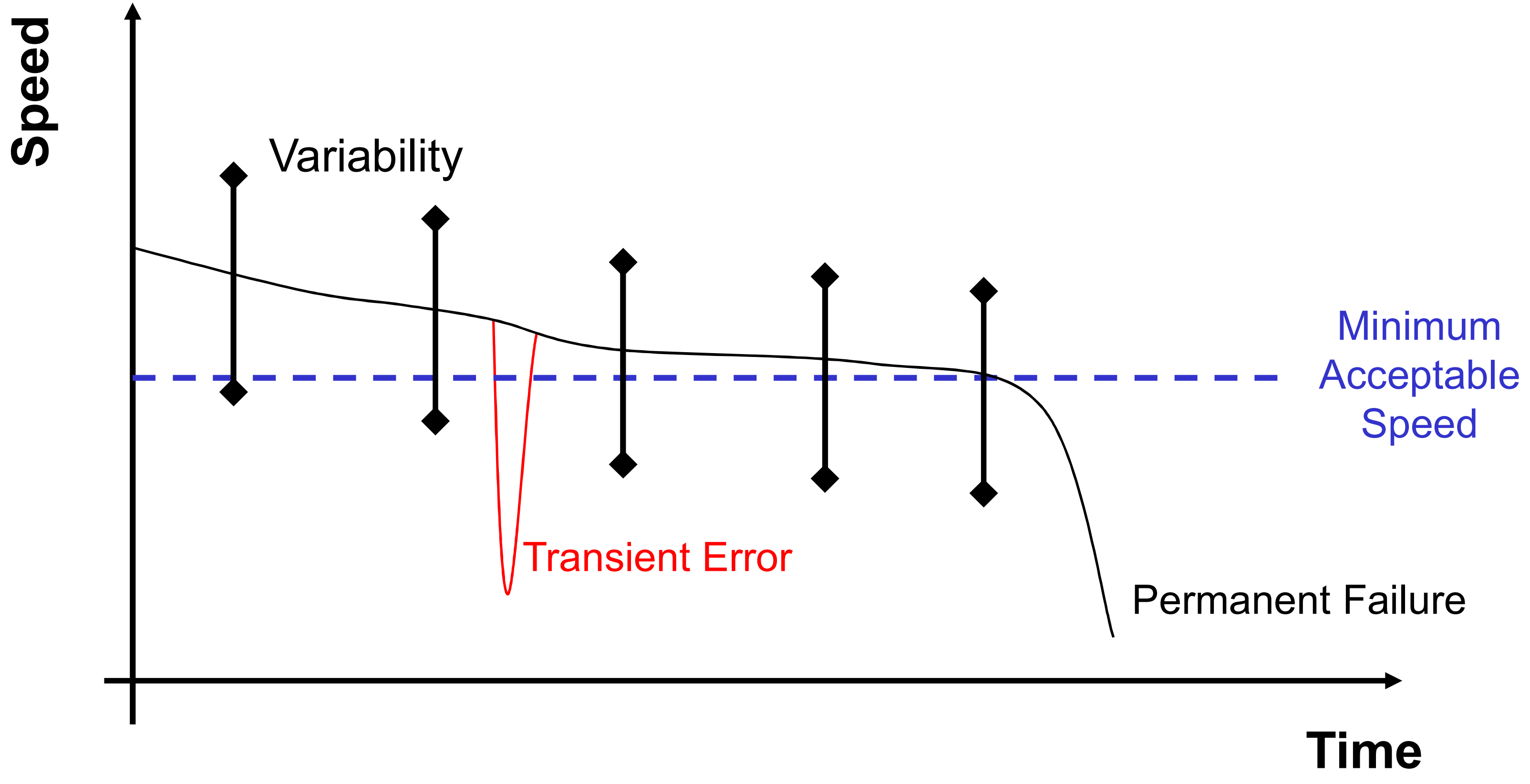
Transient:
SET/SEU, Noise, etc

There are also environmental sources of variation:
Voltage, Temperature, etc.

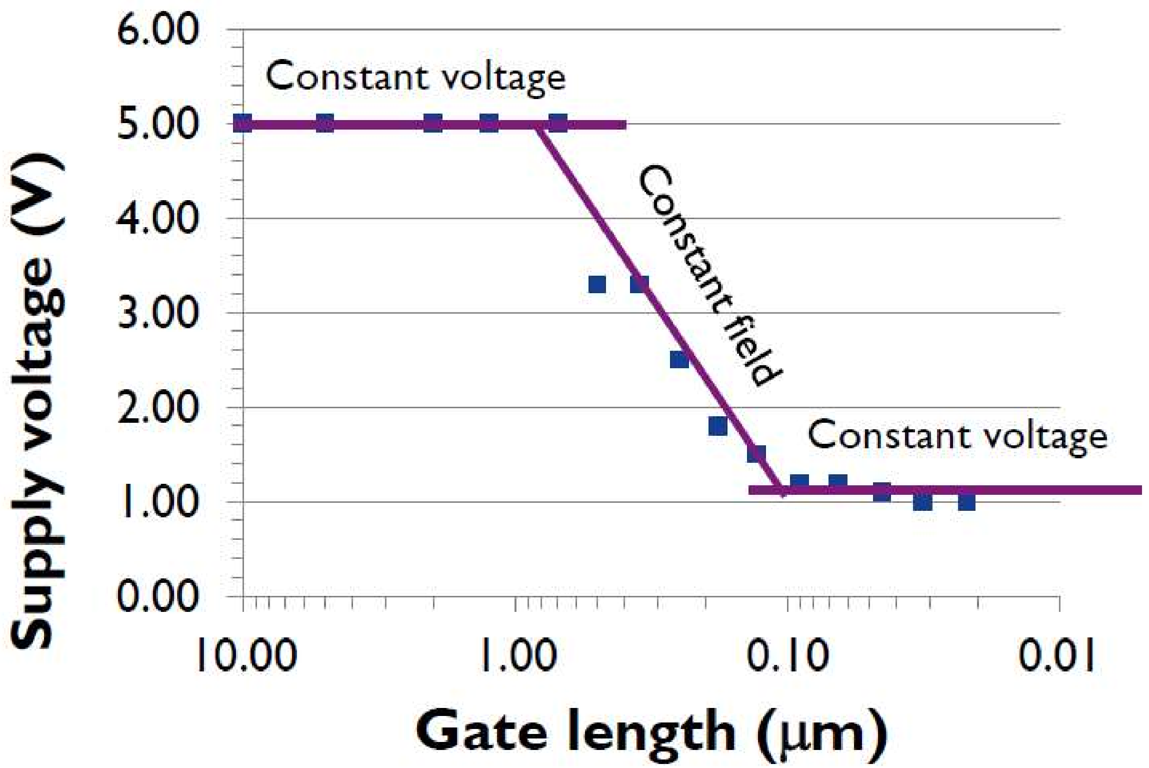
Issues in Nano-Scale Technologies



Issues in Nano-Scale Technologies



Issues in Nano-Scale Technologies



- V_{DD} saturating at ≈ 1V due to non-scaling of sub-threshold slope.
- Increased Electric Field in Gate Dielectric and Semiconductor.
- Increased power density: Increased Temperature.
- High-*K* Oxides: Increased Trap Density.

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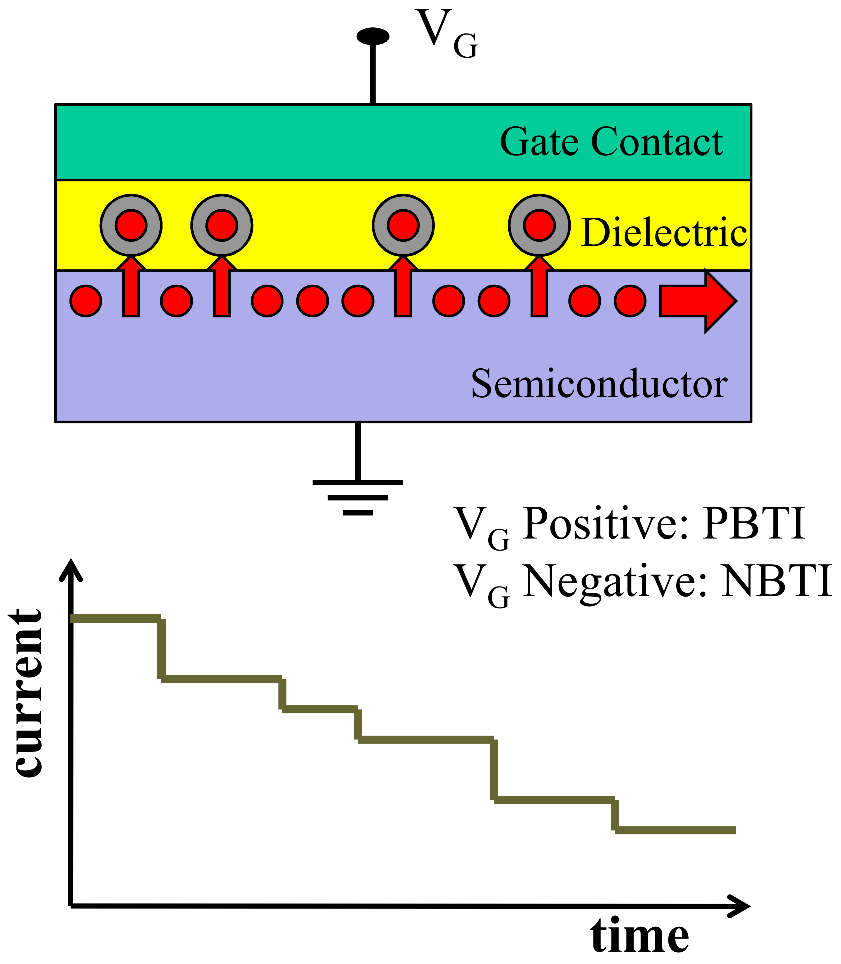
Discrete Charges and Traps

Technology node	1µm	100nm	40nm	16nm
VDD (V)	3.3	1.2	1	0.8
width = length in (µm)	1	0.1	0.04	0.016
EOT / nm	10	2.2	1	1
specific capacitance (C/nF/cm^2)	345	1568	3450	3450
oxide capacitance Cox (F)	3.45E-15	1.57E-16	5.52E-17	8.83E-18
Eox at VDD (MV/cm)	3.3	5.5	10.0	8.0
number of carriers in channel at Eox=5MV/cm	7.1E+04	1.2E+03	345	44
number of active defects	1000	10	1.6	0.3
ΔVth for single carrier (mV)	0.05	1.0	2.9	18.1

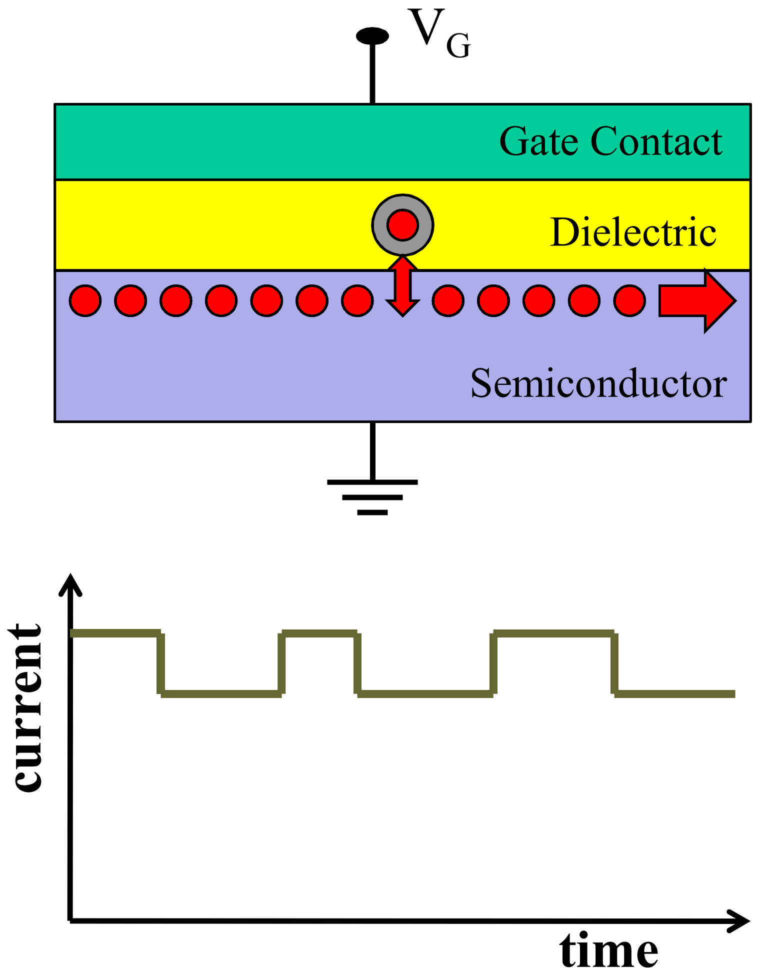
Useful numbers for some selected technology nodes. Assumption: defect density=$10^{11}/cm^2$. [Reisinger, 2014].

$$\Delta V_{th} = q / C_{ox} \quad with \quad C_{ox} = \varepsilon \times A / tox$$

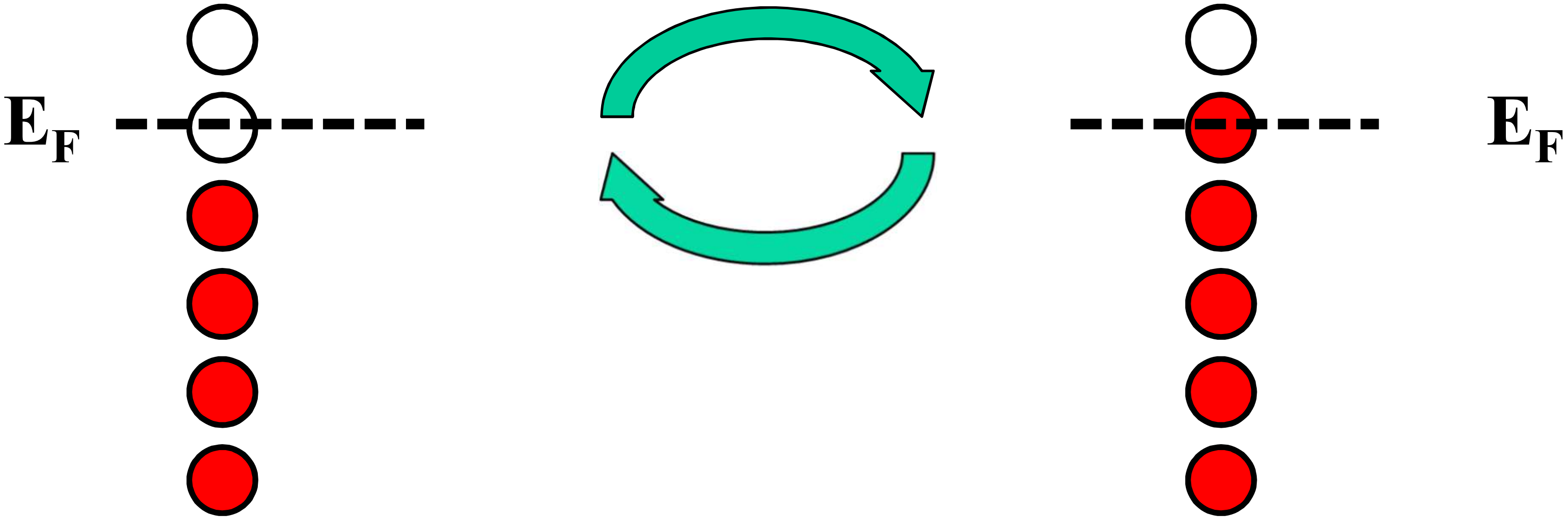
BTI x RTN



V_G Positive: PBTI
V_G Negative: NBTI

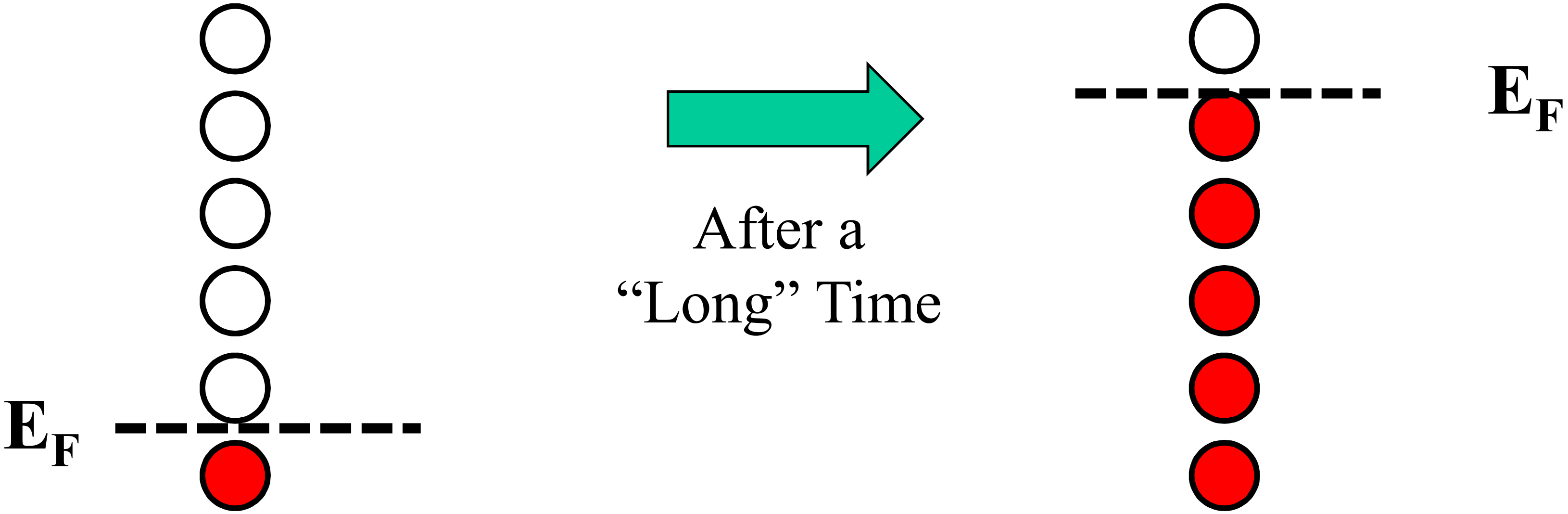


Low-Frequency Noise (RTN)



Traps within a few kT from the Fermi Level contribute to noise

Charge Trapping Component of BTI: Stress



Transistor Off

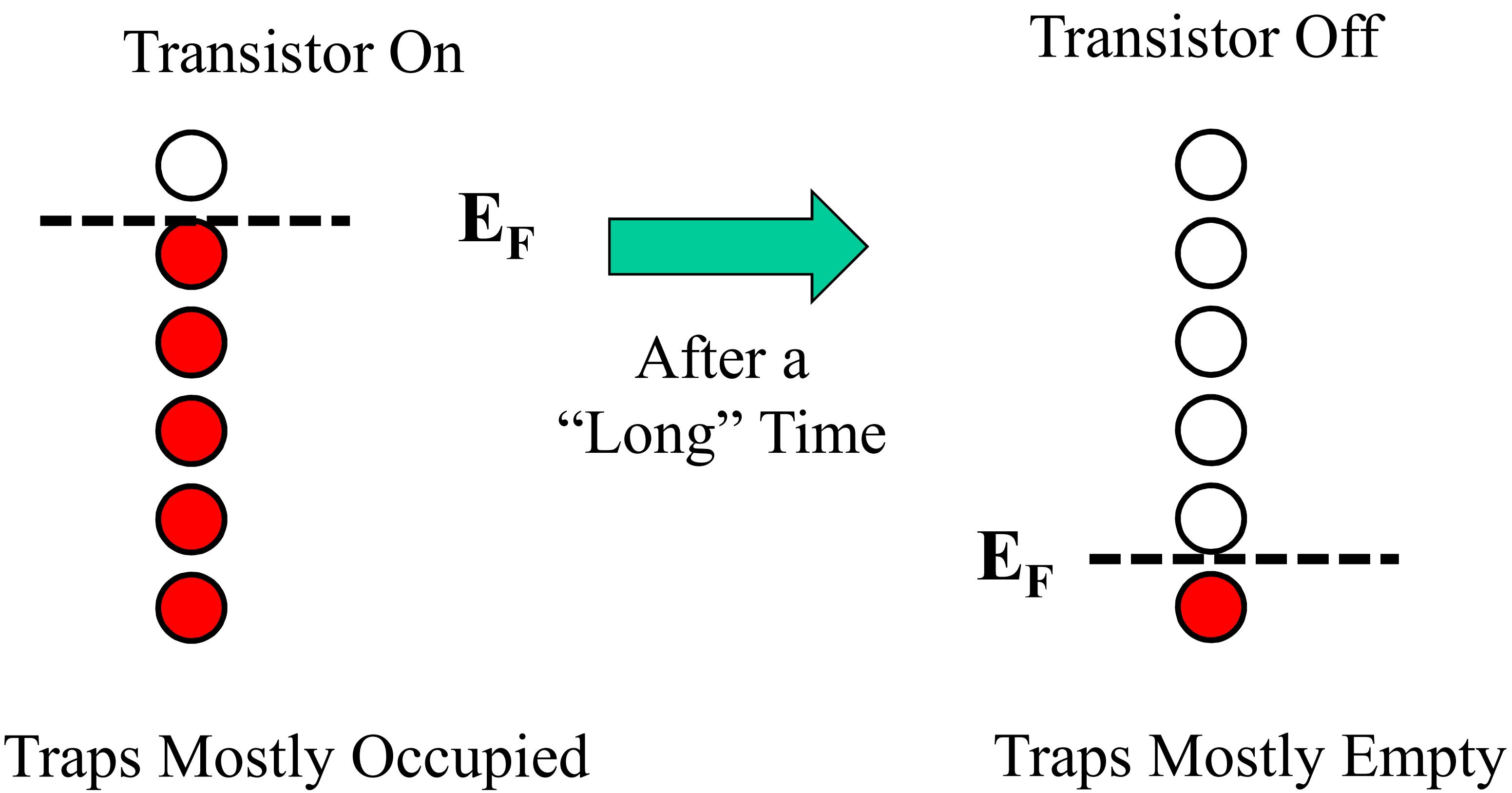
Transistor On

After a
“Long” Time

Traps Mostly Empty

Traps Mostly Occupied

Charge Trapping Component of BTI: Recovery



Transistor On

E_F

After a "Long" Time

Transistor Off

E_F

Traps Mostly Occupied

Traps Mostly Empty

BTI x RTN

Traps that contribute to noise are the ones with

$$\tau_C \cong \tau_E$$

i.e., traps that keep switching state

Traps that contribute to NBTI are the ones with

$$\tau_C < \tau_E$$

i.e, traps that become occupied

Modeling Approach

Based on Microscopic (Random) Quantities, instead of distributed (homogeneous) quantities.

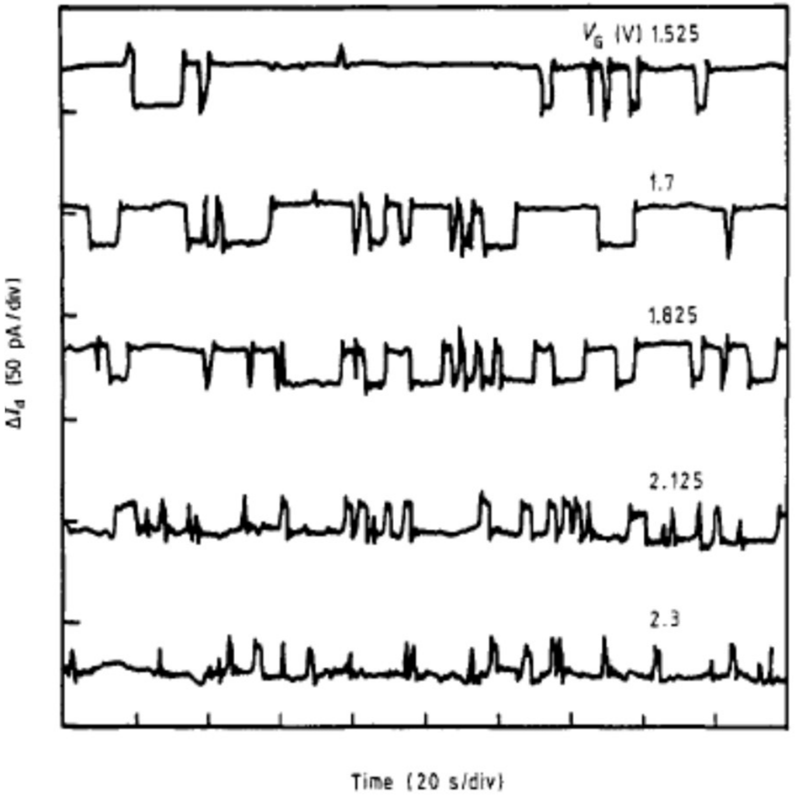
1. **Charge trapping and de-trapping are stochastic events governed by characteristic time constants, which are uniformly distributed on a log scale.**
2. **Number of traps is assumed to be Poisson distributed.**
3. **Amplitude of the fluctuation induced by a single trap is a random variable. Studied by atomistic simulations (if needed, exponential distribution assumed).**
4. **Trap energy distribution is assumed to be U shaped (key to explain the AC behavior).**

Some Advantages of our Approach

Talk Outline

1. **Can be Applied to both DC and AC Large Signal Excitation.**
2. **Can be Applied also for Transient Simulation.**
3. **Random Variables Lead to Statistical Model (Today Variability is a Major Issue). Applicable in Linear and Log Scale.**
4. **Can be Applied to Different Phenomena where Charge Trapping Plays a Role, such as Noise and NBTI.**

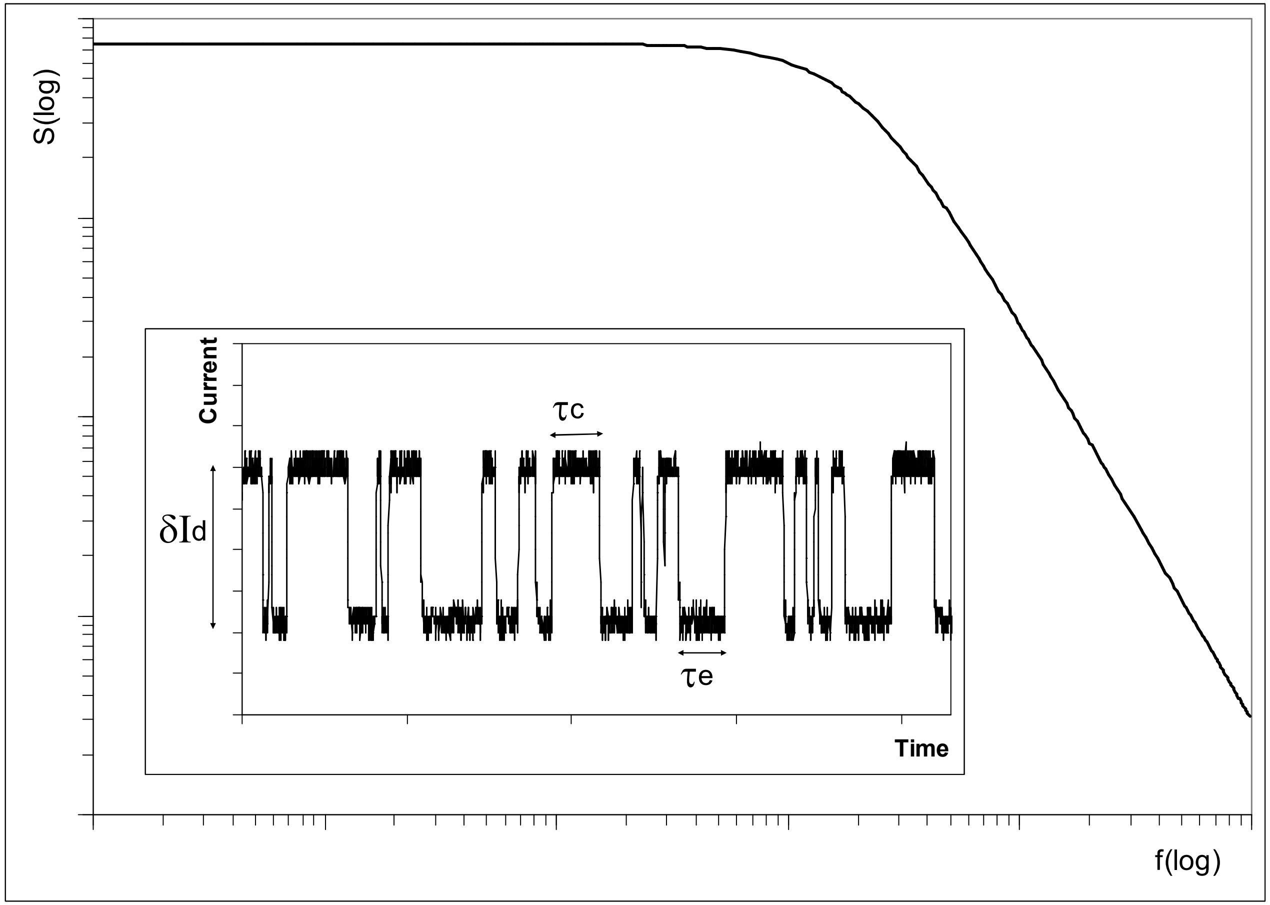
RTN Definition



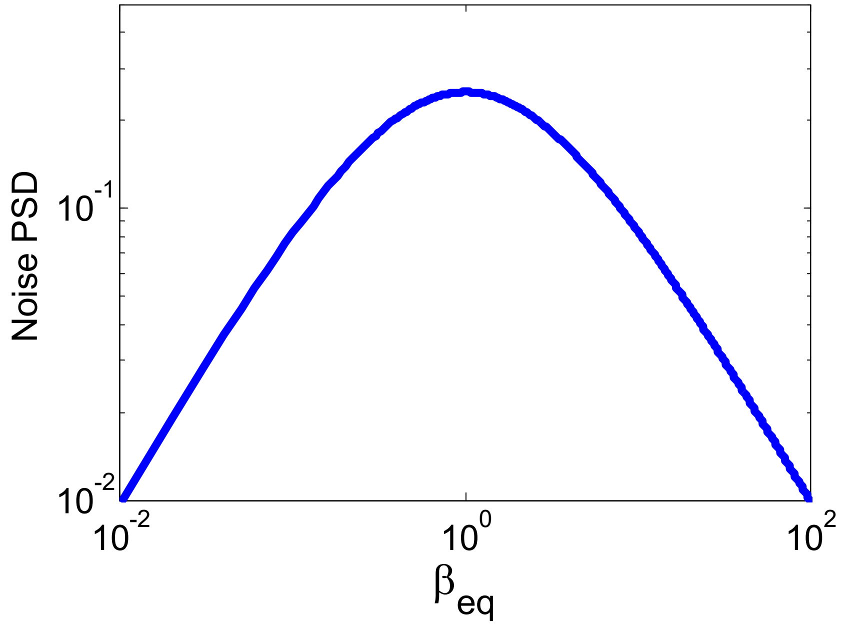
In its simplest form, RTN is a Two-Level temporal fluctuation of a signal between a high and a low state.

This is characterized by a time in the high state (**t_{high}**), in the low state (**t_{low}**) and an amplitude (**ΔI, ΔV, ΔR or ΔG**).

RTN Power



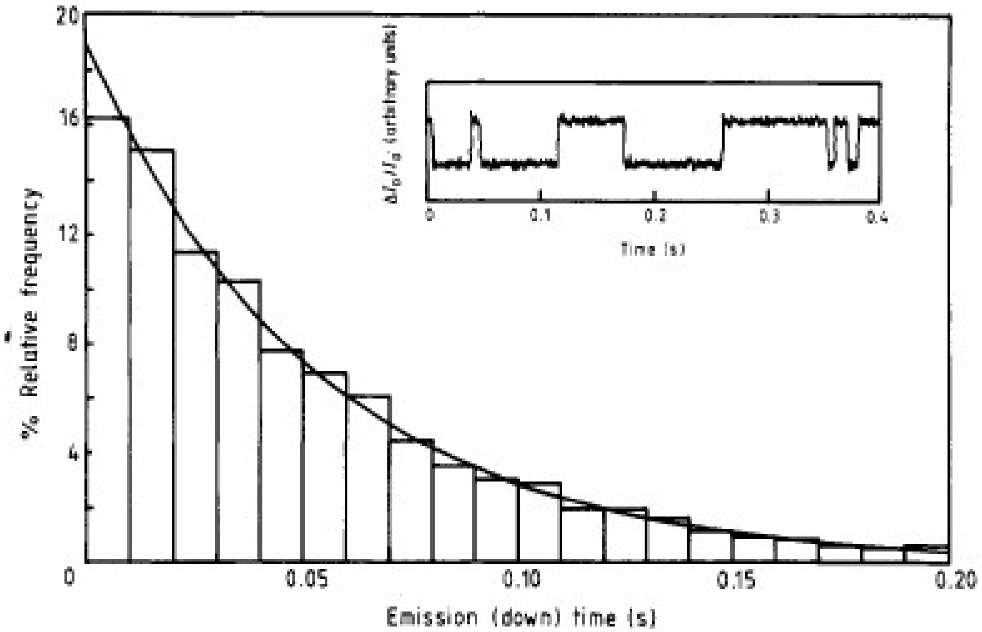
RTN Power



Noise PSP as a function of $\beta = \tau_c / \tau_{e.}$ For β=1 noise PSD is maximum.

$$S_i(\omega) = \frac{\delta_i^2}{\pi} \cdot \frac{\beta_{eq}}{(1+\beta_{eq})^2} \cdot \frac{1}{\omega_i} \cdot \frac{1}{1+(\omega/\omega_i)^2}$$

Behavior of Time Constants



4425 emission times, showing that it is distributed exponentially.
τ_e=0.0528 s, standard deviation = 0.505 s.

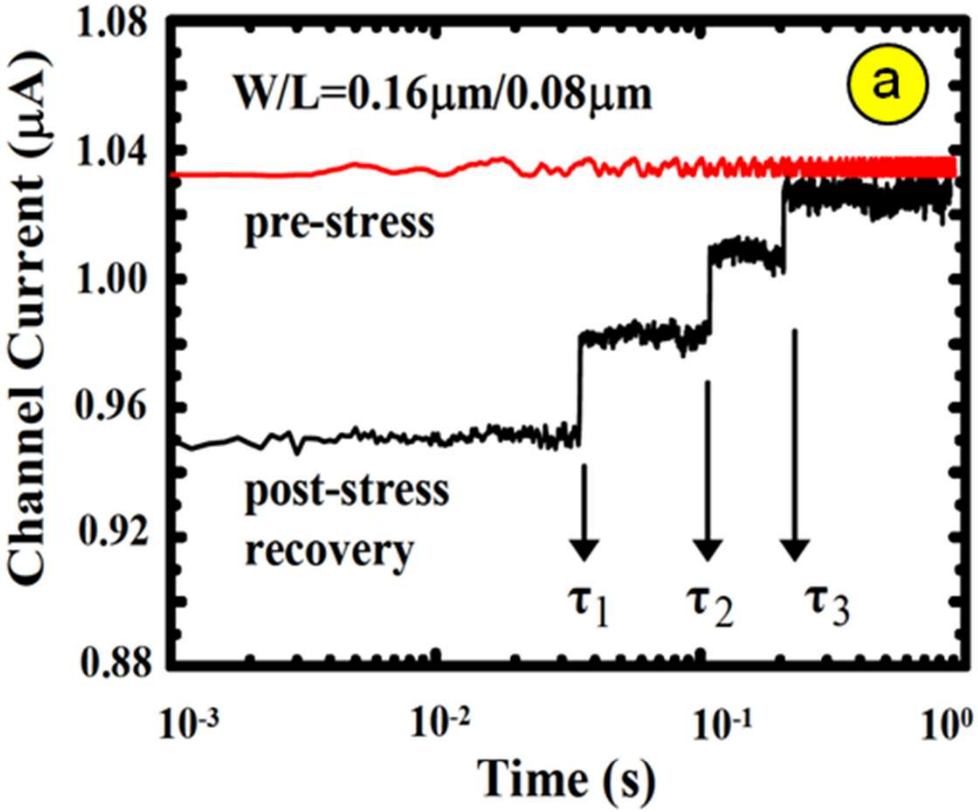
Up and down time constants follow a Poisson distribution for simple two-level RTNs, given by:

$$P_1(t) = \frac{1}{\tau_1} \exp\left(-\frac{t}{\tau_1}\right)$$

with τ_1 the average value.
$P_1(t)dt$ the probability that the high state 1 will not make a transition for time t, then will make one in the interval t and t+dt.

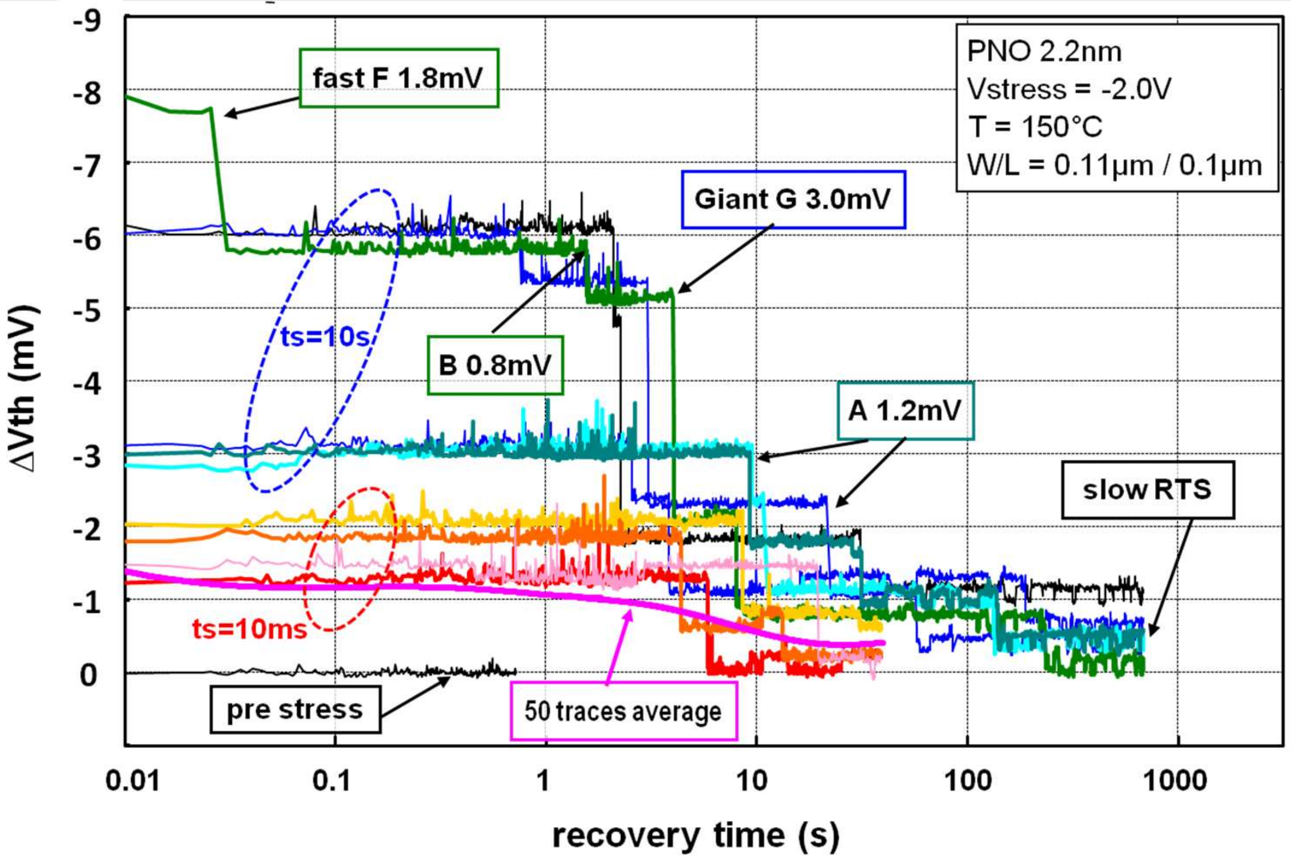
$$P_{1\to 0}(\Delta t) = \Delta t/\tau_1$$

Trap Amplitude



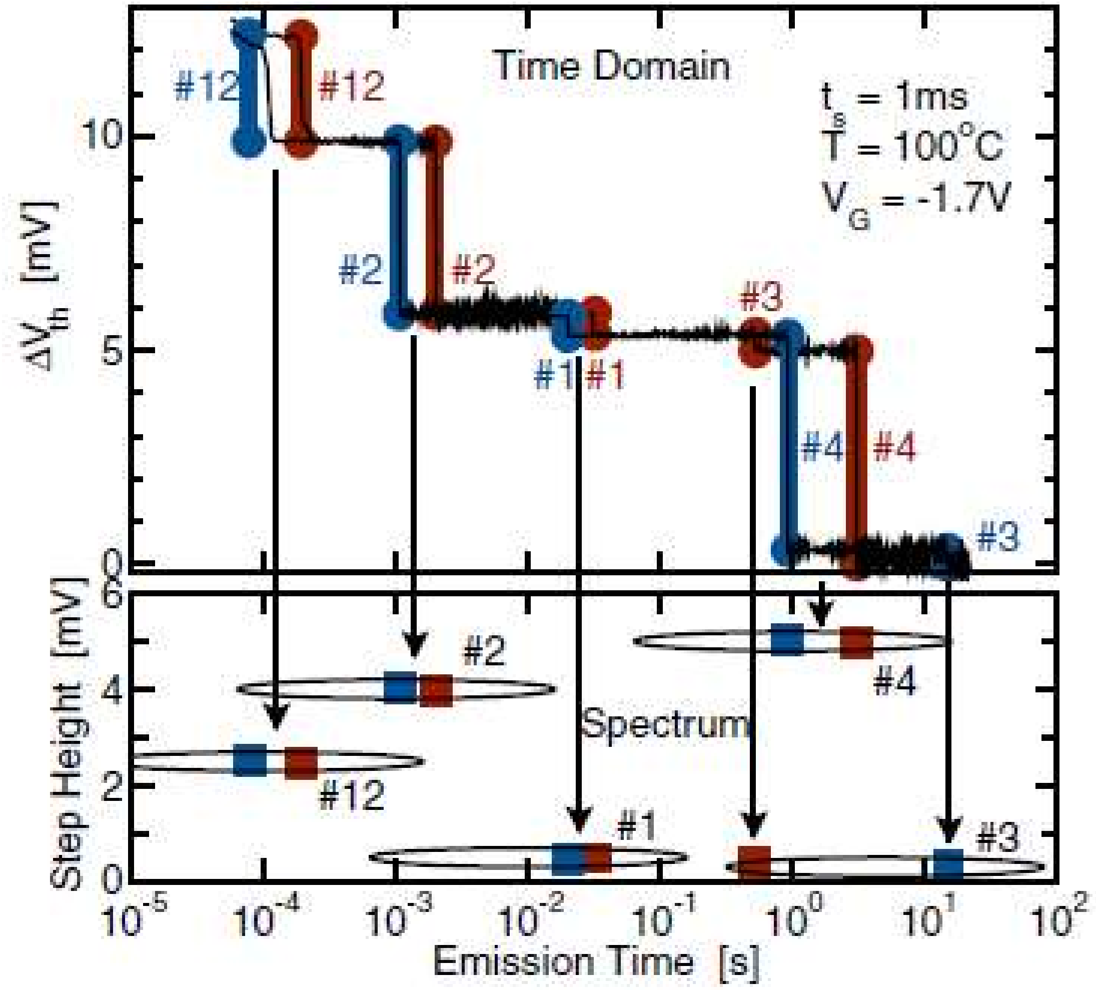
C. T. Chan, H. C. Ma, C. J. Tang and T. Wang, VLSI Digest of tech. papers, p. 90 (2005).

Trap Amplitude



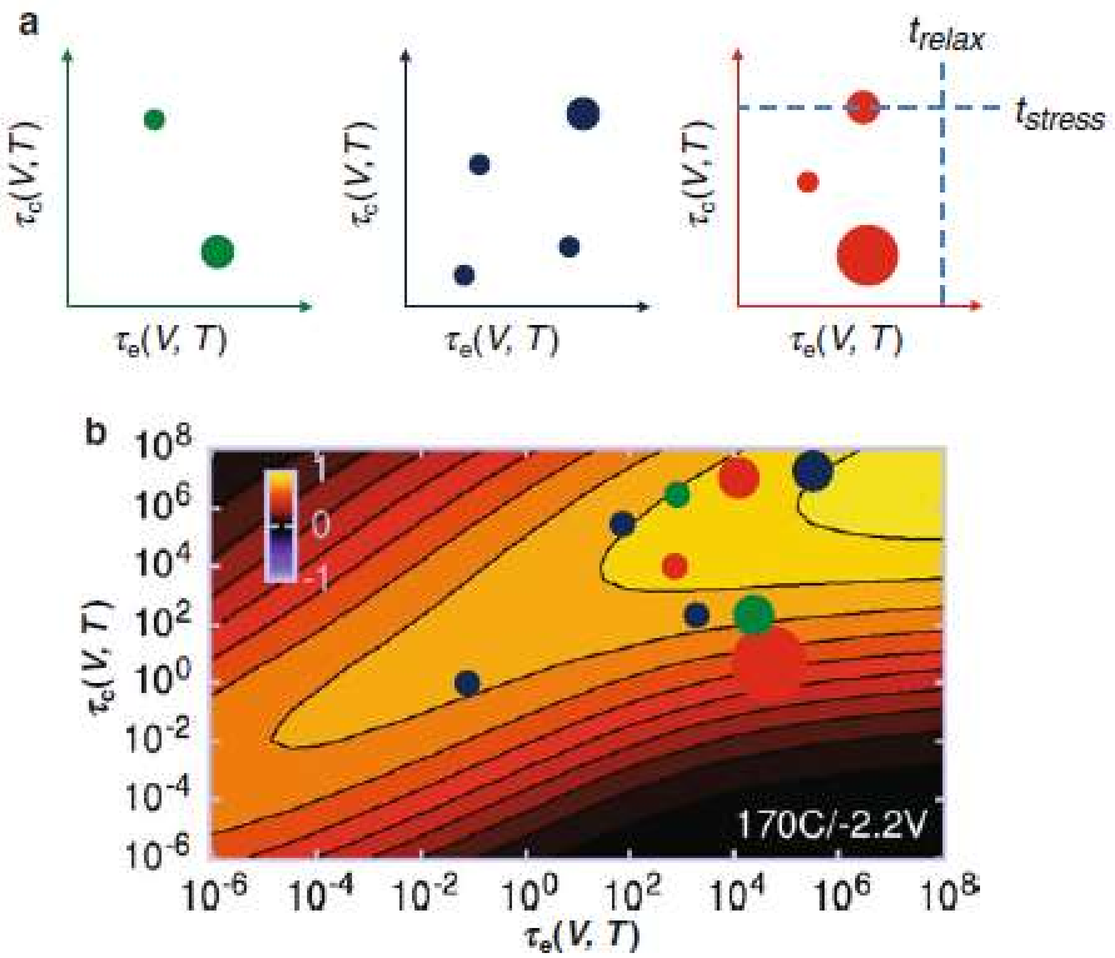
Recovery traces after repeated stress pulses with t_S= 10 ms and 10 s pulse length. Four different defects (named A, B, F, G) with different capture and emission time constants and step heights are charged. For the given gate area, ΔV_{th} after the charge sheet approximation is 1 mV, the resolution is about 0.2 mV [Reisinger, 2014].

The Time-Dependent Defect Spectroscopy

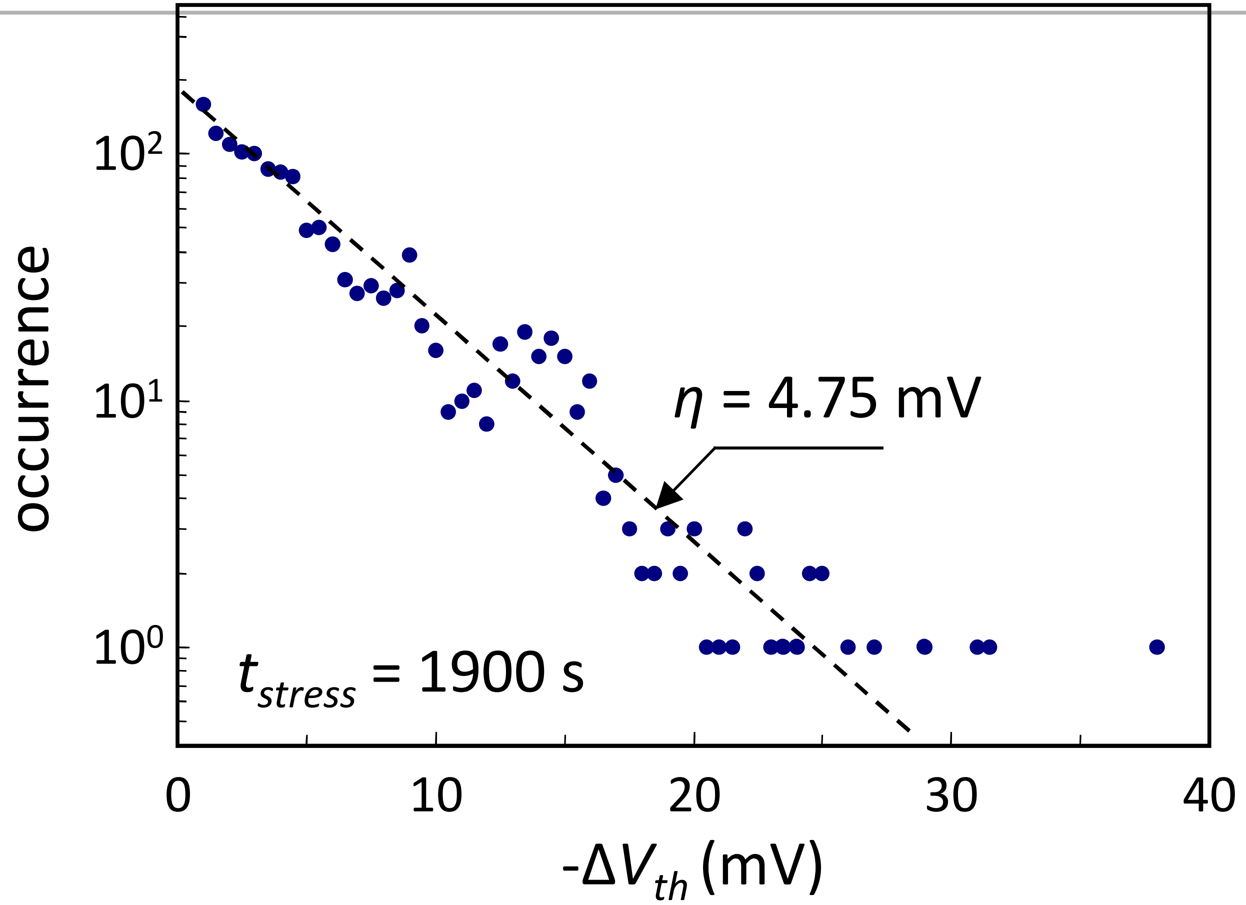


GRASSER, 2010

Time Constants and Tunneling



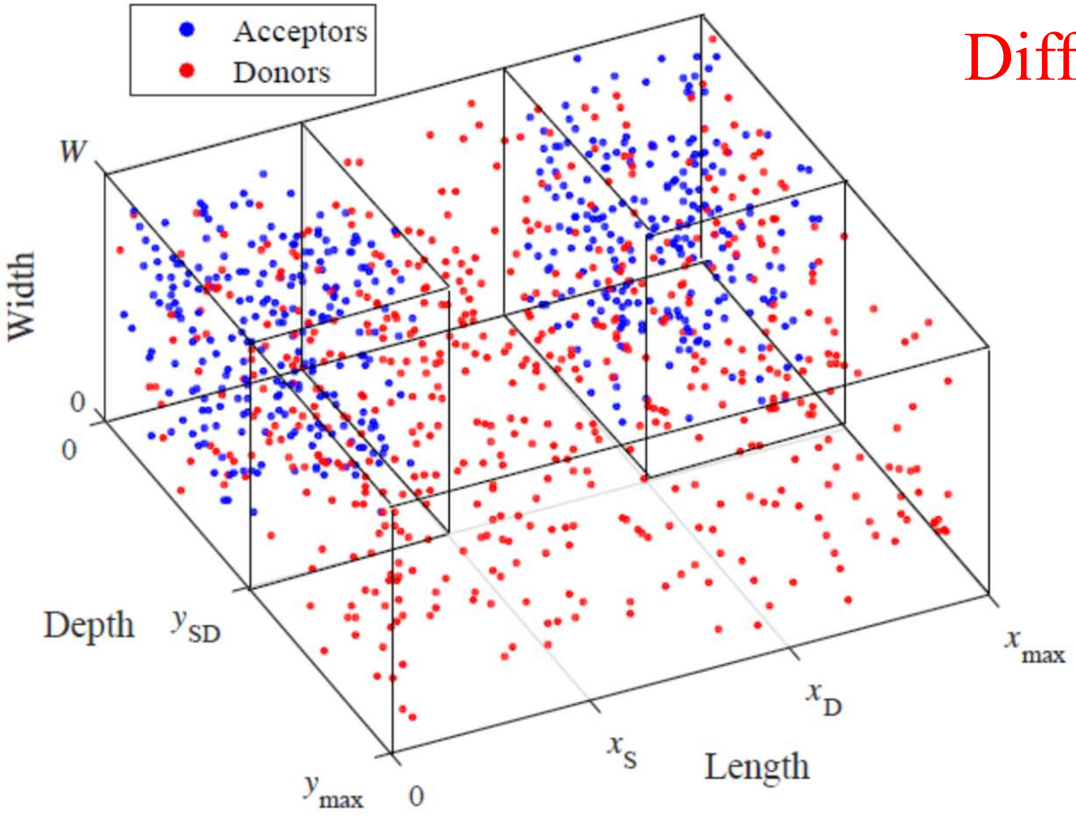
Trap Amplitude



NBTI step heights measured on 72 devices shows a clear exponential distribution. The average V_{th} shift η is 4.75±0.30 mV in the pFETs with metallurgic length L = 35 nm, width W = 90 nm, and HfO_2 dielectrics with EOT = 0.8 nm.

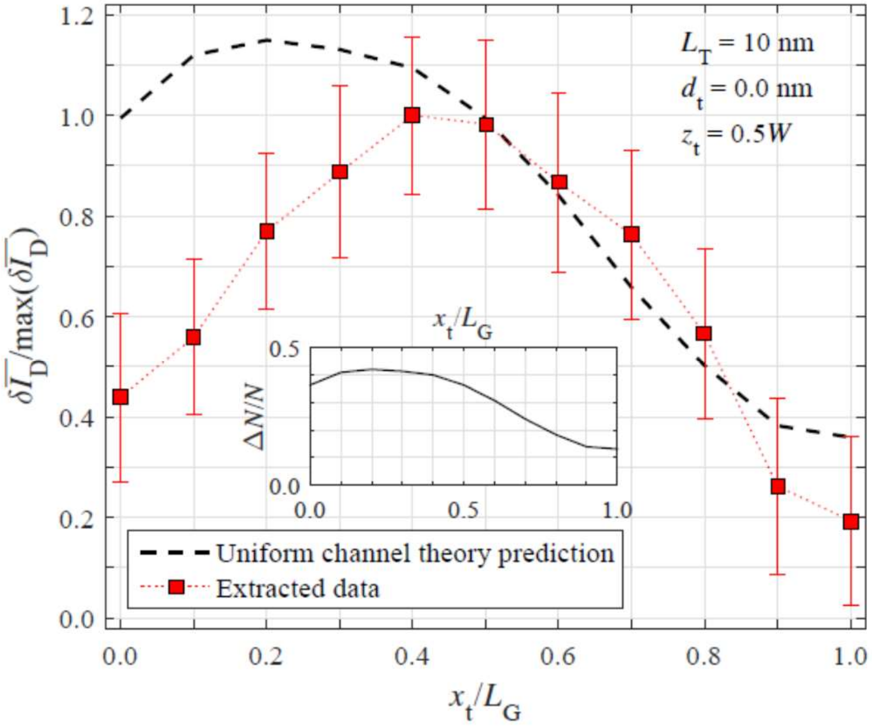
RDF: Random Dopant Fluctuations

In the **past** all transistors were similar because of *self averaging*

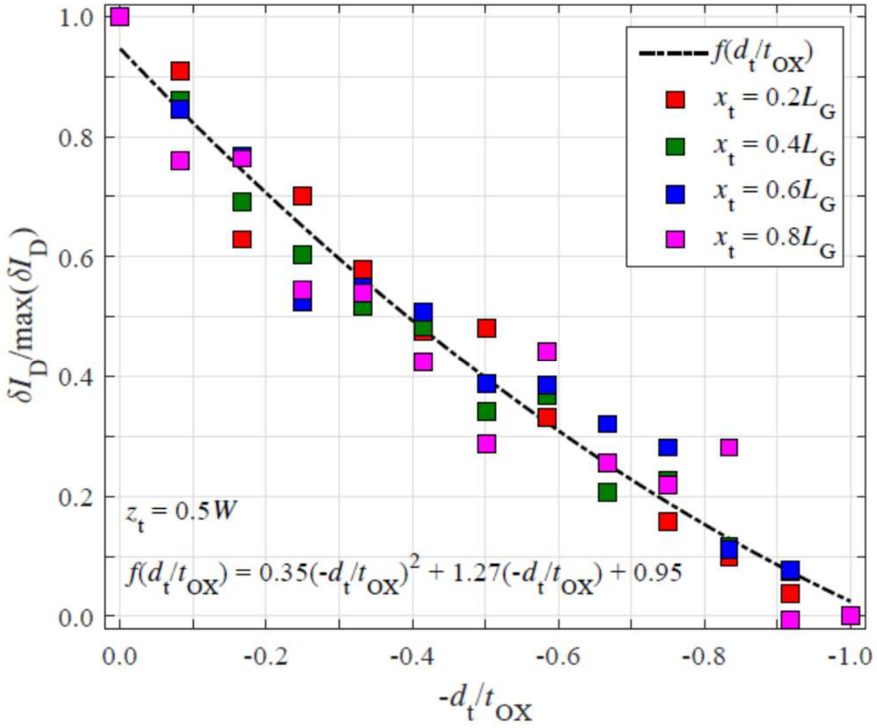


Today, Each Transistor is Different

Drain Current Fluctuations For Different RDF Configurations

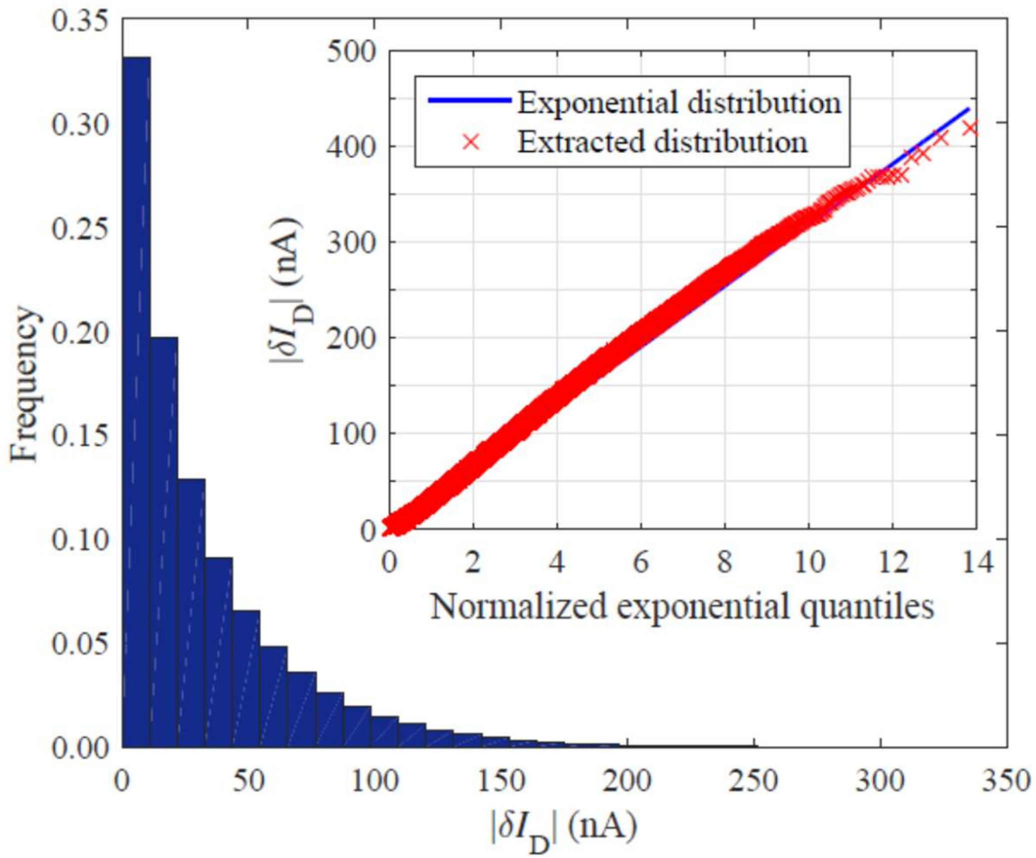


As a function of the trap position along the channel length



As a function of the trap depth into the oxide

Drain Current Fluctuations For Different RDF Configurations and Trap Positions



Different RDF, different trap position along the channel length (L), width (W) and different trap depth into the oxide: **Exponential Distribution**

Low-Frequency Noise

- **Frequency Domain Modeling (DC)**
  - **Noise due to a Single Trap**
  - **Noise due to the Ensemble of Traps**
- **AC Large Signal Excitation**

- **Time Domain (Transient) Analysis and Simulation**

Evaluating the Noise Power due to One Trap

- Poisson Process

$$p(0 \rightarrow 1)dt = \frac{dt}{\tau_c} \qquad \text{(capture)}$$

$$p(1 \rightarrow 0)dt = \frac{dt}{\tau_e} \qquad \text{(emittion)}$$

$$\text{average time in state 1} = \langle t \rangle_1 = \tau_c = \frac{1}{\tau_c}\int_0^\infty t \exp(-t/\tau_c)dt$$

$$\text{average time in state 0} = \langle t \rangle_0 = \tau_e = \frac{1}{\tau_e}\int_0^\infty t \exp(-t/\tau_e)dt$$

Evaluating the Noise Power due to One Trap

- The autocorrelation is given by

$$A(t) = \frac{\tau_e \tau_c}{(\tau_c + \tau_e)^2} + \left(\frac{\tau_c}{\tau_c + \tau_e}\right)^2 \exp\left[-\left(\frac{1}{\tau_e} + \frac{1}{\tau_c}\right)t\right]$$

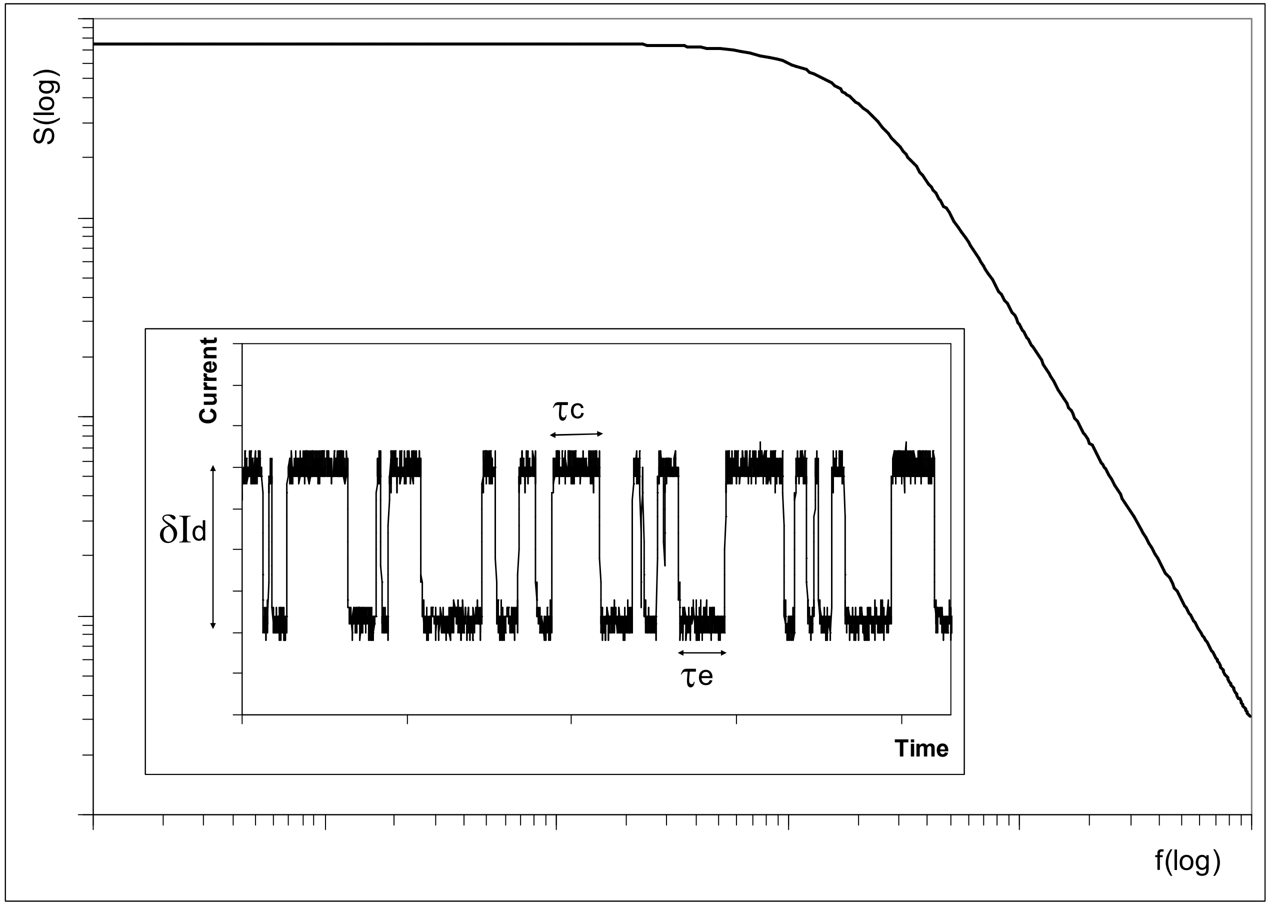
- And the power spectrum density (Fourier Transform) is a Lorentzian

$$S(\omega) = \frac{\delta^2}{(\tau_c + \tau_e)} \frac{1}{\left(\frac{1}{\tau_c} + \frac{1}{\tau_e}\right)^2 + \omega^2}$$

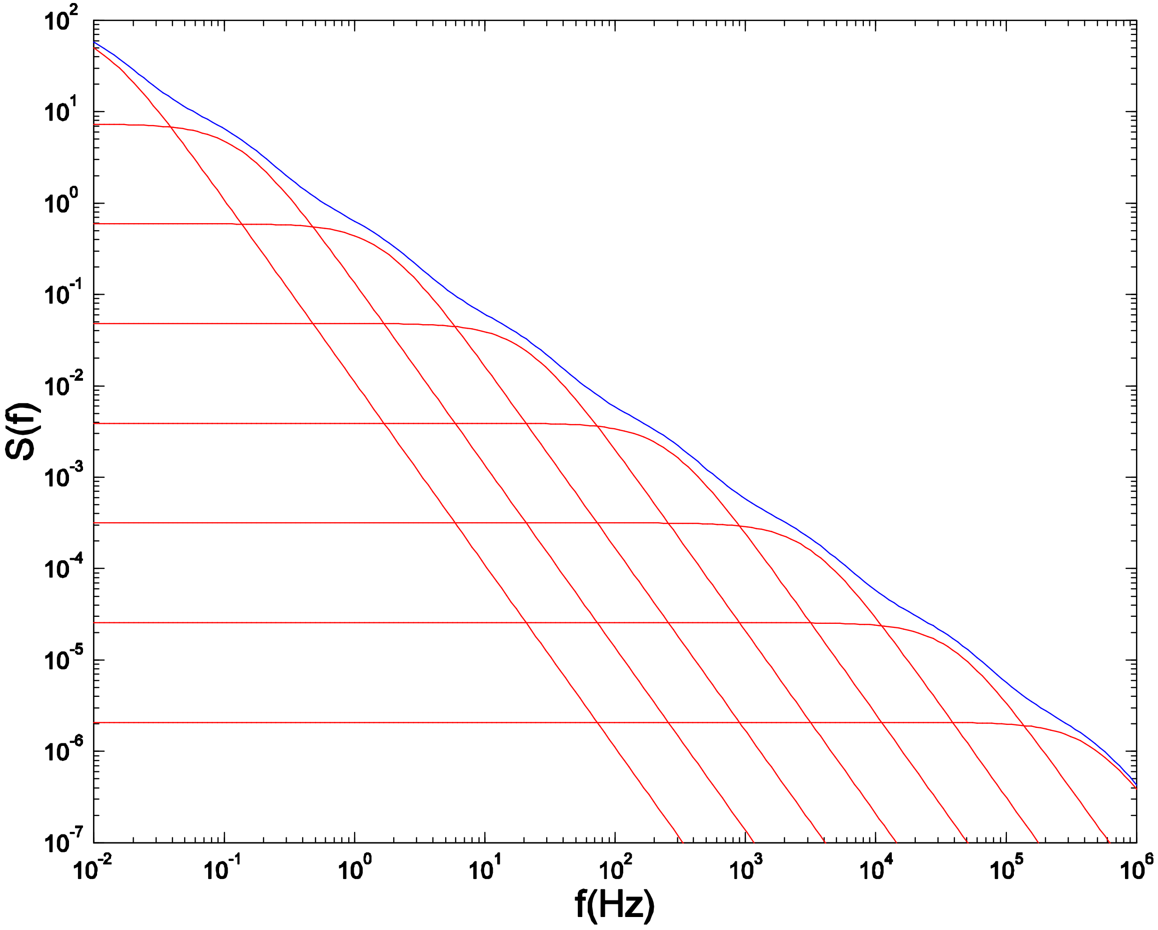
+ Singular term

It is not important

RTN: Random Telegraph Noise



Evaluating the Noise Power due to Many Traps



$$S(f) = \sum_{i=1}^{N_{tr}} A_i^2 \, \frac{1}{f_i} \, \frac{1}{1+\left(\frac{f}{f_i}\right)^2}$$

Evaluating the Noise Power due to **Many** Traps

- Superposition of Lorentzians

$$S(f,\omega_1,\ldots,\omega_{N_{tr}},A_1,\ldots,A_{N_{tr}}) = \sum_{i=1}^{N_{tr}} S_i(\omega) = \sum_{i=1}^{N_{tr}} A_i^2 \frac{1}{\omega_i}\frac{1}{1+\left(\frac{\omega}{\omega_i}\right)^2}$$

- Averaging on many variability sources

$$\langle S\rangle = \underbrace{\ln^{-1}\left(\frac{\omega_{\max}}{\omega_{\min}}\right)}_{\text{normalization}} \underbrace{\sum_{N_{tr}=0}^{\infty}\frac{N^{N_{tr}}e^{-N}}{N_{tr}!}}_{\substack{\text{number of traps per} \\ \text{sample is Poisson distributed}}} \sum_{i=1}^{N_{tr}}\langle A_i^2\rangle \underbrace{\int_{\omega_{\min}}^{\omega_{\max}} \frac{1}{\omega_i^2}\frac{1}{1+\left(\frac{\omega}{\omega_i}\right)^2}\,df_i}_{\substack{p(\tau_i)\ \propto\ \tau_i^{-1} \\ \Rightarrow \\ p(\omega_i)=\ln^{-1}\left(\frac{\omega_{\max}}{\omega_{\min}}\right)\omega_i^{-1}}}$$

Evaluating the Noise Power due to Many Traps

- Average Value

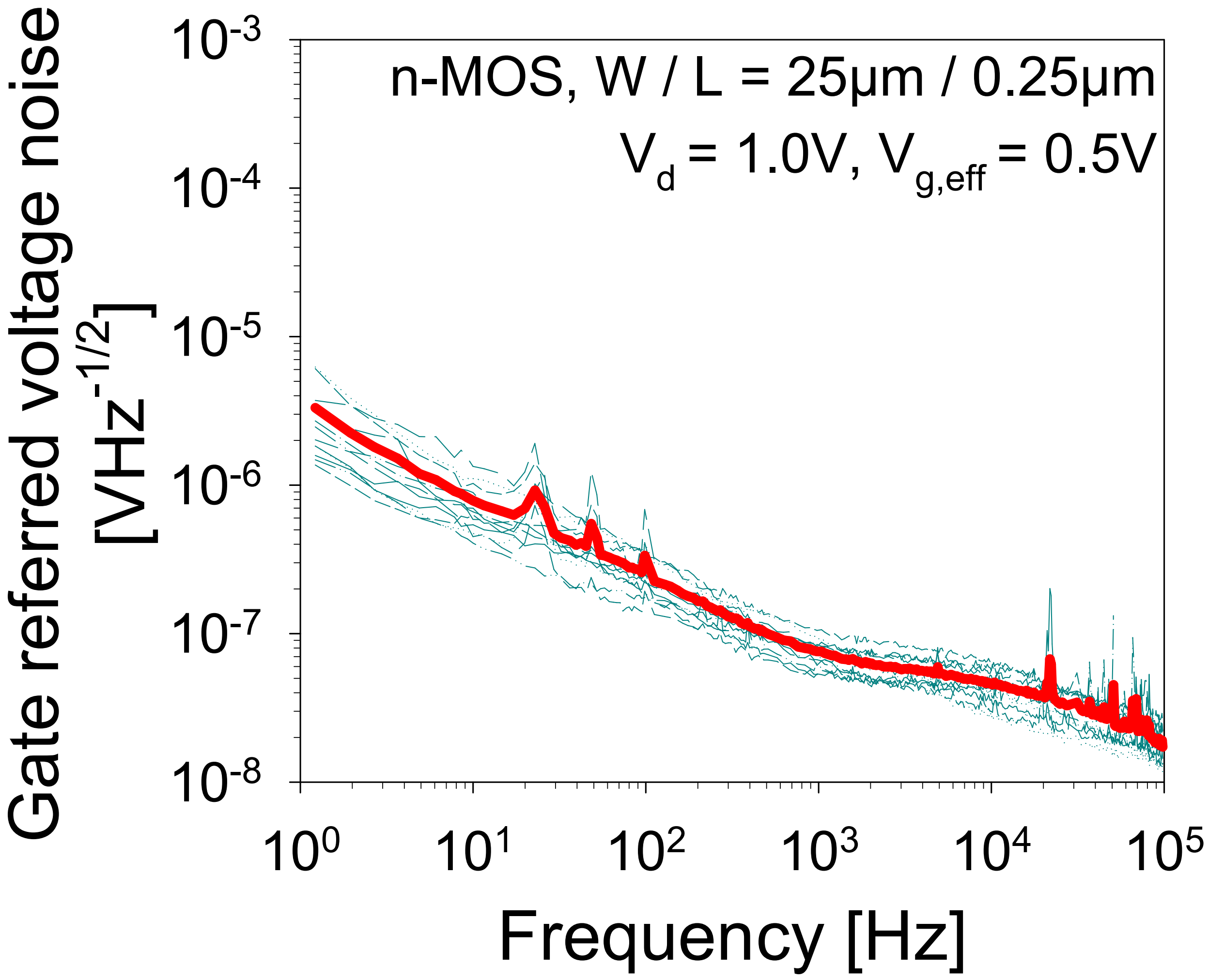
$$< S(f) > = \frac{<A^2> N_{dec} WL}{f} \frac{\pi}{2}$$

- Standard Deviation

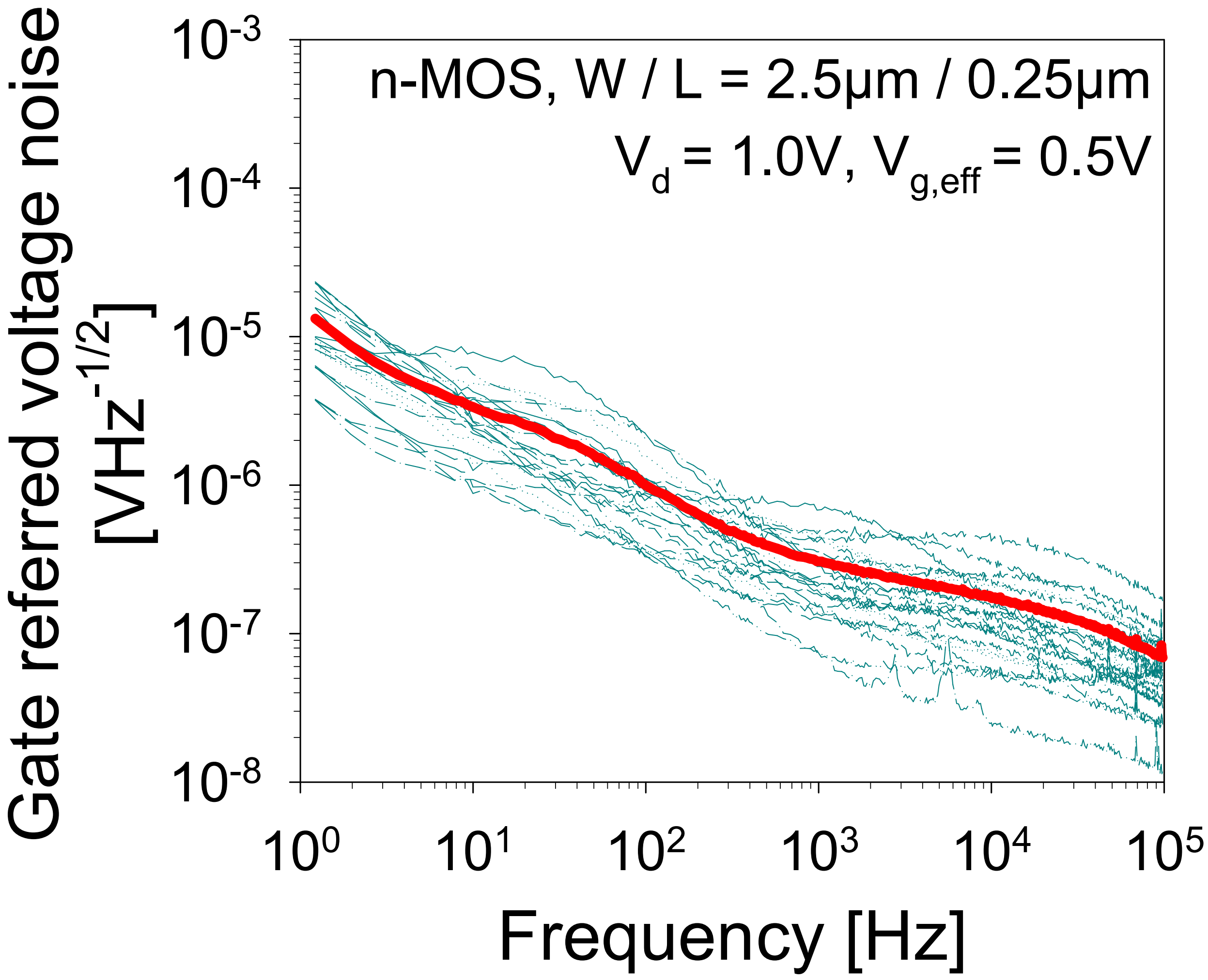
$$\frac{\sigma_{S(f)}}{< S(f) >} = \frac{\sqrt{2}}{\pi \sqrt{N_{dec} WL}} \sqrt{\frac{<A^4>}{<A^2>^2}}$$

G Wirth et al. IEEE Trans Electron Dev, 2005

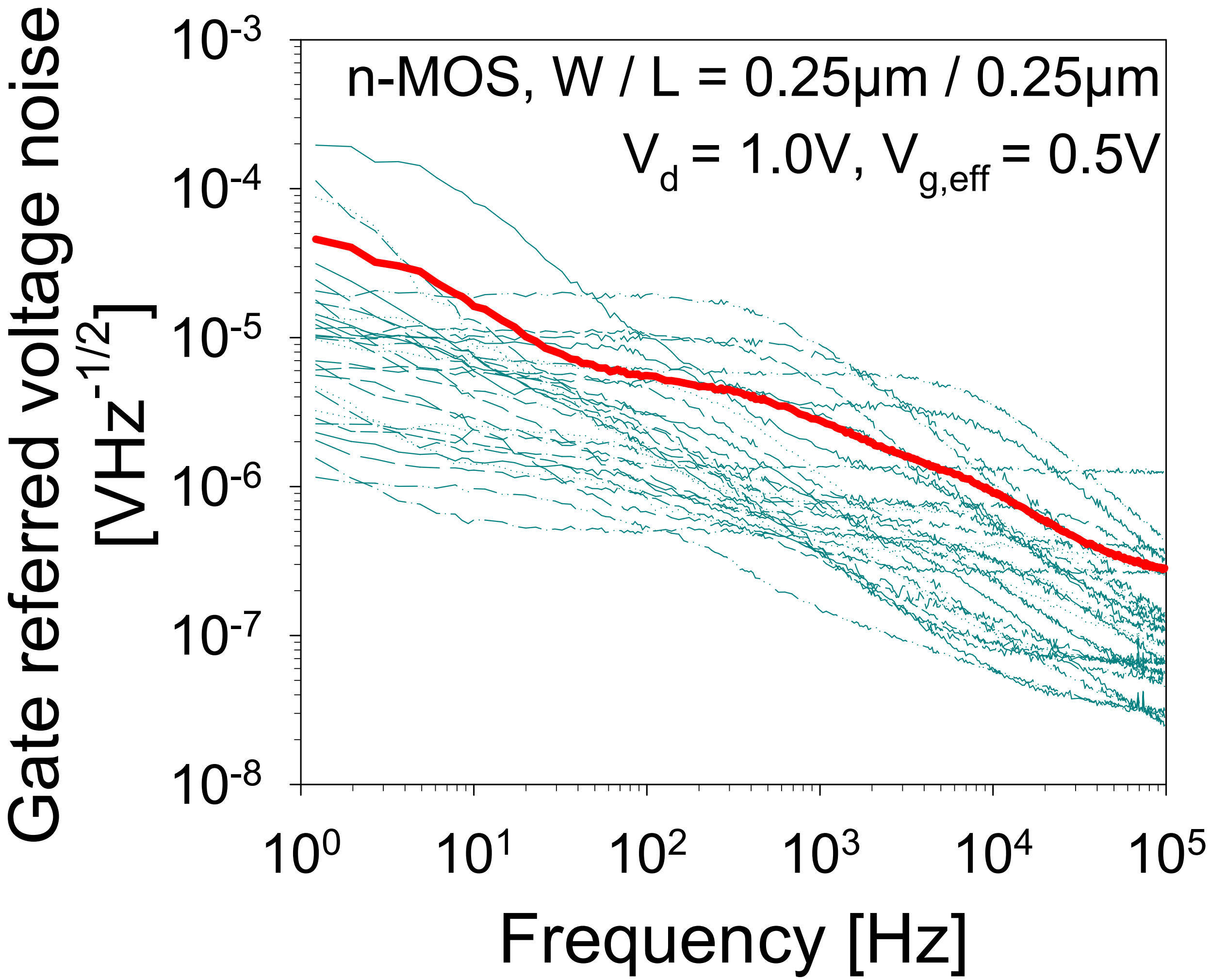
Average Value and Variability



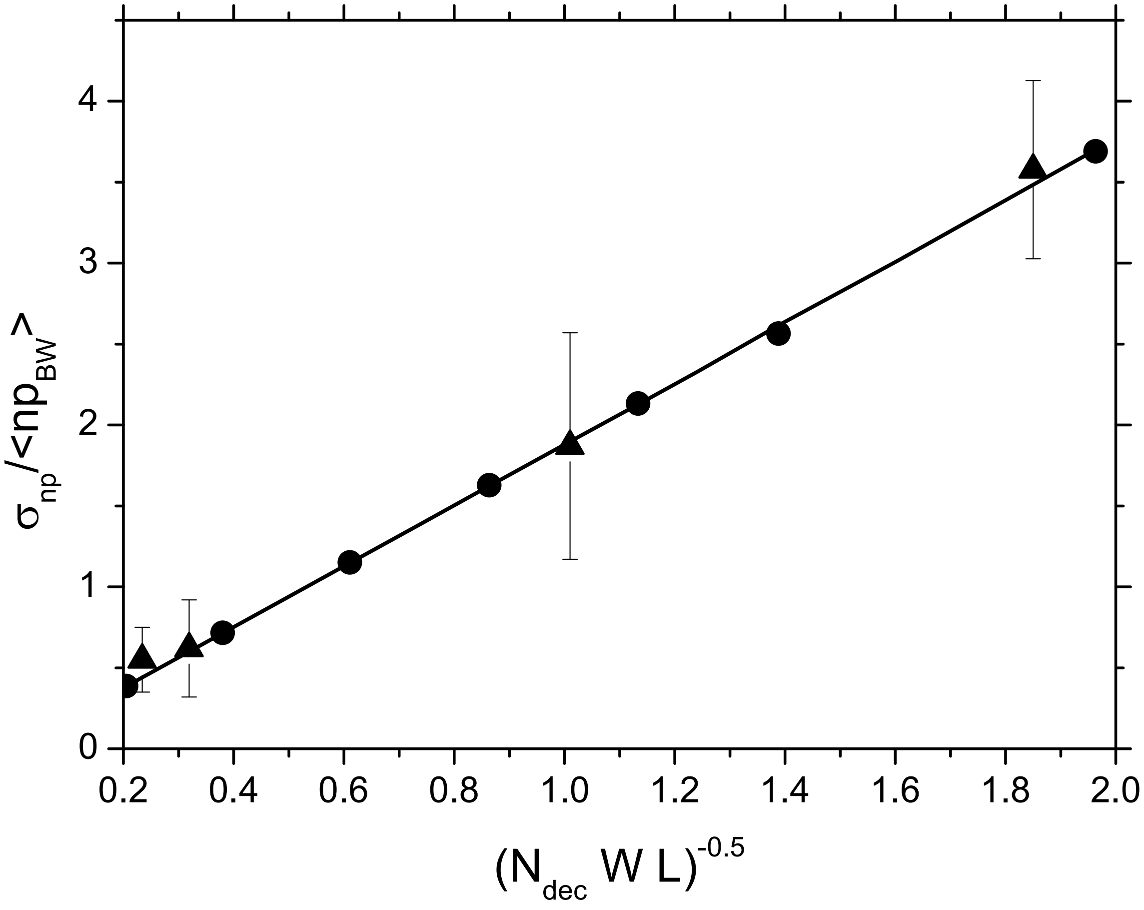
Average Value and Variability



Average Value and Variability

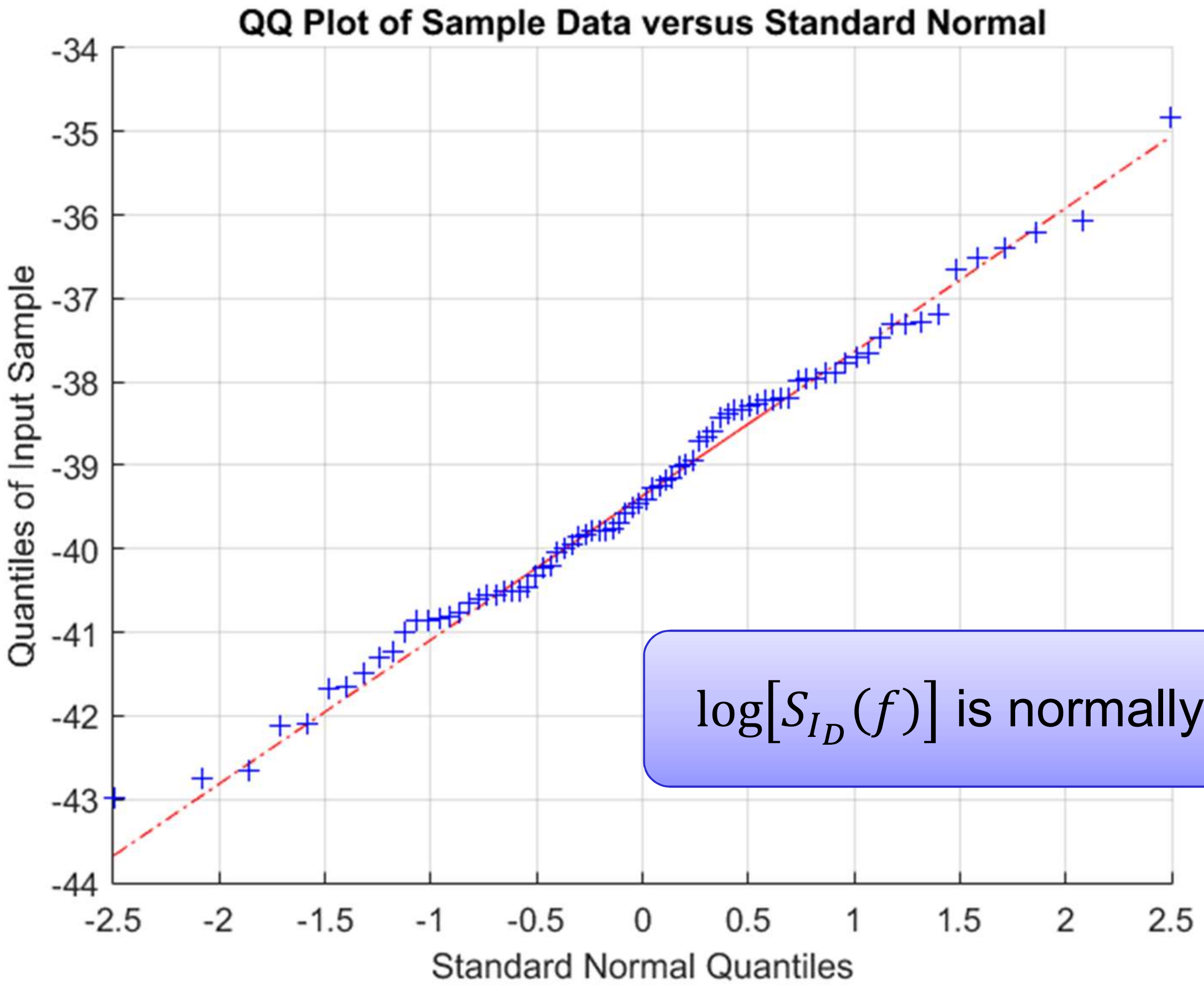


Variability Scaling



Triangles: Measurement
Dots: Monte Carlo Simulation
Line: Model

How to statistically describe the noise?

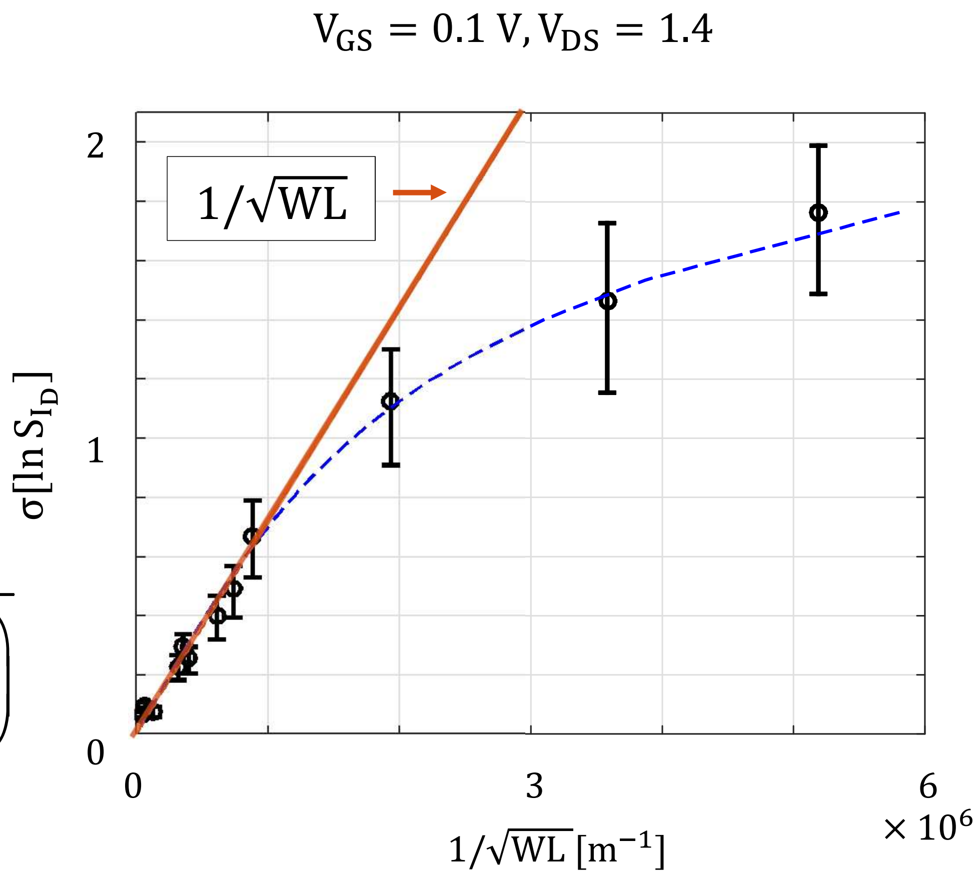


$\log\left[S_{I_D}(f)\right]$ is normally distributed!

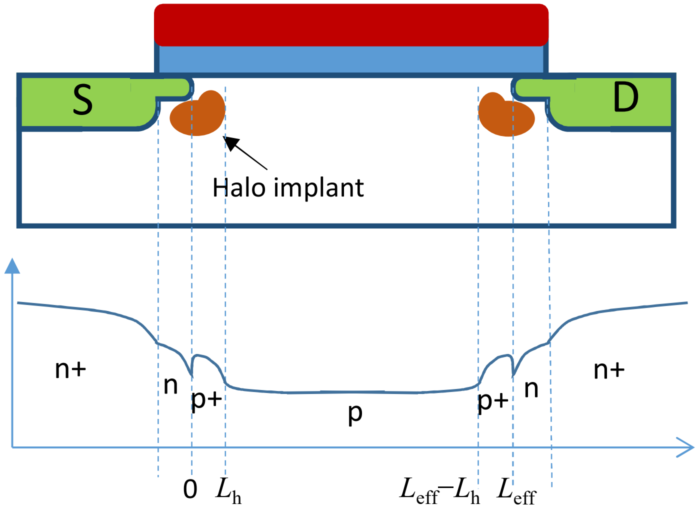
How to statistically describe the noise?

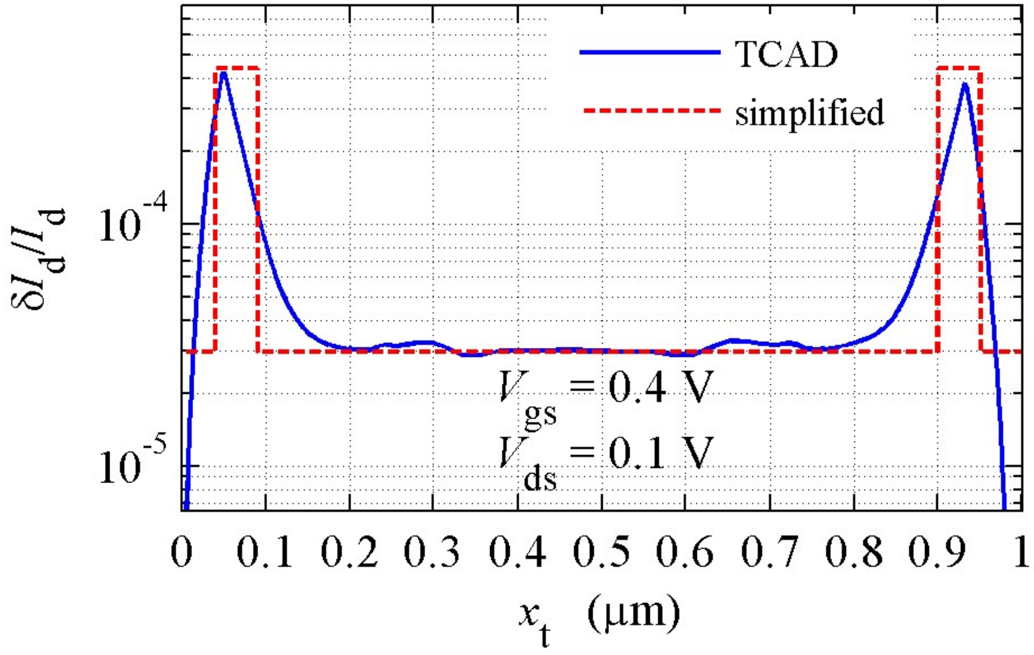
- $\sigma[\ln S_{Id}]$ should not and does not follow a $\frac{1}{\sqrt{WL}}$ dependence.

$$\sigma\left[\ln\left(S_{Id}(f)\right)\right]=\sqrt{\ln\left(1+\frac{K}{WL}\right)}$$

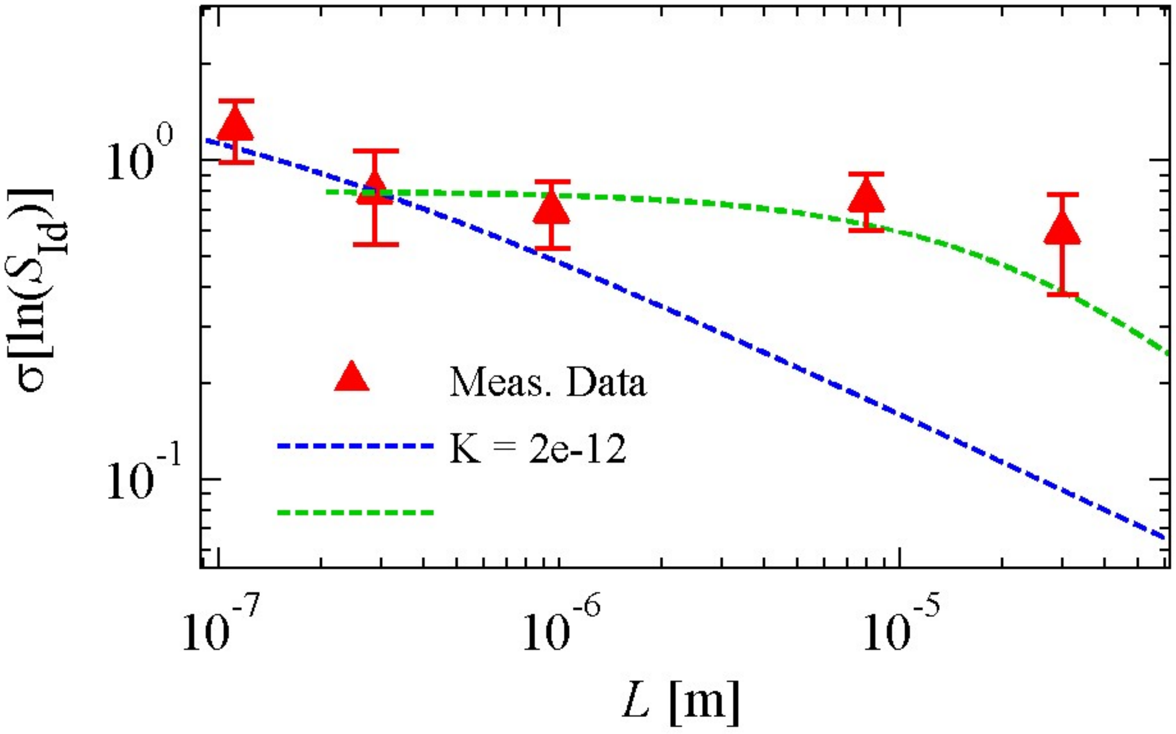


Dependence of I_D Fluctuations on Trap Position. Conventional TCAD, Halo, Long Dev.



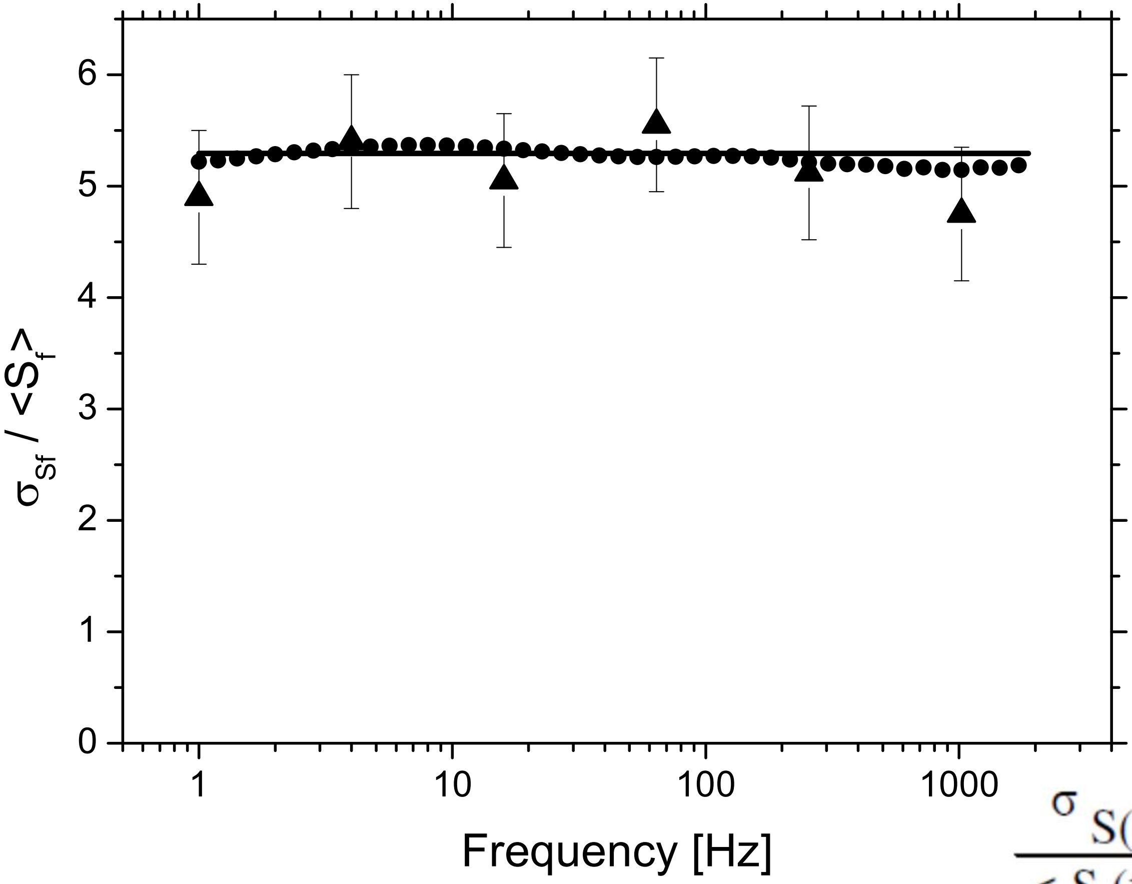


Dependence of I_D Fluctuations on Trap Position. Conventional TCAD, Halo, Long Dev.



$V_{gs} = 0.5$ V and $V_{ds} = 0.1$ V

Variability: Dependency on Frequency



$$\frac{\sigma_{S(f)}}{<S(f)>} = \frac{\sqrt{2}}{\pi\sqrt{N_{dec}WL}}\sqrt{\frac{<A^4>}{<A^2>^2}}$$

Low-Frequency Noise

- Frequency Domain Modeling (DC)
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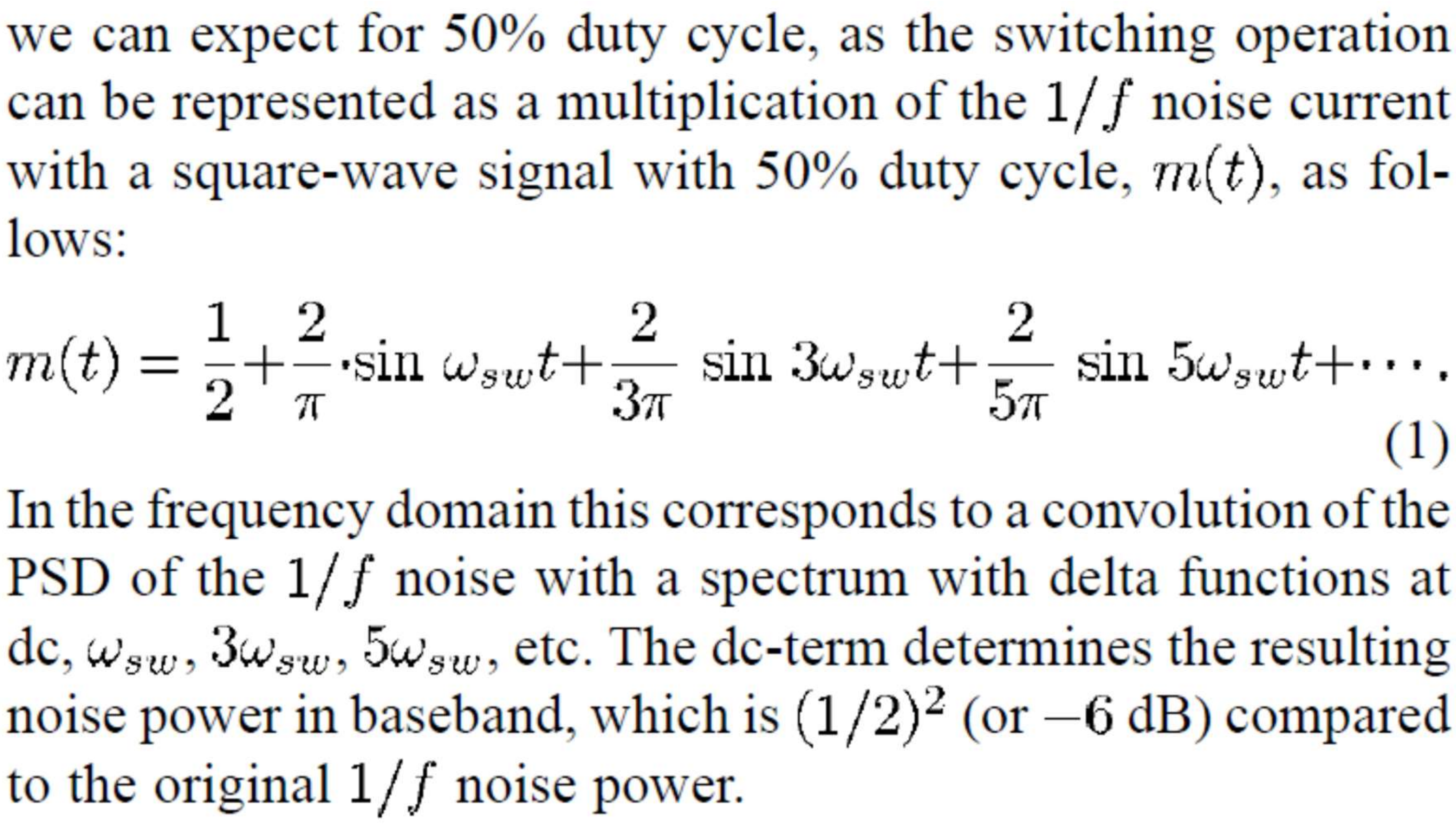
Switched Bias: Modulaton Theory



we can expect for 50% duty cycle, as the switching operation can be represented as a multiplication of the $1/f$ noise current with a square-wave signal with 50% duty cycle, $m(t)$, as follows:

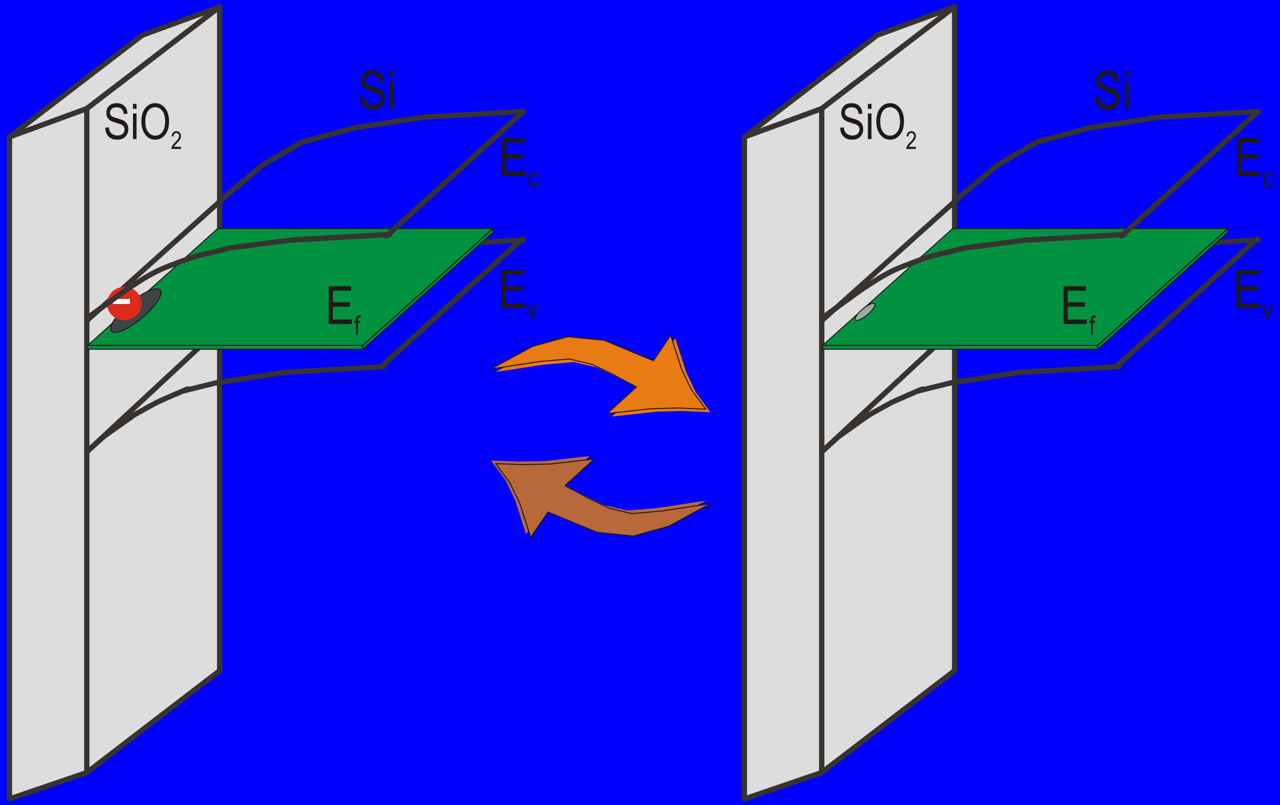
$$m(t) = \frac{1}{2} + \frac{2}{\pi} \cdot \sin \omega_{sw} t + \frac{2}{3\pi} \sin 3\omega_{sw} t + \frac{2}{5\pi} \sin 5\omega_{sw} t + \cdots . \quad (1)$$

In the frequency domain this corresponds to a convolution of the PSD of the $1/f$ noise with a spectrum with delta functions at dc, ω_{sw}, $3\omega_{sw}$, $5\omega_{sw}$, etc. The dc-term determines the resulting noise power in baseband, which is $(1/2)^2$ (or -6 dB) compared to the original $1/f$ noise power.

Klumperink et al., IEEE J. SOLID-STATE CIRC, VOL. 35, NO. 7, 2000

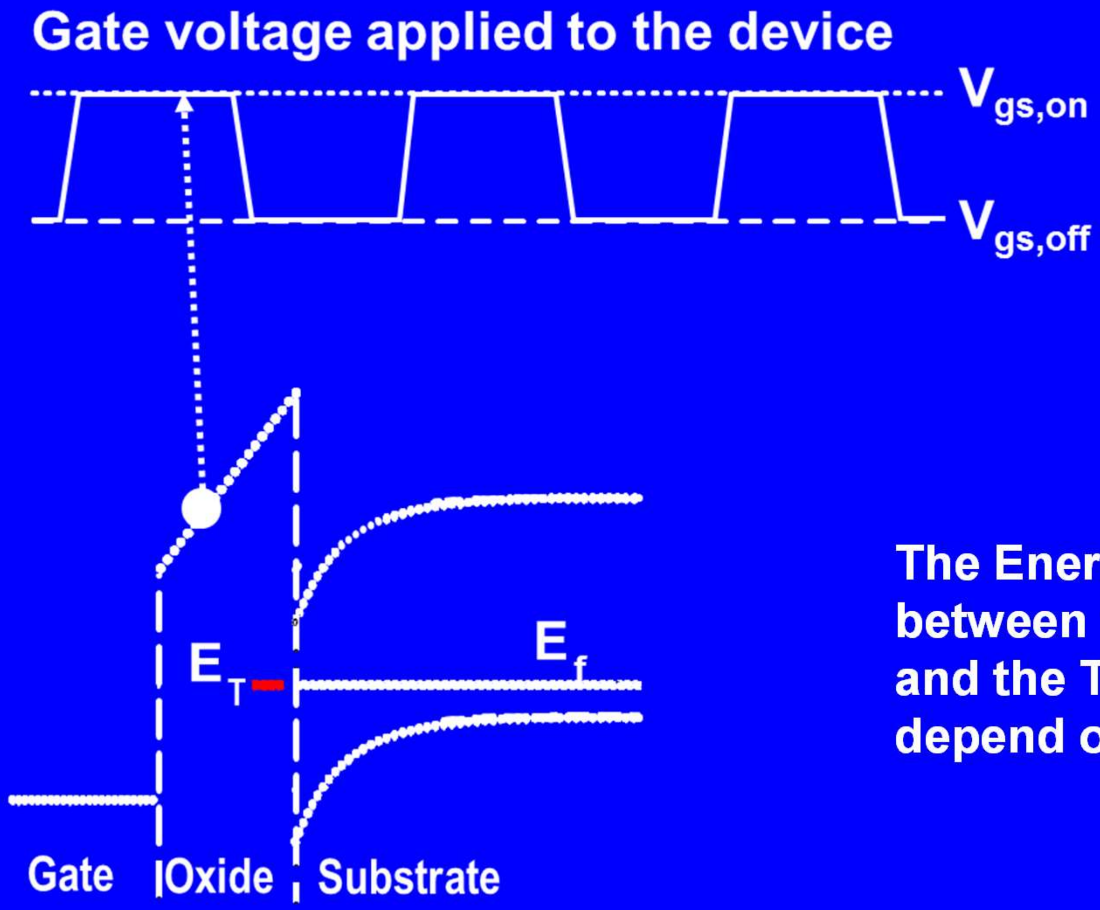
Noise Produced by Interface States

- LF-noise of MOSFETs is generated by trap-states at the Si/SiO$_2$ interface which are randomly charged and discharged in time



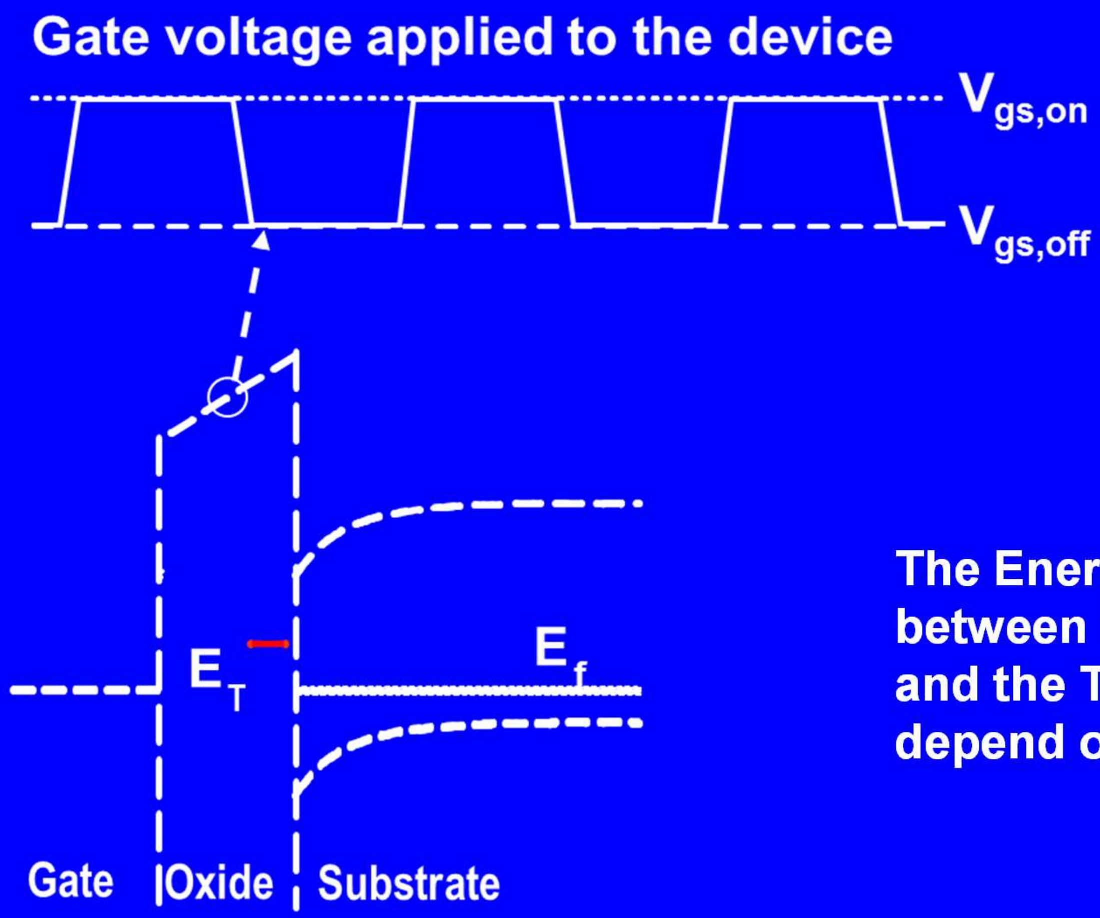
- This leads to modulation of both local mobility and number of free carriers in the channel
- Probability of a trap state to switch its occupation level depends on the energetic position of the local Fermi level

Trap State and Fermi Level at $V_{gs,on}$



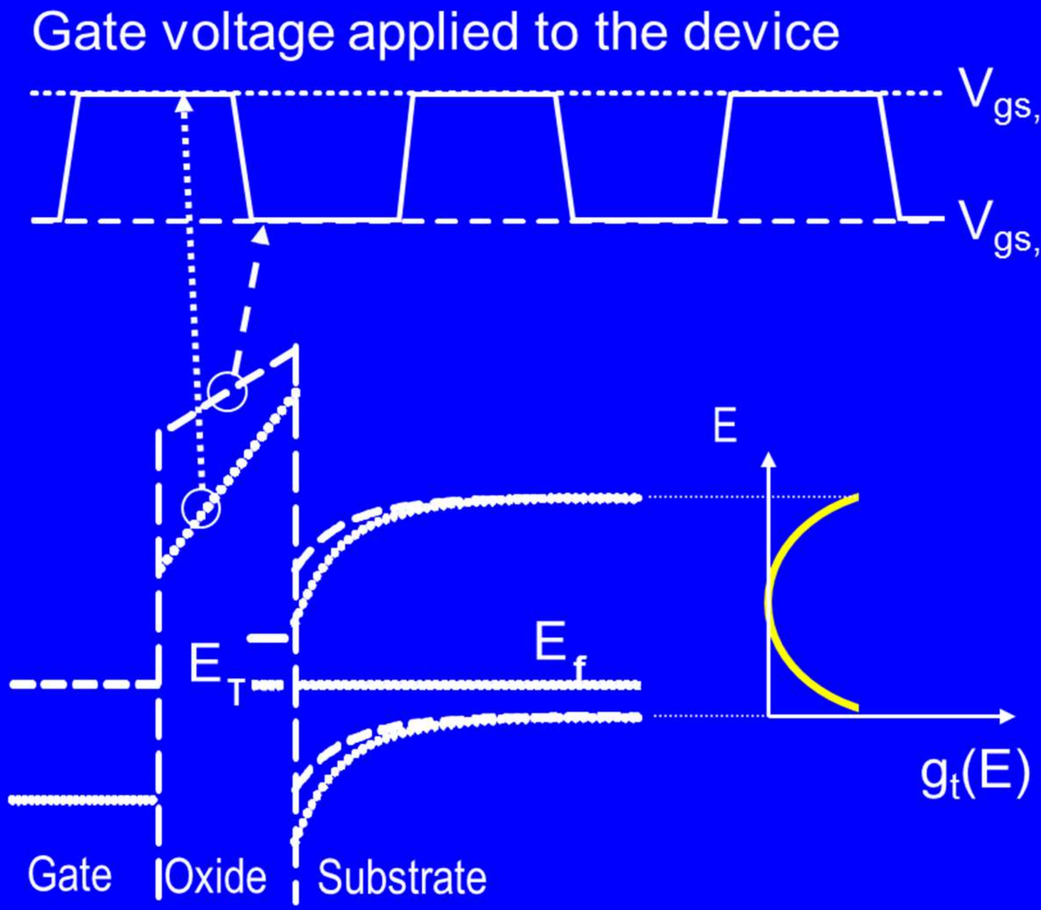
The Energy difference between the Fermi Level and the Trap Level depend on bias (time)

Trap State and Fermi Level at $V_{gs,off}$



The Energy difference between the Fermi Level and the Trap Level depend on bias (time)

Trap State at Switched Bias Operation



Noise Spectra for a Single Trap under Cyclo-Stationary Excitation

$$S_i = \frac{\delta_i^2}{\pi} \cdot \frac{\beta_{eq}}{(1+\beta_{eq})^2} \cdot \frac{1}{\omega_i} \cdot \frac{1}{1+(\omega/\omega_i)^2}$$

where

$\beta_{eq} = \langle 1/\tau_e \rangle / \langle 1/\tau_c \rangle$, **with** $\langle \bullet \rangle = (1/T) \int_0^T \bullet \, dt$

$\omega_i = \langle 1/\tau_e \rangle + \langle 1/\tau_c \rangle$

For Switching Frequency >> ω_i

Noise Spectra for a Single Trap under Square Wave Excitation

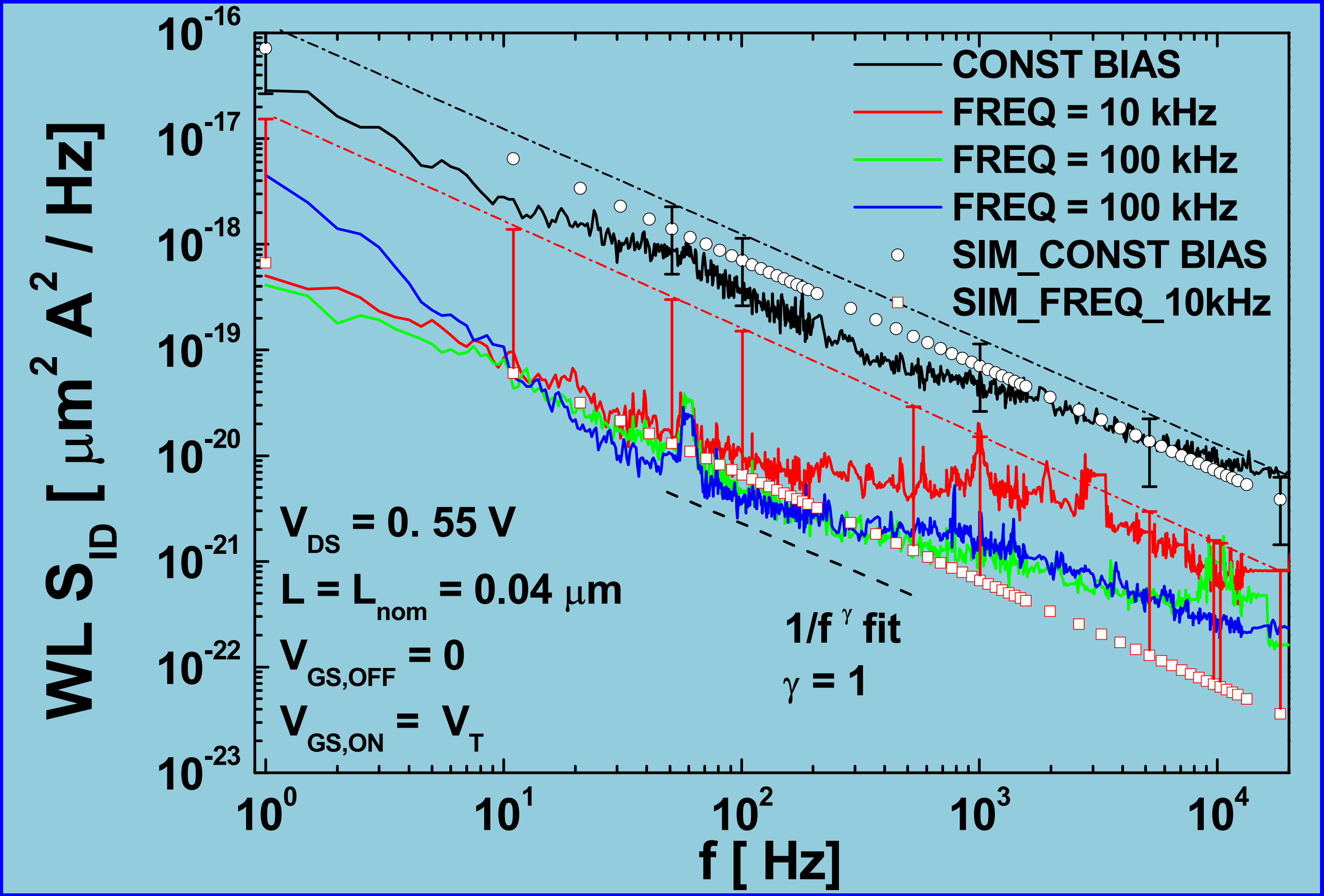
$$<1/\tau_c> = (\alpha/\tau_{c,on} + (1\text{-}\alpha)/\tau_{c,off})$$

$$<1/\tau_e>=(\alpha/\tau_{e,on} + (1\text{-}\alpha)/\tau_{e,off})$$

$$\beta_{eq} = \psi(E_{on}, E_{off}, \alpha)e^{2E_t/k_BT}$$

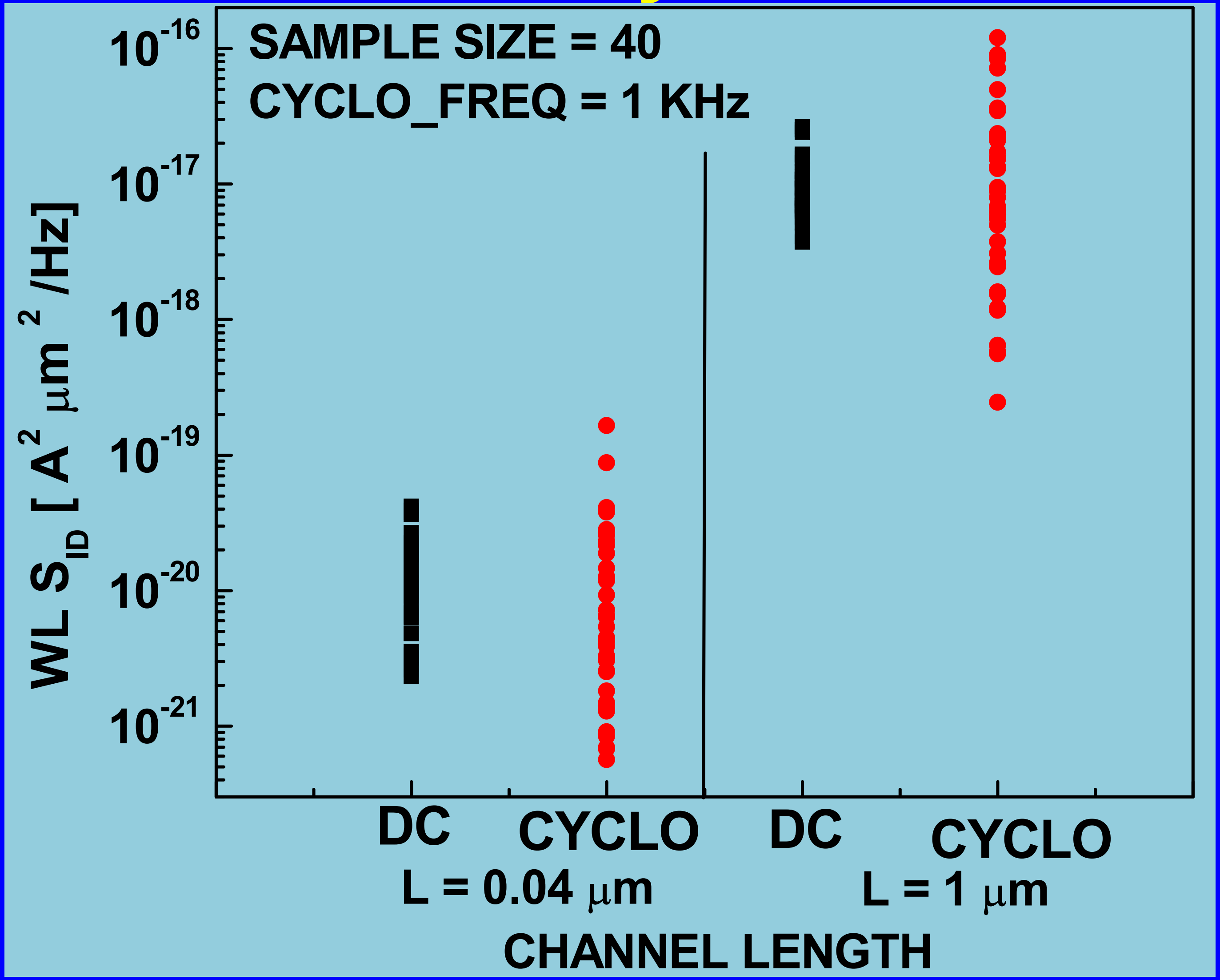
$$\psi(E_{on}, E_{off}, \alpha) = \frac{\alpha e^{-E_{on}/k_BT} + (1-\alpha)e^{-E_{off}/k_BT}}{\alpha e^{E_{on}/k_BT} + (1-\alpha)e^{E_{off}/k_BT}}$$

Noise Reduction under Cyclo-Operation



- Modulation theory predicts four times noise reduction for CS operation
- Noise reduction is larger and in good agreement to the proposed model.

Normalized Variability of Noise Behavior



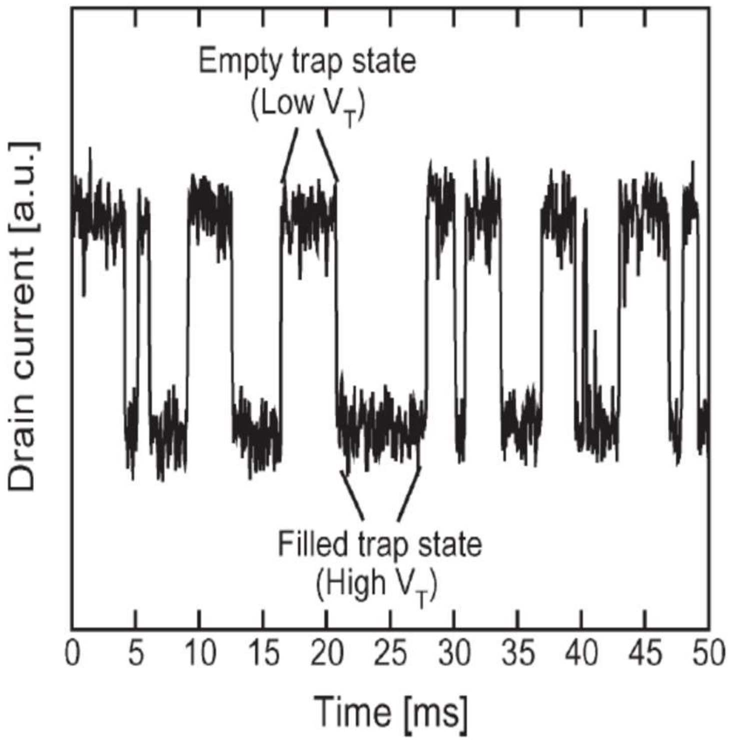
Variability is seen to increase under Cyclo-Stationary Operation.

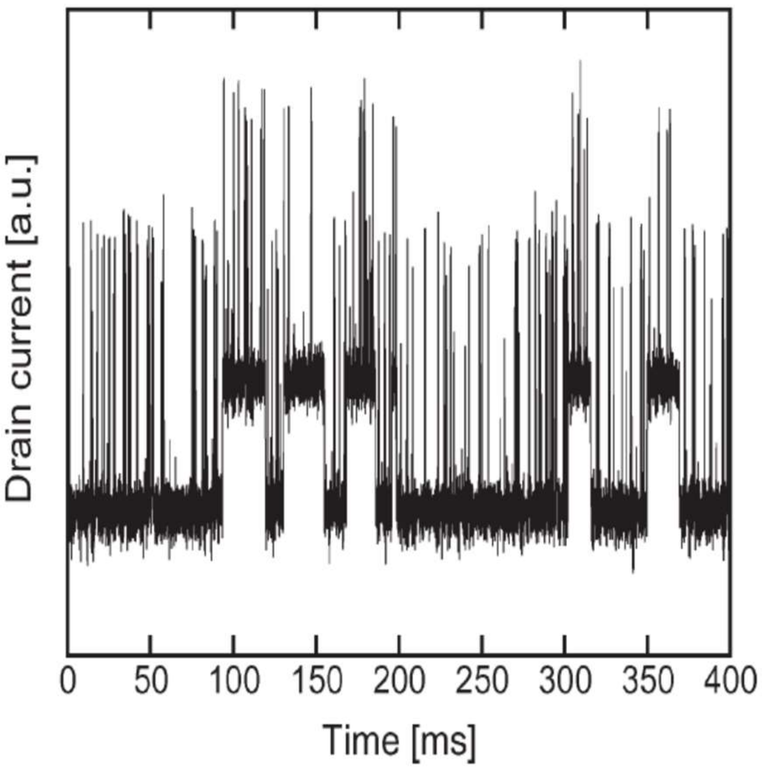
Low-Frequency Noise

- Frequency Domain Modeling (DC)
  - Noise due to a Single Trap
  - Noise due to the Ensemble of Traps
- AC Large Signal Excitation

- Time Domain (Transient) Analysis and Simulation

RTN and Time Domain

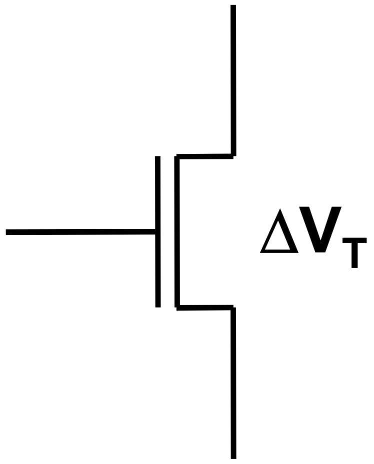




V_T Fluctuations

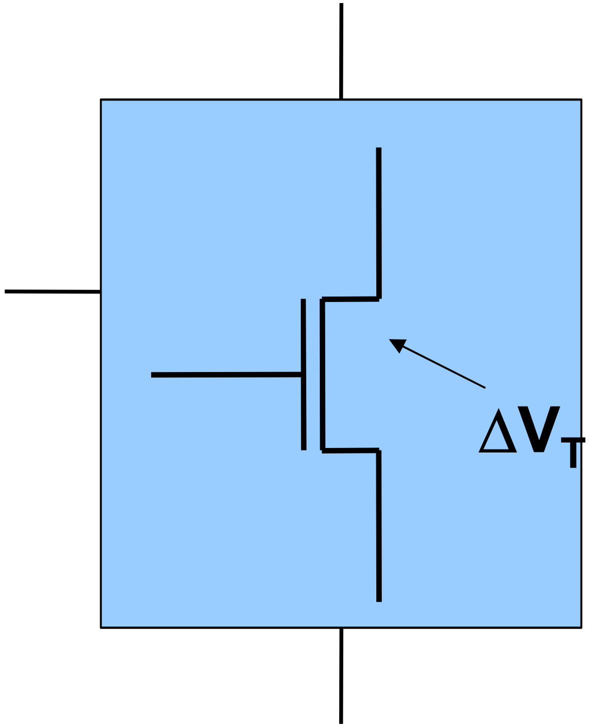
Possible Simulation Methodologies

Static

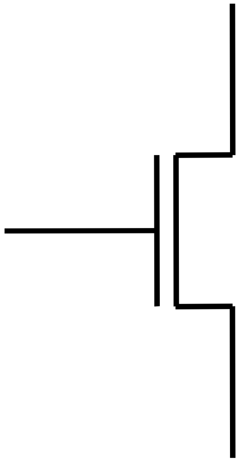


Change dVt at instantiation

Dynamic



Verilog-A wrapper to Trans. model



Ids = … + f(delvto(t))

Change transistor Model equations

RTN: Transient Simulation (1)

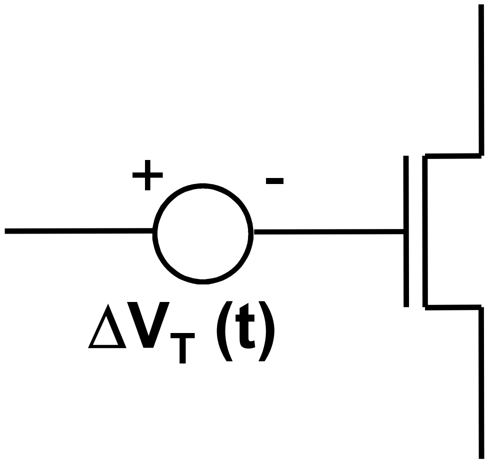
- Charge trapping and de-trapping are stochastic events, governed by capture and emission time constants, τ_c and τ_e, which are uniformly distributed on a log-scale;
- the number of traps (N_{tr}) is assumed to be Poisson distributed, and the average number of traps (parameter of the Poisson) is assumed to be proportional to the channel area;
- trap energy distribution, $g(E_T)$, is assumed to be U-shaped;
- the amplitude of the V_T fluctuation induced by a single trap, is a random variable given by atomistic device simulations.

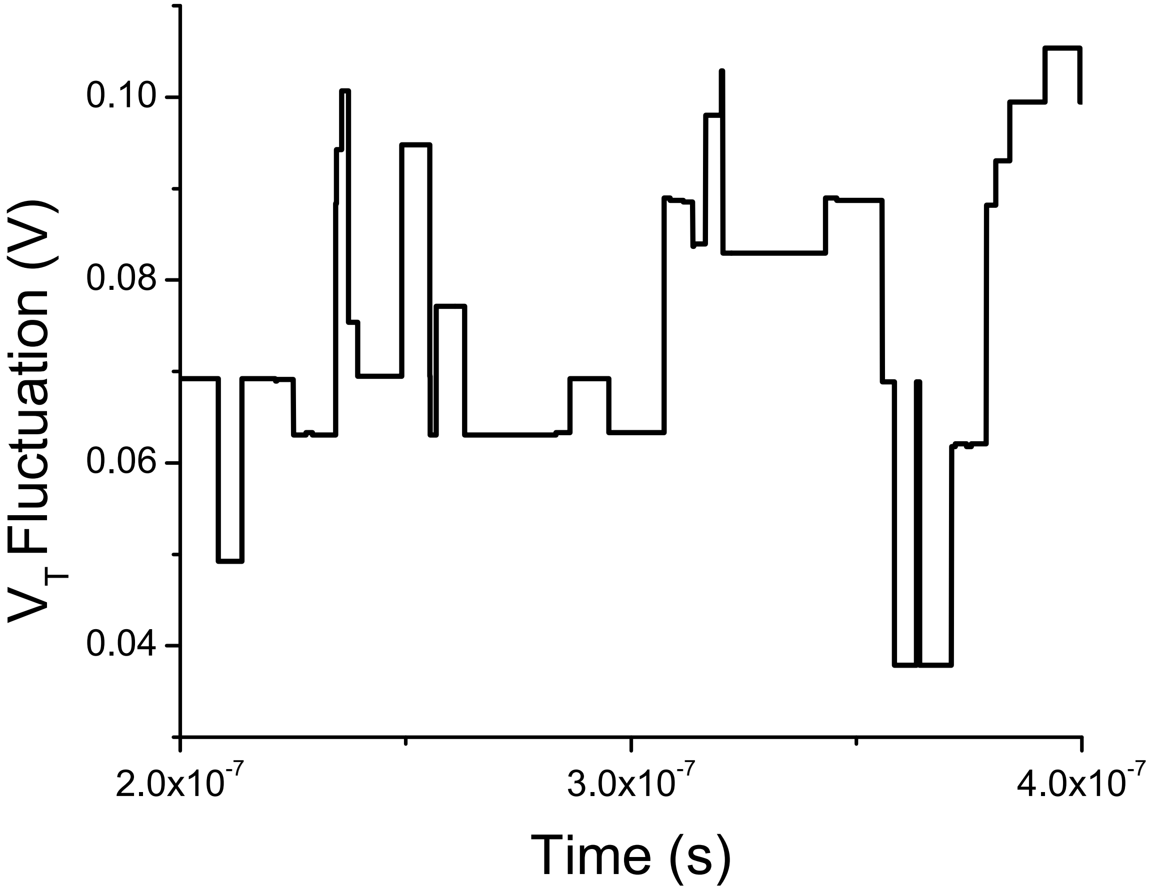
RTN: Transient Simulation (2)

- At each simulation time step, it is checked if a trap changes state.
- Trap switching probability is evaluated based on the device bias point at each transient simulation step.
- If one or more trap change state, transistor threshold voltage is changed accordingly.

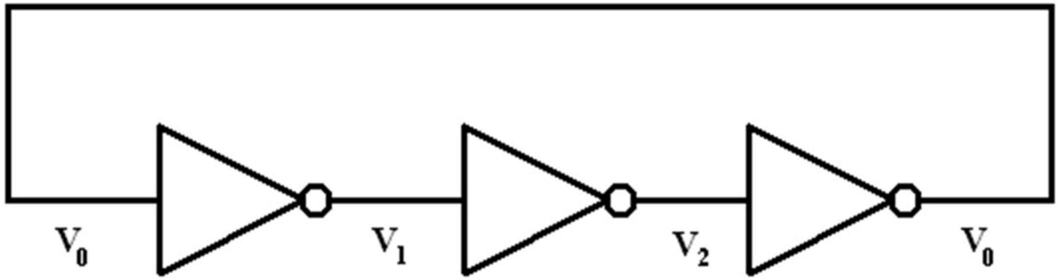
- **Simulators do not support this kind of simulation:**
  - ngspice and BSIM4 code modified.

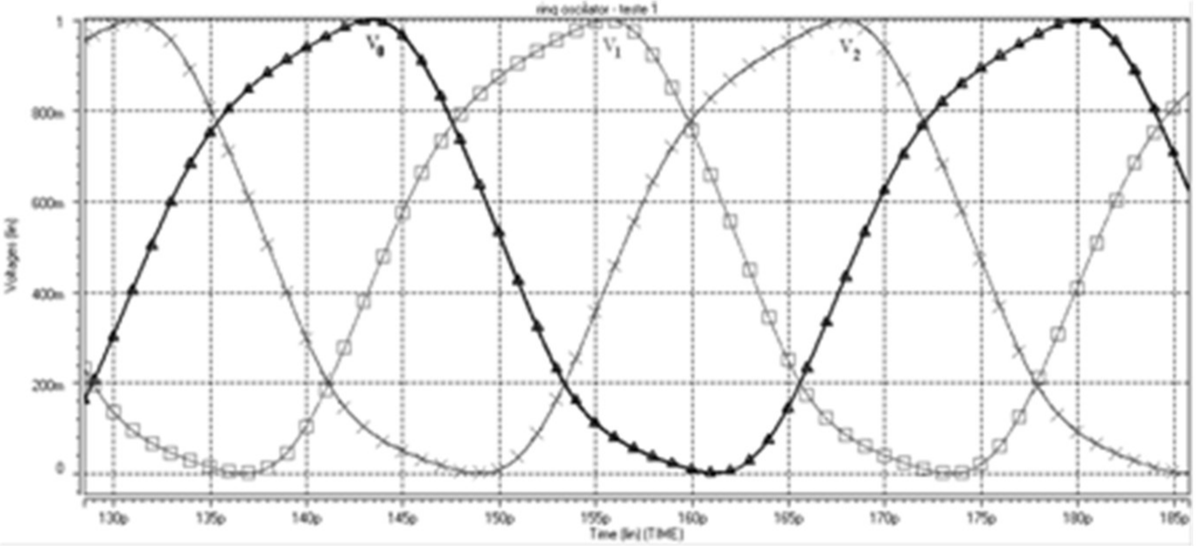
V_T Fluctuates Over Time





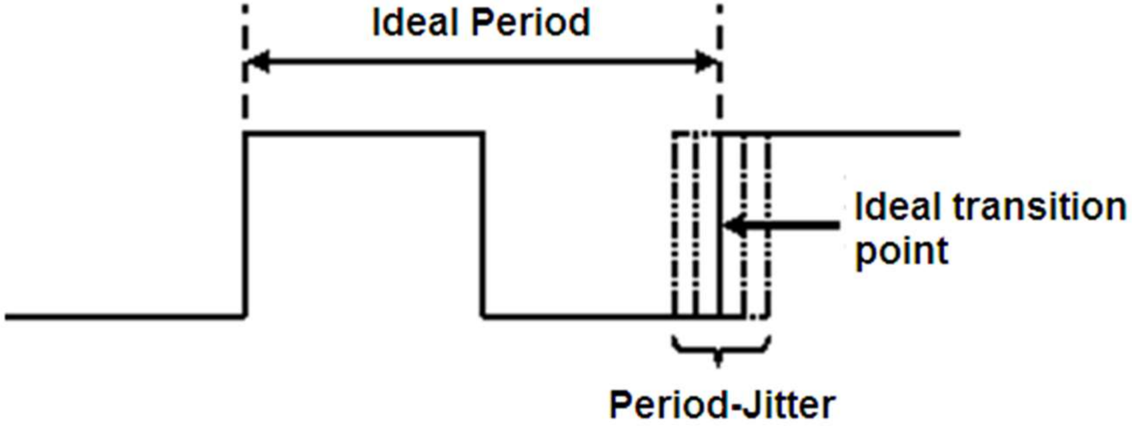
Transient Simulation of Ring Oscillators



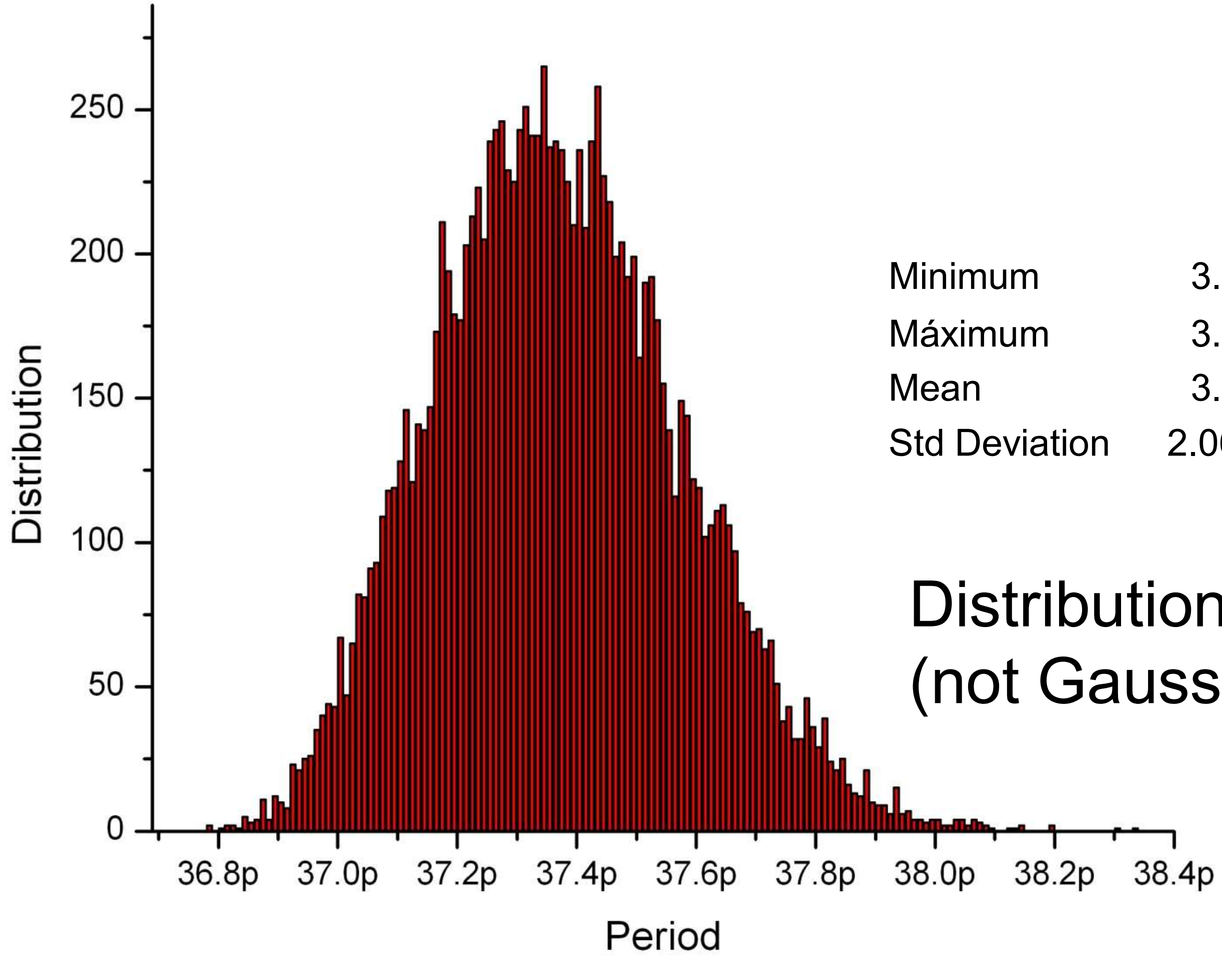


Period Jitter

- **Period Jitter**
  - Period Jitter is the difference between a clock period and the ideal clock period (it can occur after or before the ideal transition).



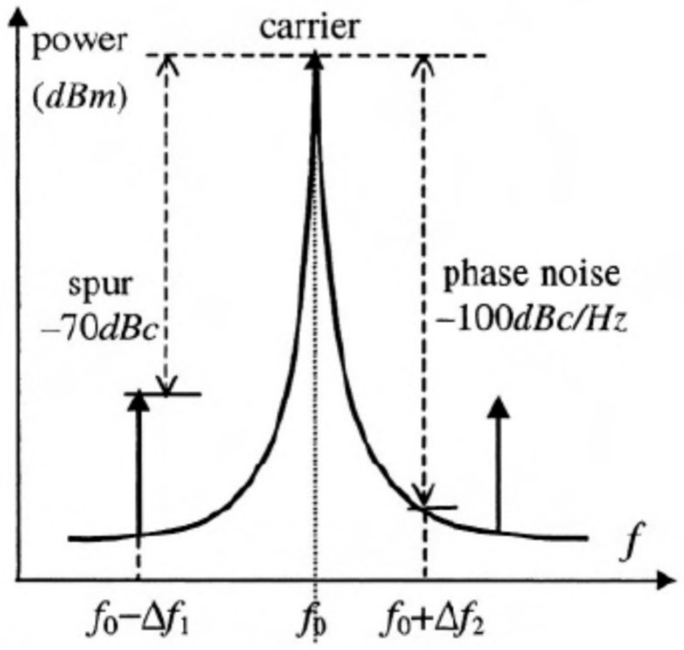
Statistical Simulation Results

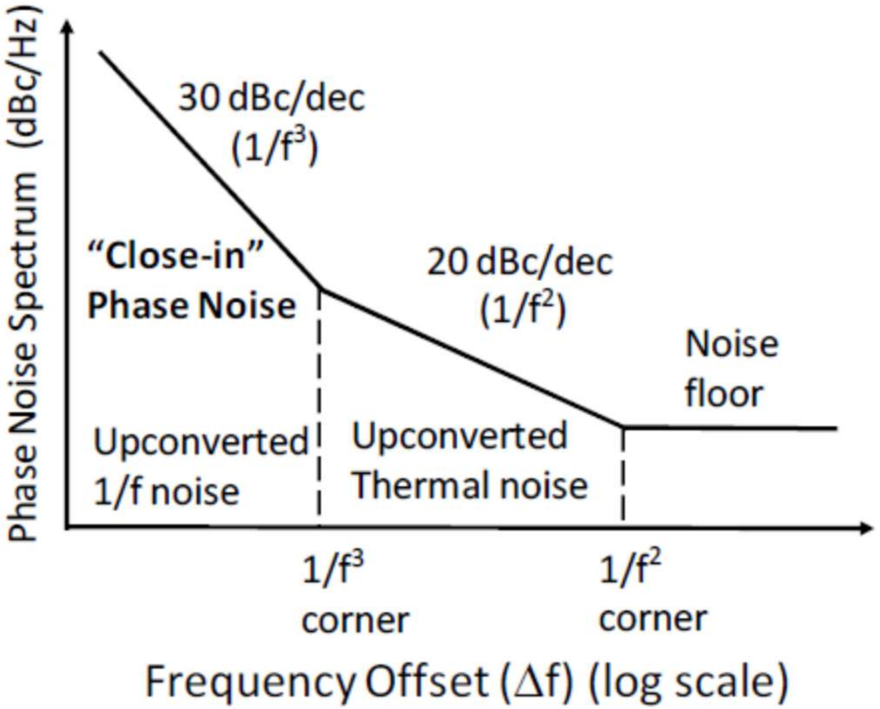


Minimum	3.6784E-11
Máximum	3.8338E-11
Mean	3.7370E-11
Std Deviation	2.06329E-13

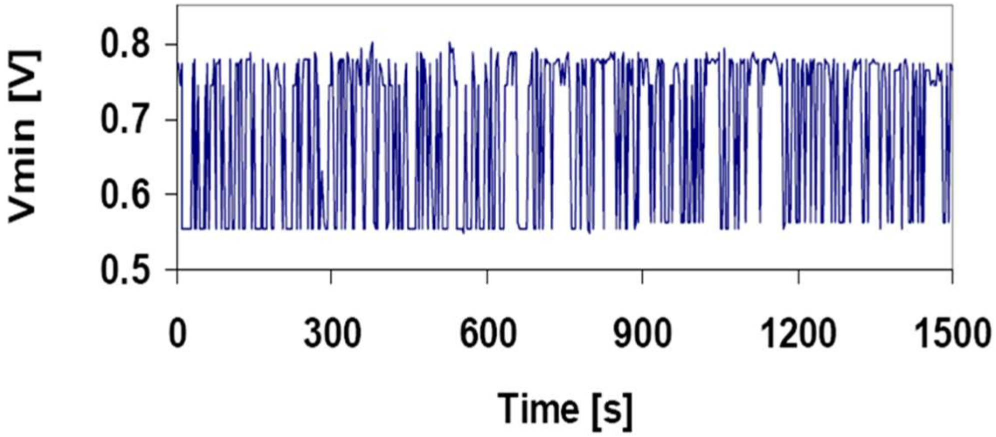
Distribution is skewed (not Gaussian)

Phase Noise: Up-converted 1/f Noise





RTN and SRAM



Vmin on some SRAM arrays varied from one measurement to the next (90nm node).

Source: M Agostinelli et al. (Intel), IEDM 05

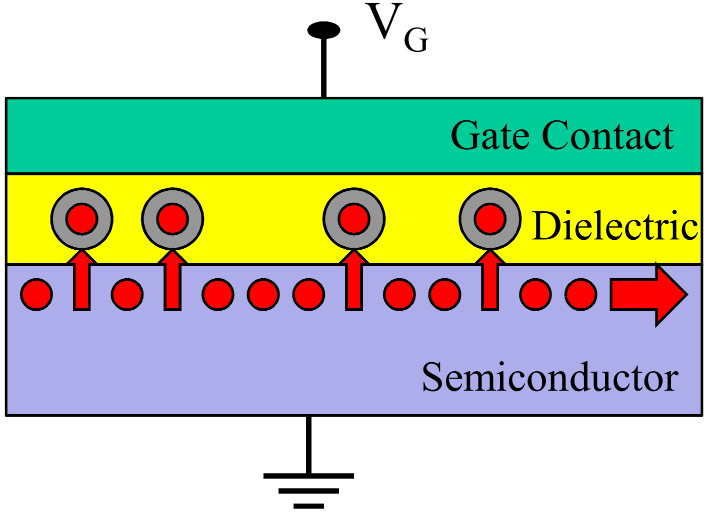
Comments

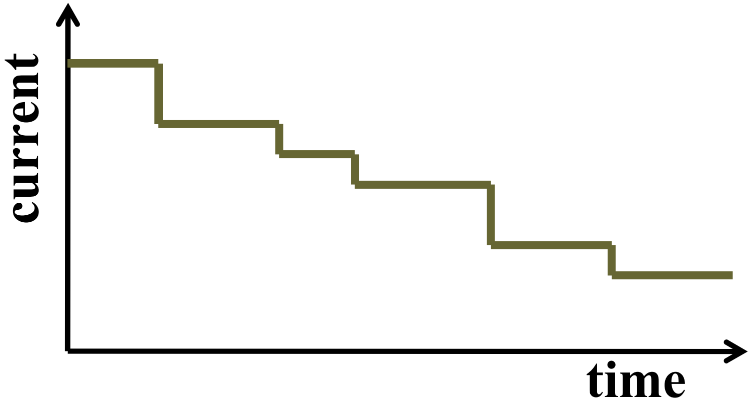
- **Pros**
  - Properly implements the physical-based equations into a circuit simulator
  - Computationally efficient (minor impact on the run time of the transient simulation)
  - Easy to use: Transparent for the circuit designer (no change needed in the netlist).
  - Monte Carlo “by its nature”.
- **Cons**
  - Changes made on simulator source code: time intensive work, and restriction to access proprietary code (HSpice, Spectre, etc.)

Outline

- Our Modeling Approach for Charge Trapping
- Low-Frequency Noise:
  - Frequency Domain Models (DC and AC Large Signal)
  - Time Domain Analysis and Simulation
- NBTI: Charge Trapping Component
- Amplitude of the ΔV_T Induced by a Trap
- Conclusion

Modeling Approach

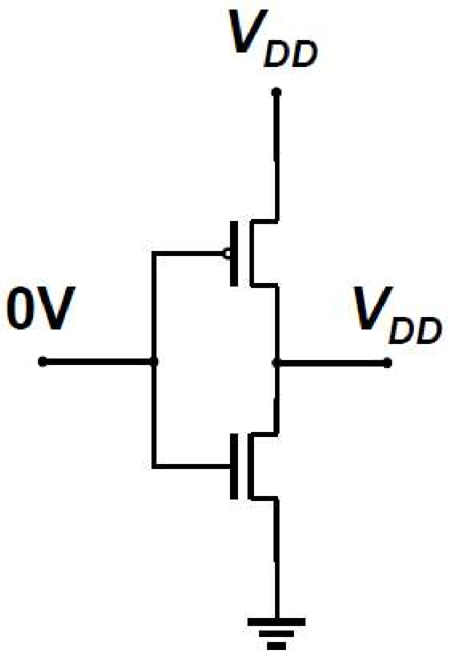


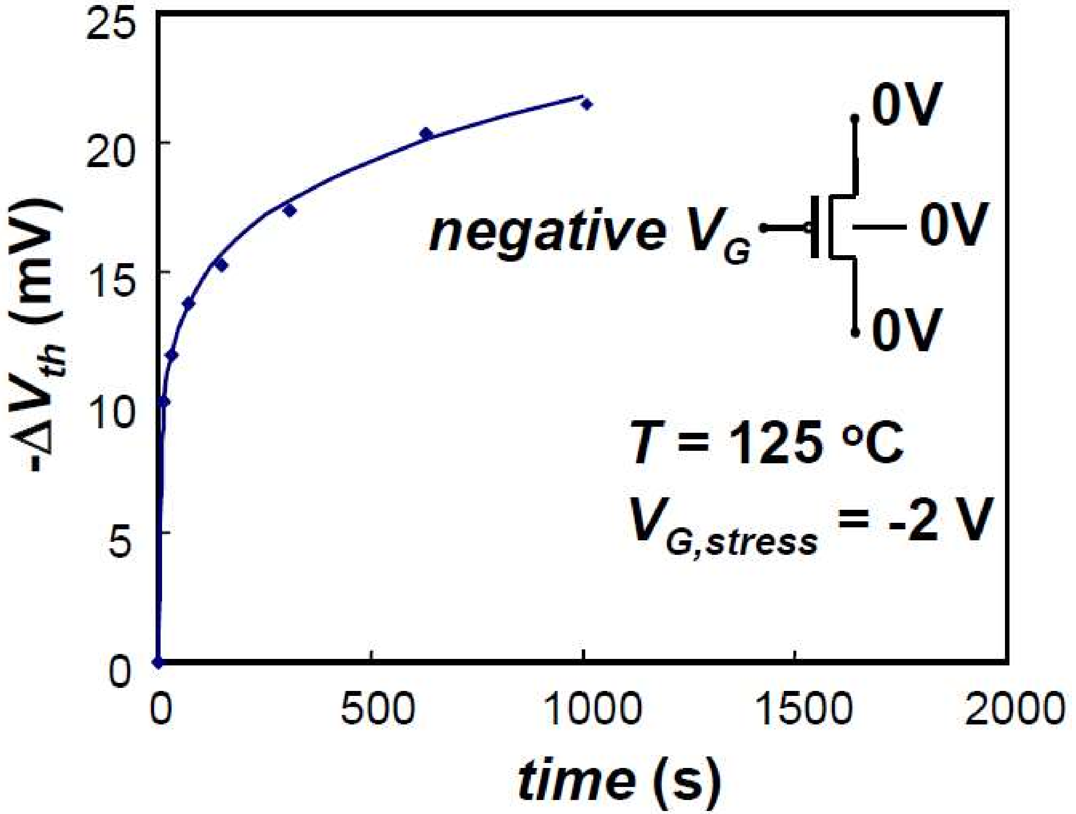


V_G Positive: PBTI
V_G Negative: NBTI

$$< \Delta V_T(t) >=< \delta > \langle n(t) \rangle$$

BTI: Bias and Temperature Stress

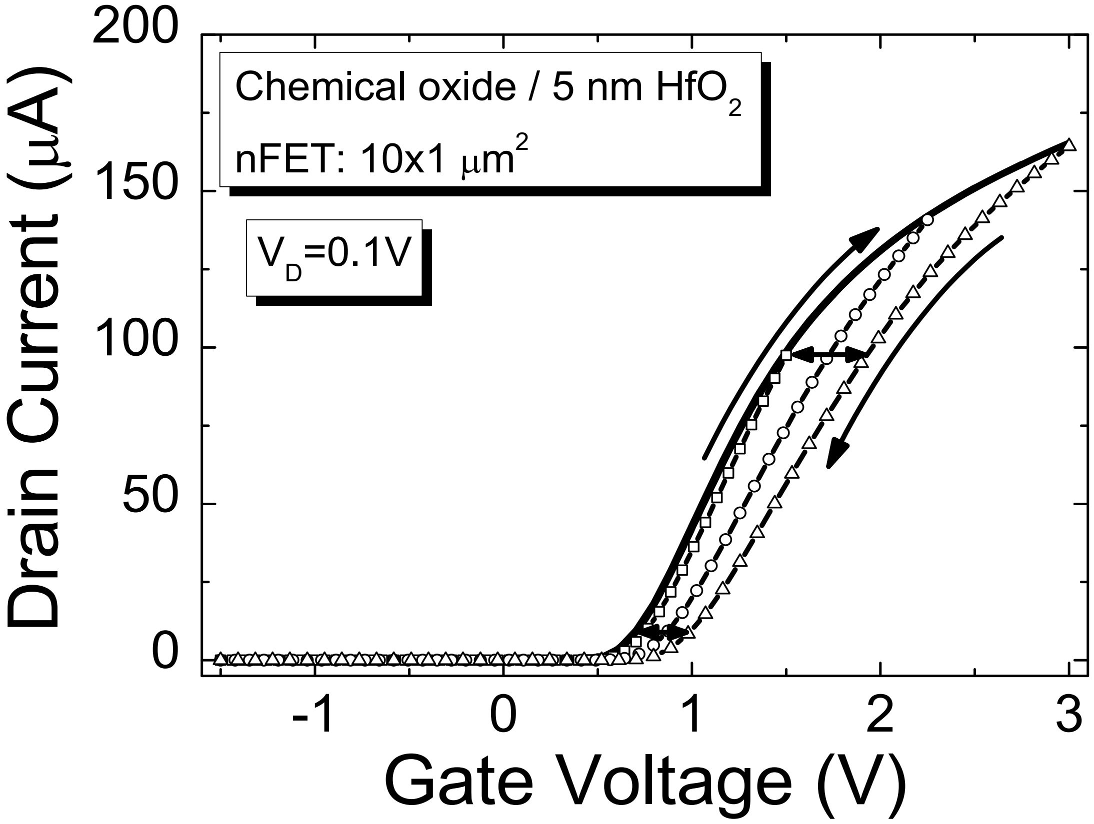




PFET V_{th} at **Negative** gate **Bias** (and typically at elevated **Temperature**) starts shifting (shows **Instability**) → **NBTI**

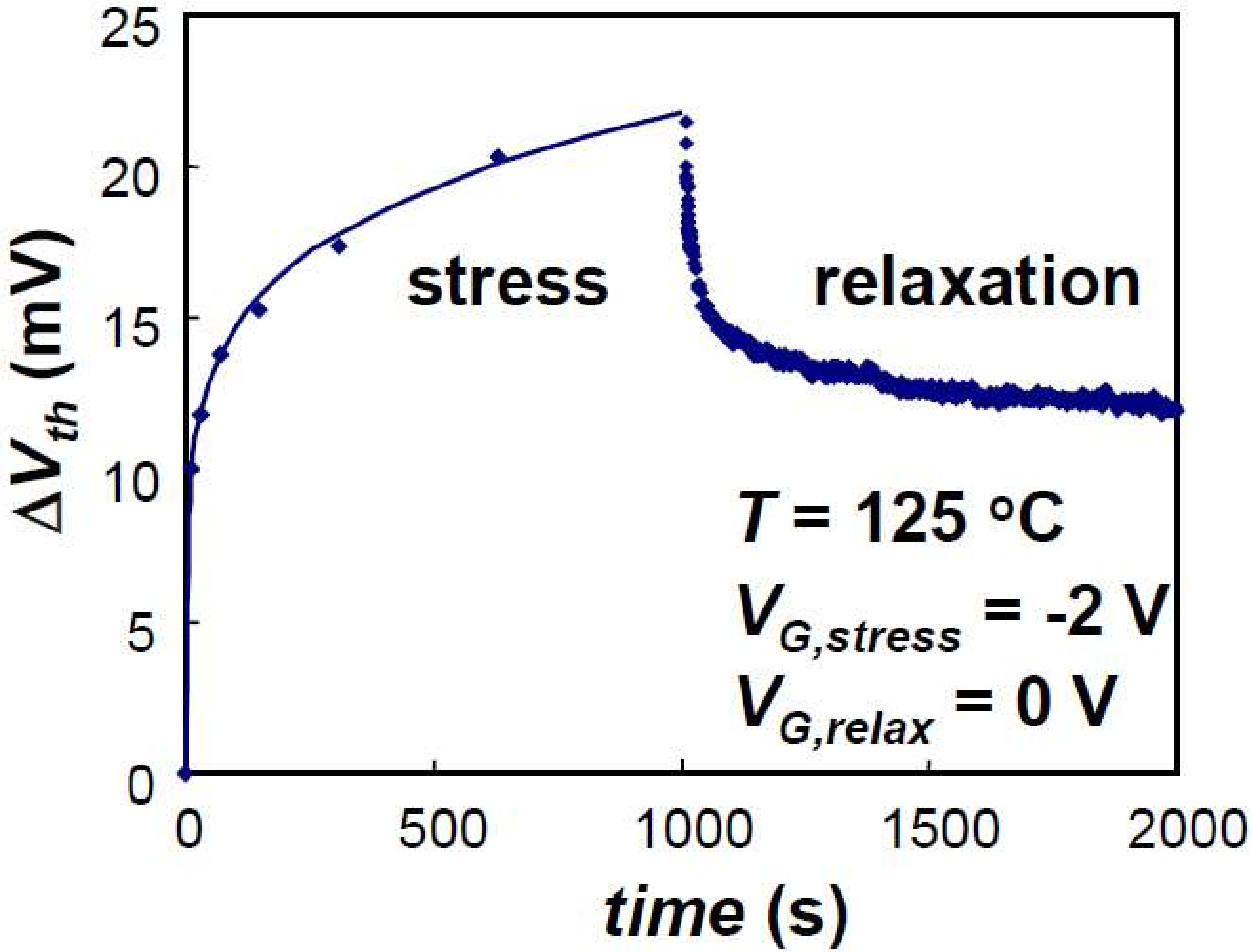
Charging of interface and oxide defects → ΔV_{th} and $\Delta \mu$

BTI: Bias and Temperature Stress

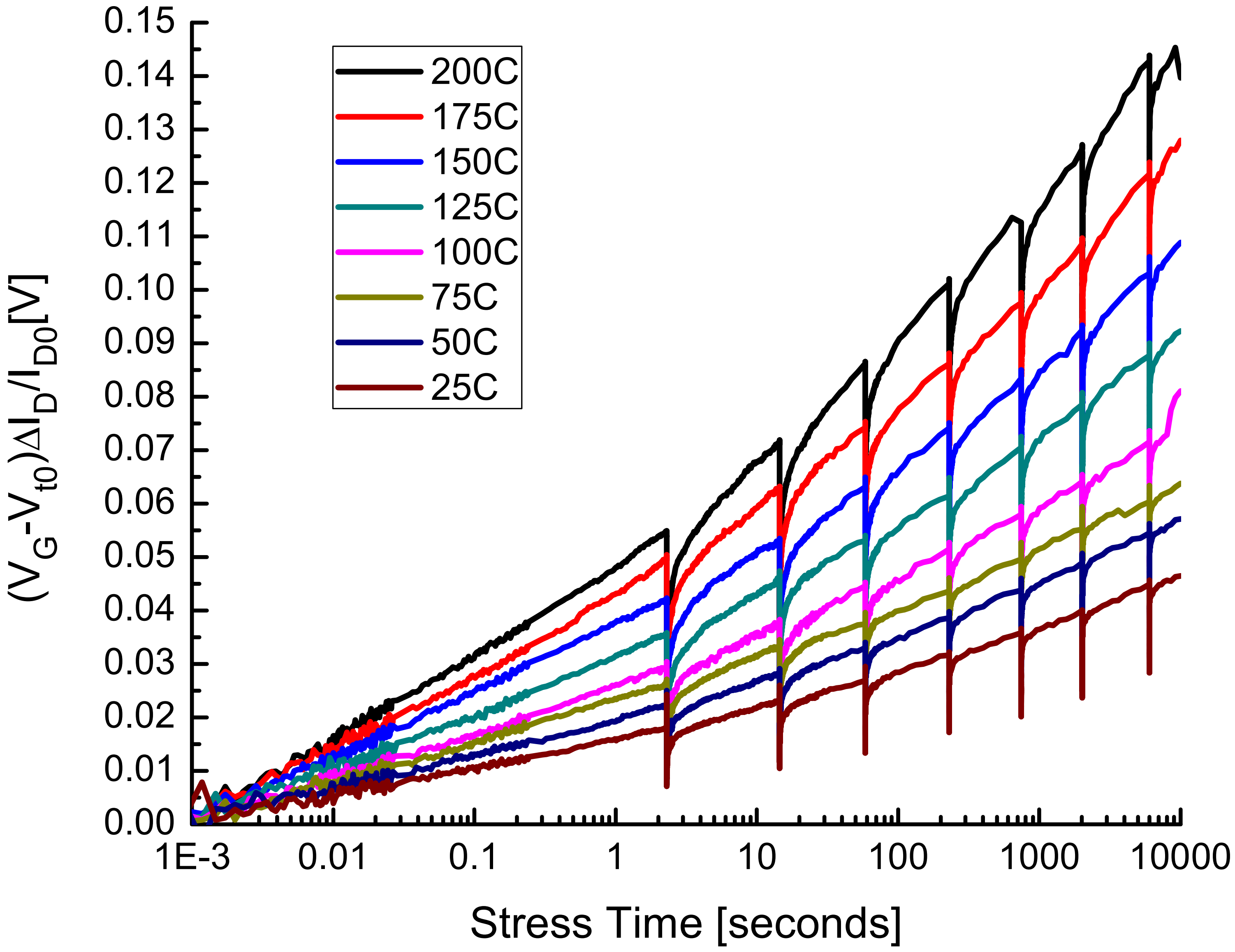


I_D x V_G Hysteresis [Kerber et al, 2004]

BTI: Stress and Recovery



BTI: Stress and Recovery



NBTI: Charge Trapping Component

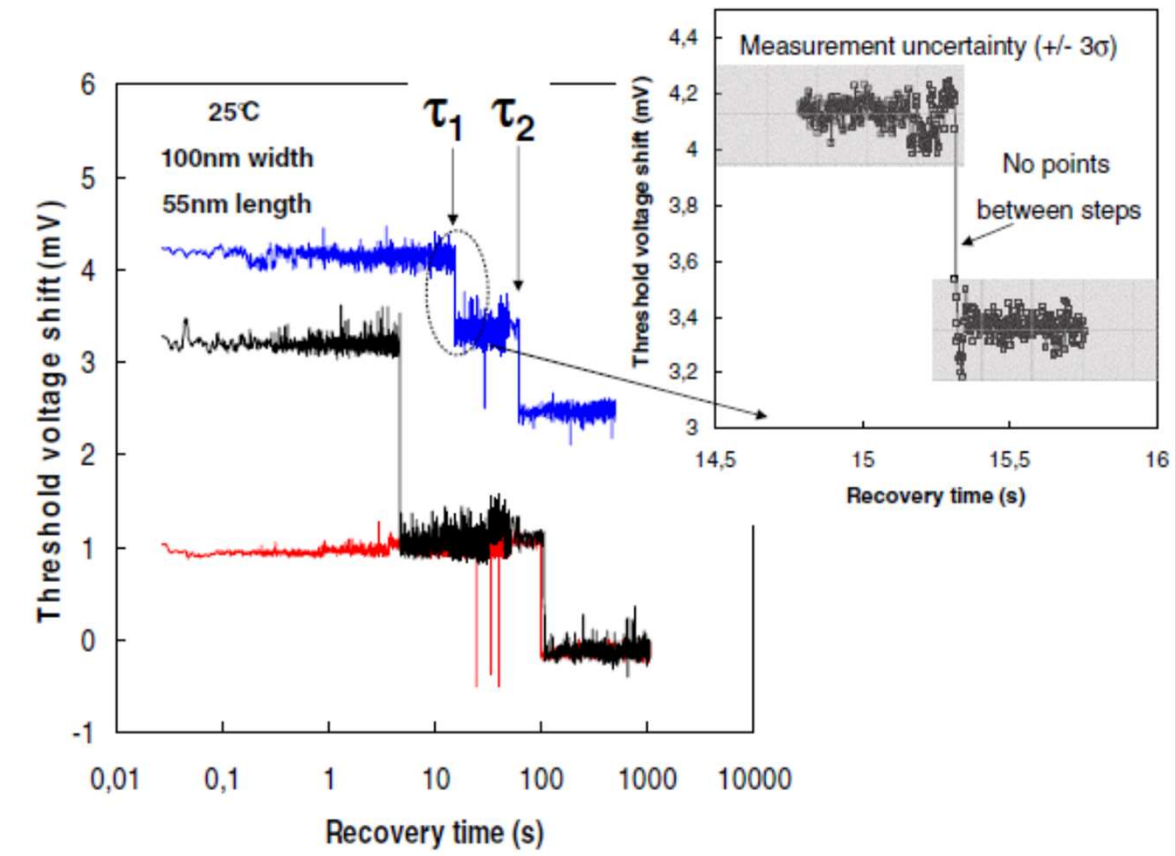
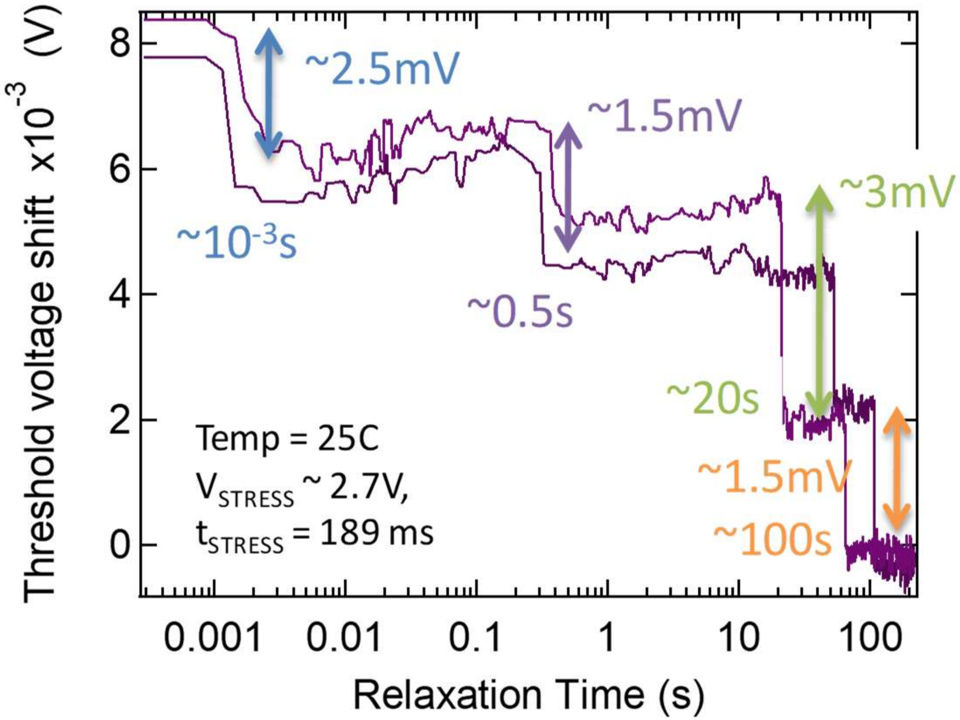


Figure 7: Recovery of V_{TP} shifts for several SRAM-sized devices showing the discrete nature of detrapping events. The inset shows that there are no intermediary values between steps in spite of the small measurement step time (shaded area represents the measurement uncertainty (+/- 3σ).

Huard et al.,
IRPS 2008

NBTI: Charge Trapping Component



Characteristic ΔV_{th} transients of a single 70×90 nm^2 1 nm-SiO_2/1.8nm-HfSiO nMOSFET device stressed at 25 ºC and $V_G = 2.8$ V for 184 ms. Four discrete drops are observed indicating the existence of four active traps at the stress condition [Kaczer, 2014].

Modeling Approach

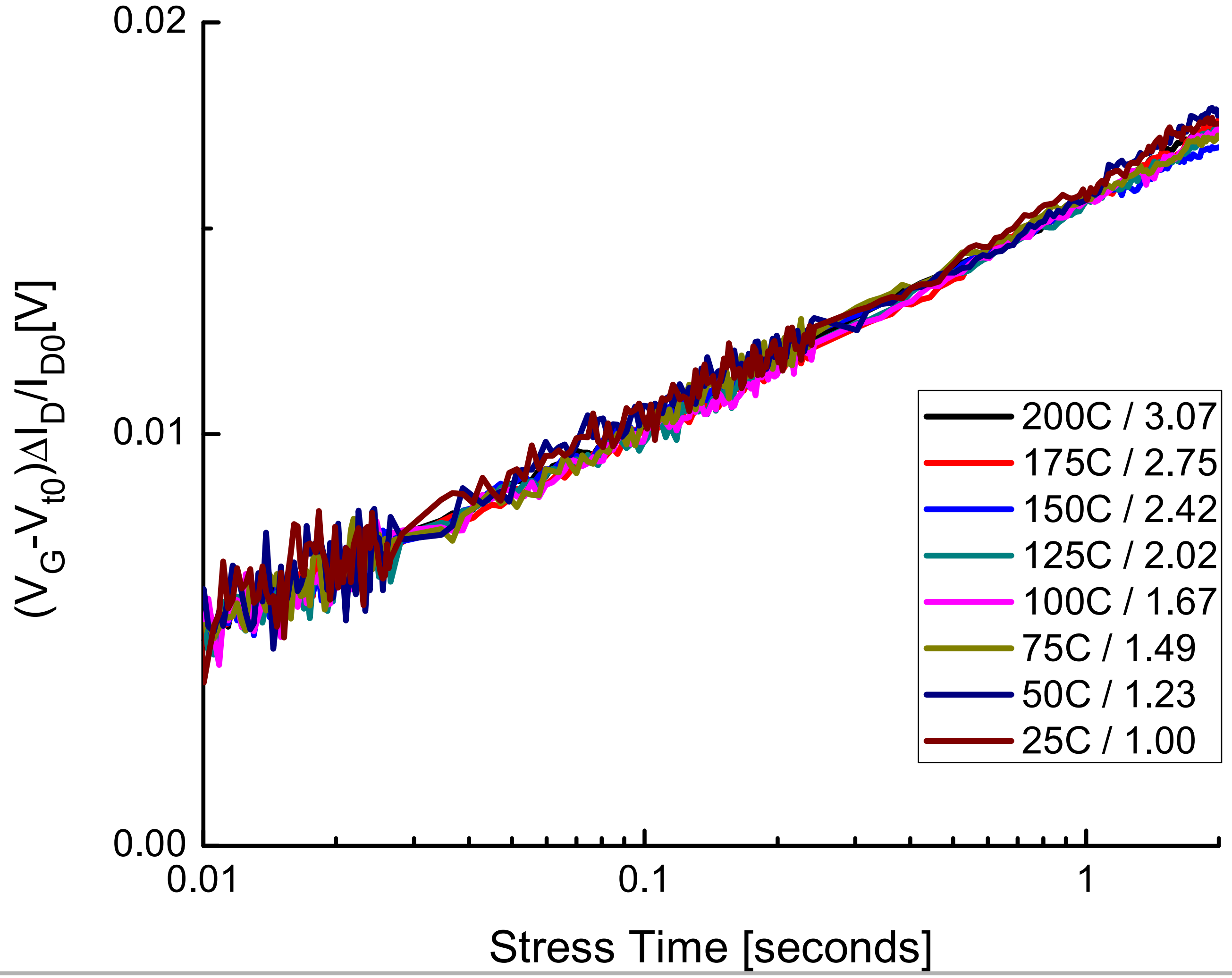
$$< \Delta V_T(t) >=< \delta > \langle n(t) \rangle$$

$$\langle \overline{n(t)} \rangle = \overline{\mathrm{P}_{01}(\tau_\mathrm{c}, \tau_\mathrm{e}, \mathrm{t})} \sum_{Ntr=0}^{\infty} \frac{N^{Ntr} e^{-N}}{N_{tr}!} N_{tr} = N \, \overline{\mathrm{P}_{01}(\tau_\mathrm{c}, \tau_\mathrm{e}, \mathrm{t})}$$

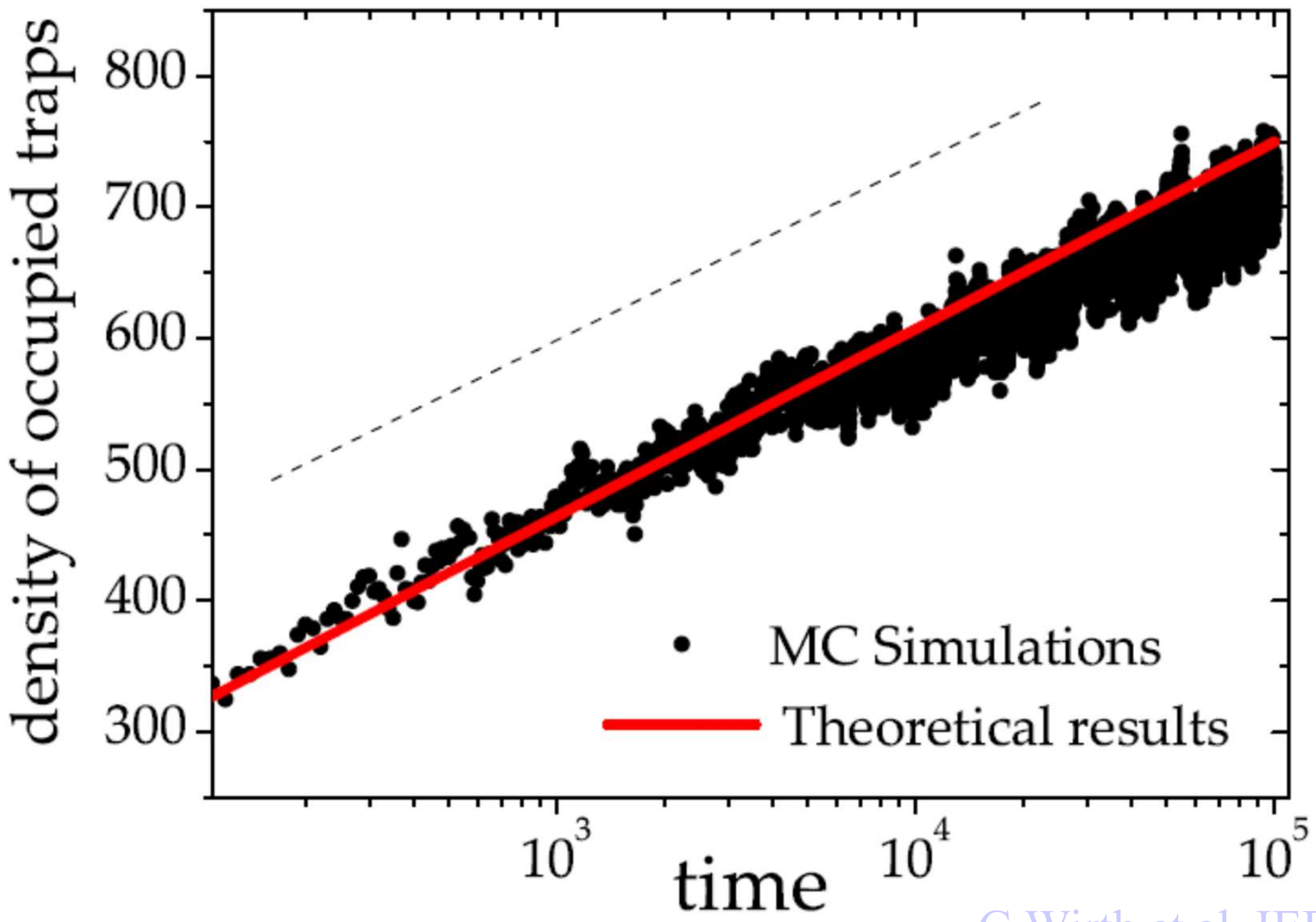
$$= \frac{N}{ln10 \ (p_{max} - p_{min})} \left(\int_{Ev}^{Ec} \frac{g(E_T) dE_T}{1 + e^{-(E_T - E_F)/k_B T}} \right) \left(\int_{10^{-pmi} \ t}^{10^{-pmax} t} \frac{(e^{-u} - 1)}{u} du \right)$$

$$\langle n(t) \rangle \sim \varphi(T, E_F)(A + B \ log(t))$$

NBTI: Temperature Dependence



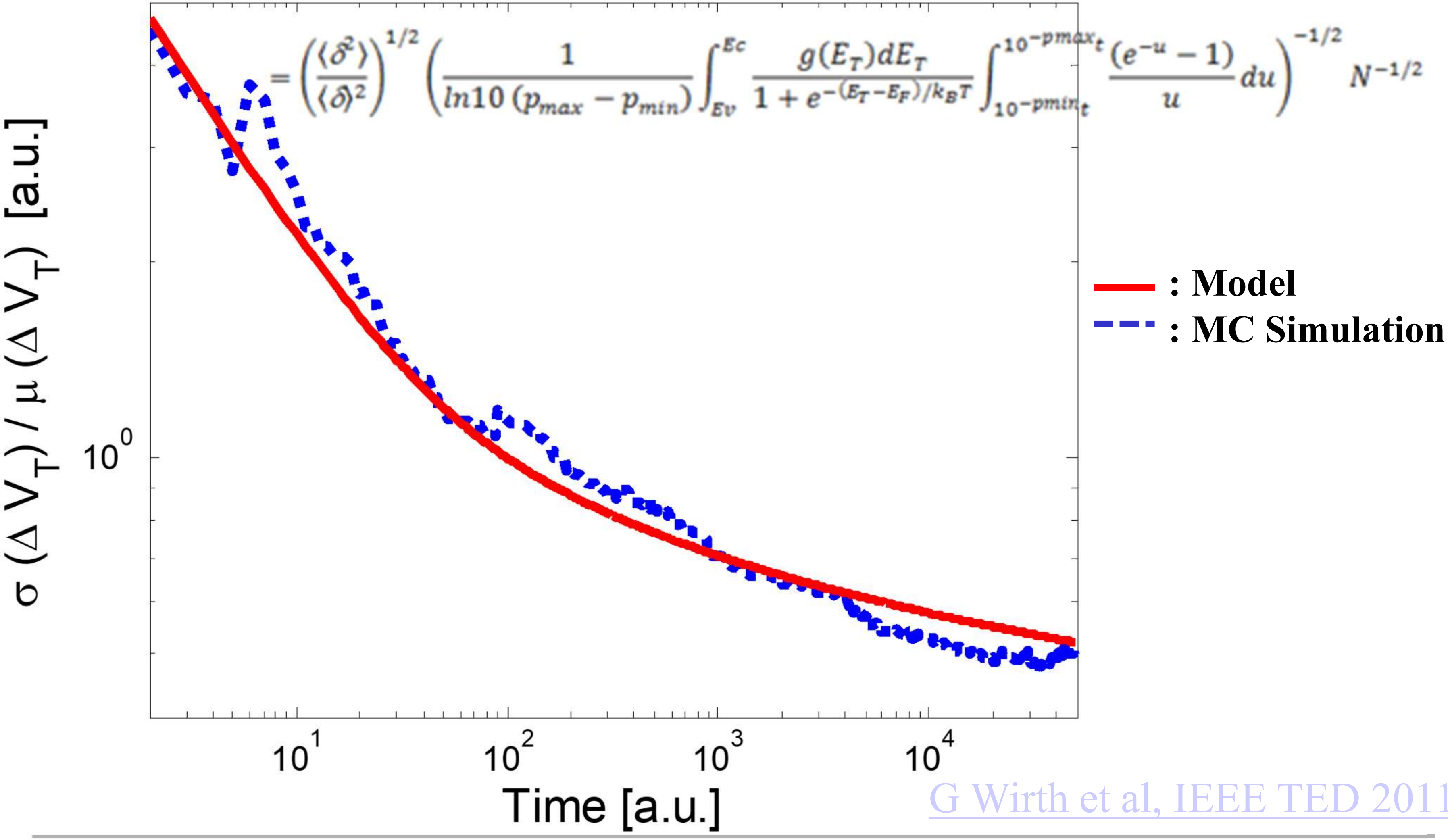
Model for the Charge Trapping Component



G Wirth et al, IEEE TED 2011

$$\overline{\langle n(t)\rangle} \sim \varphi(T, E_F)(A + B\log t)$$

Normalized standard deviation of the BTI induced V_T shift



$$= \left(\frac{\langle\delta^2\rangle}{\langle\delta\rangle^2}\right)^{1/2} \left(\frac{1}{\ln 10\,(p_{max} - p_{min})} \int_{Ev}^{Ec} \frac{g(E_T)dE_T}{1 + e^{-(E_T - E_F)/k_BT}} \int_{10^{-pmin}t}^{10^{-pmax}t} \frac{(e^{-u} - 1)}{u} du\right)^{-1/2} N^{-1/2}$$

: Model

: MC Simulation

G Wirth et al, IEEE TED 2011

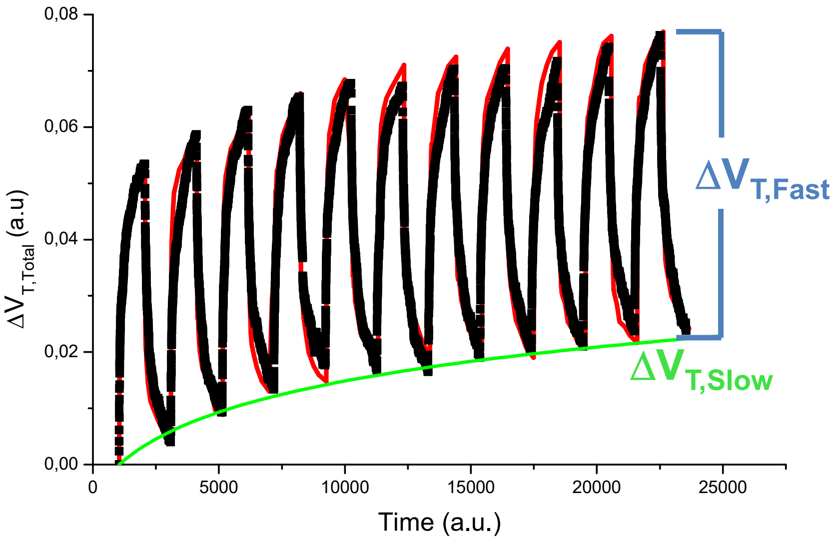
Motivation

To propose a **Unified Model for DC and AC** Bias Temperature Instability.

The model should be based on **first principles** able to model both **short term** (cycle-to-cycle or ripple) and **long term** ("permanent") components of AC BTI.

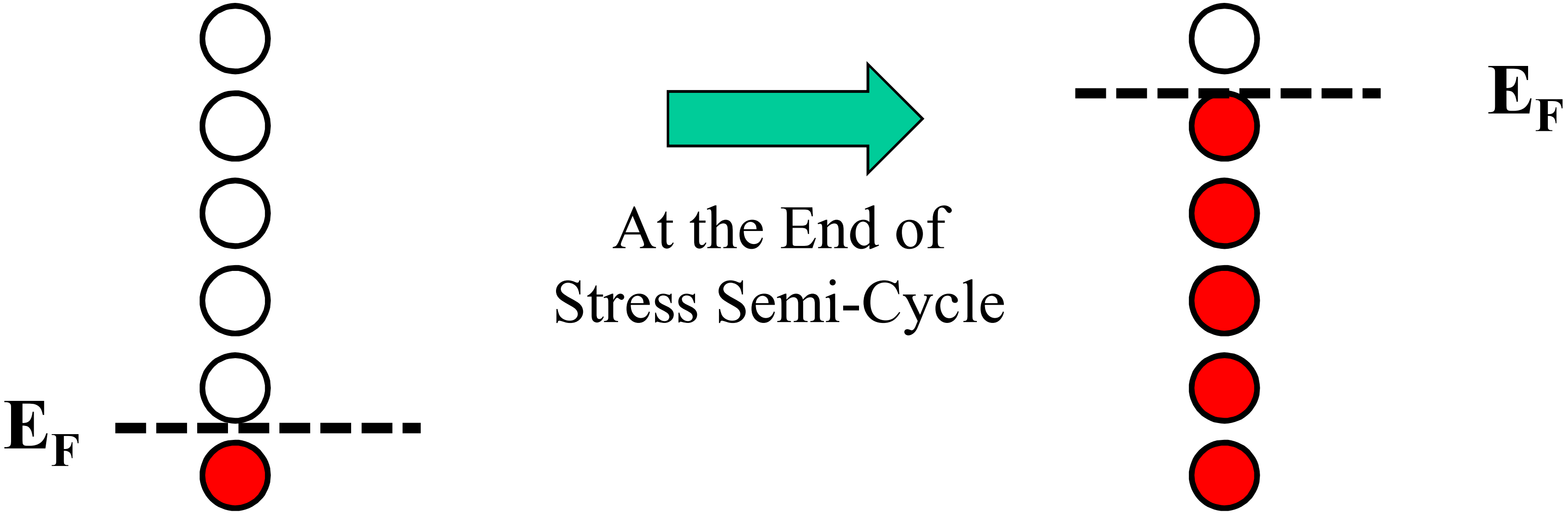
Model equations should be **simple** and ease to implement in simulation tools.

Fast and Slow Traps



$$\Delta V_{T,Total} = \Delta V_{T,Slow} + \Delta V_{T,Fast}$$

Fast Traps



Transistor Off

At the End of
Stress Semi-Cycle

Transistor On

Fast Traps Mostly Empty

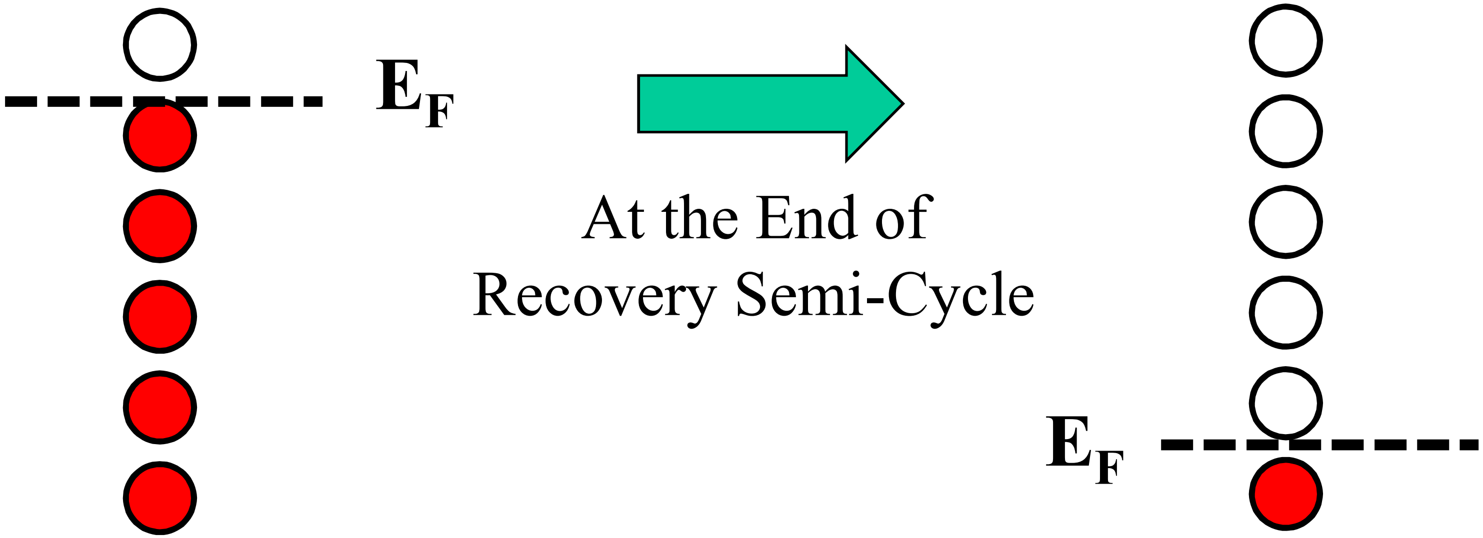
Fast Traps Mostly Occupied

Relevant Trap Time Constant: $\boldsymbol{\tau}_{\mathbf{C,On}}$

Fast Traps

Transistor On

Transistor Off



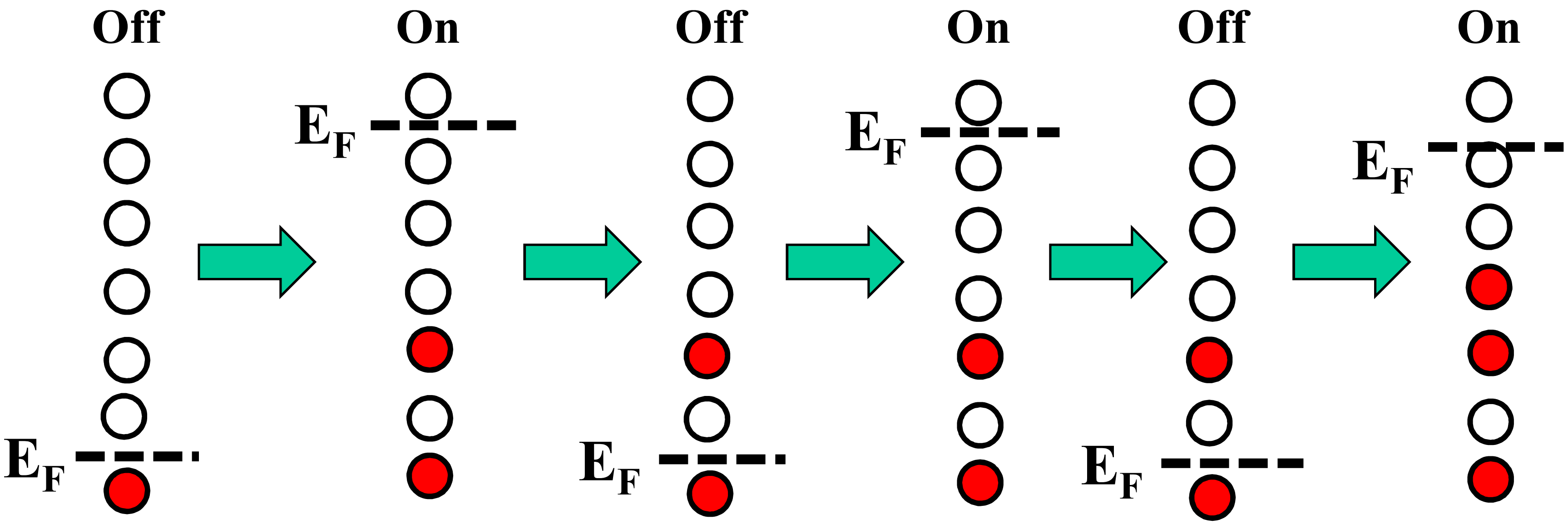
At the End of
Recovery Semi-Cycle

Fast Traps Mostly Occupied

Fast Traps Mostly Empty

Relevant Trap Time Constant: $\boldsymbol{\tau_{e,Off}}$

Slow Traps

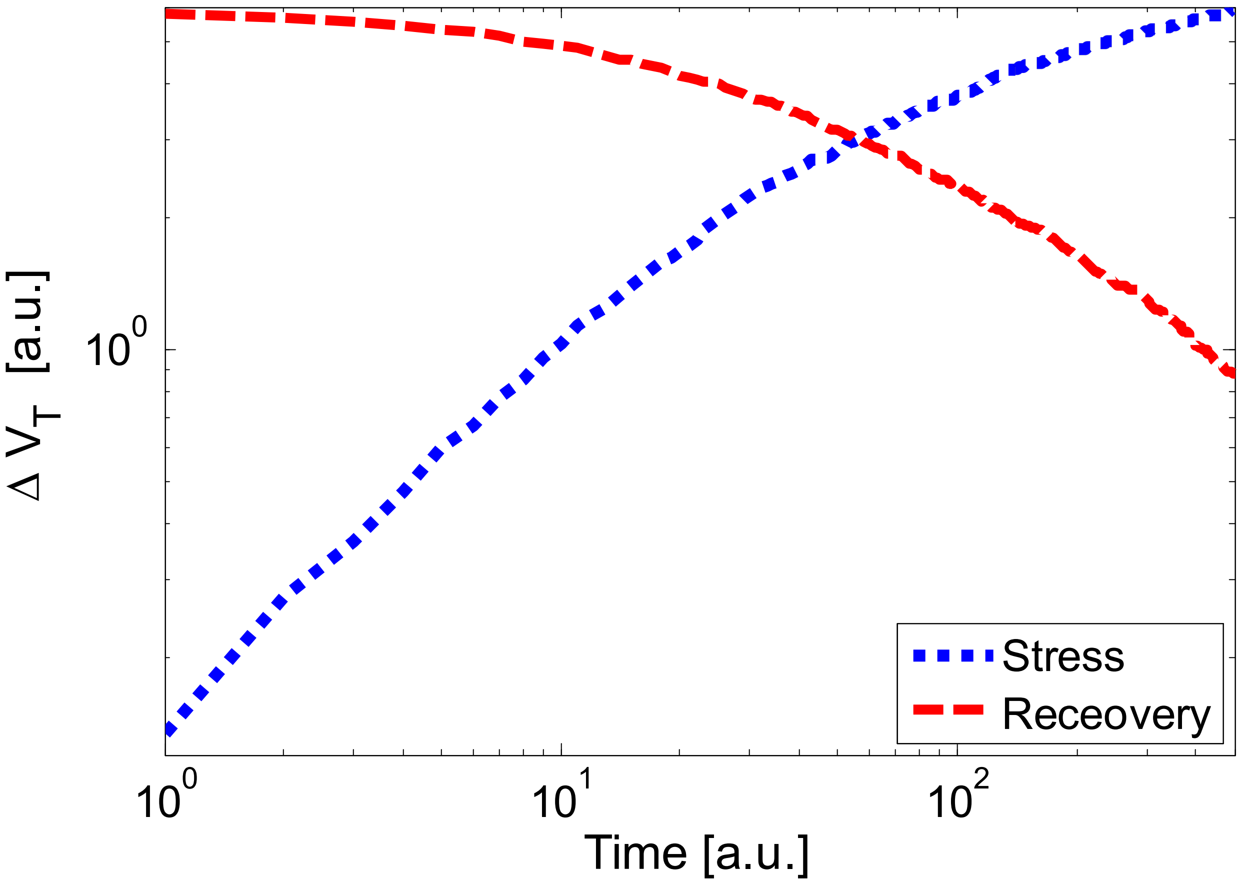


Traps are too slow to follow bias point change.
Equivalent Time Constants

$$<1/\tau_c>=(\alpha/\tau_{c,stress}+(1-\alpha)/\tau_{c,recovery})$$

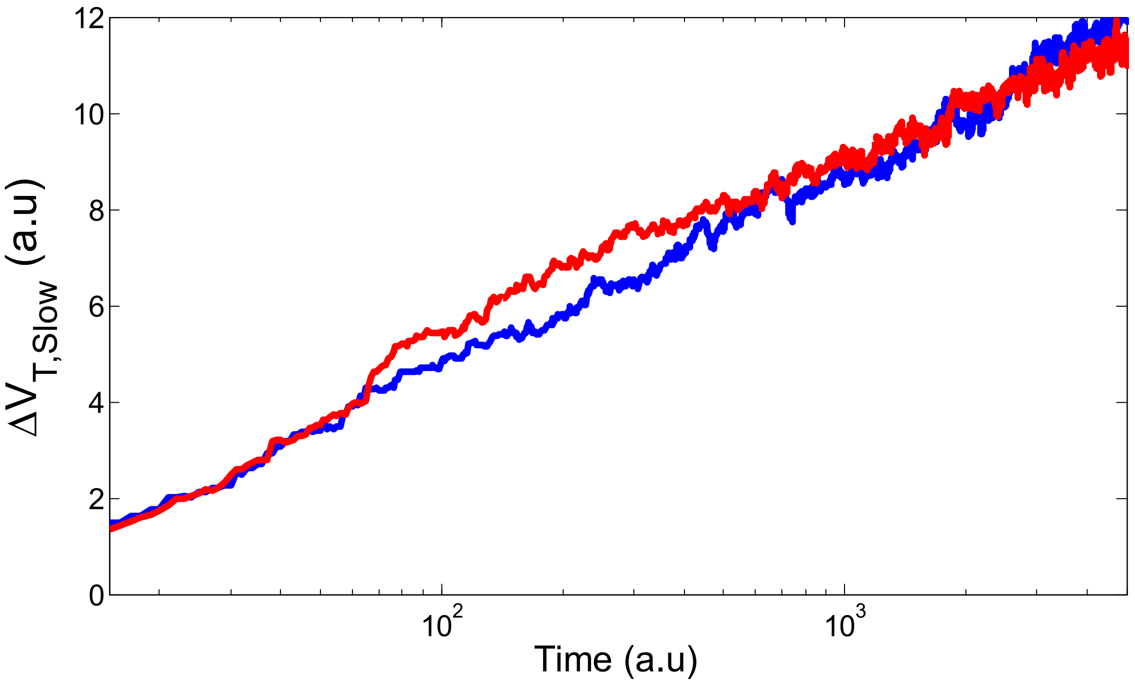
$$<1/\tau_e>=(\alpha/\tau_{e,stress}+(1-\alpha)/\tau_{e,recorery})$$

Fast and Slow Traps



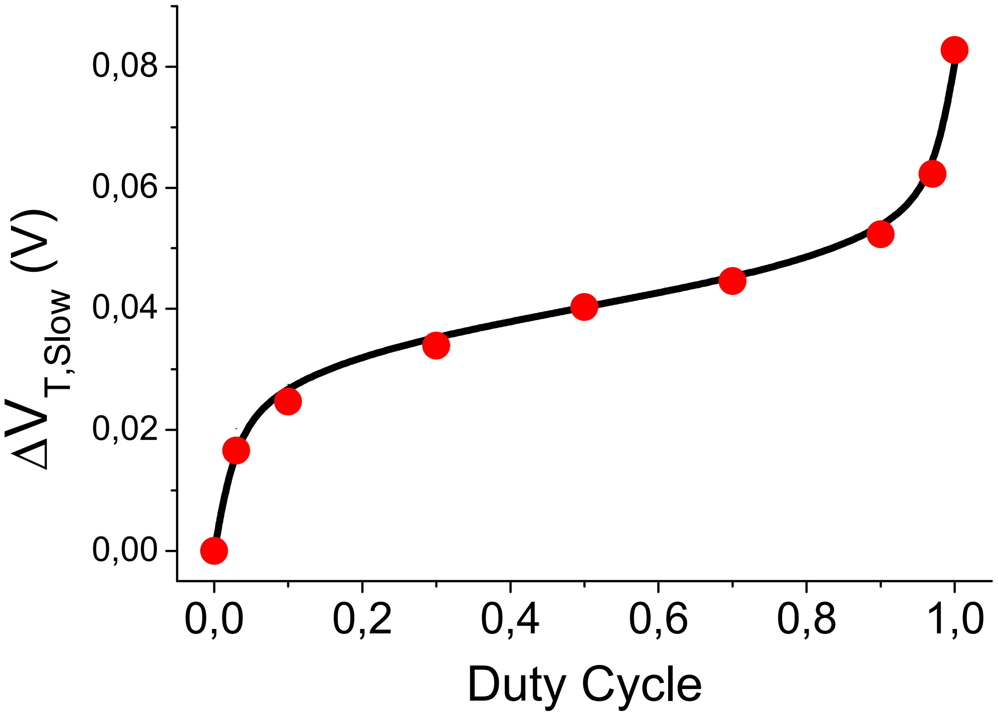
Stress followed by Recovery.
Stress of 500 time units, followed by 500 time units of Recovery.
Please note that Recovery is shifted by 500 time units in the Time axis, so that start of both Stress and Recovery correspond to time equal to zero.

Slow Traps



$$\Delta V_{T,Slow} \approx k_S.\ [\log(\alpha + k_A) - \log(1 - \alpha + k_A)].\log(t)$$

Slow Traps



$$\Delta V_{T,Slow} \approx k_S .\ [\log(\alpha + k_A) - \log(1-\alpha + k_A)].\log(t)$$

Fast Traps

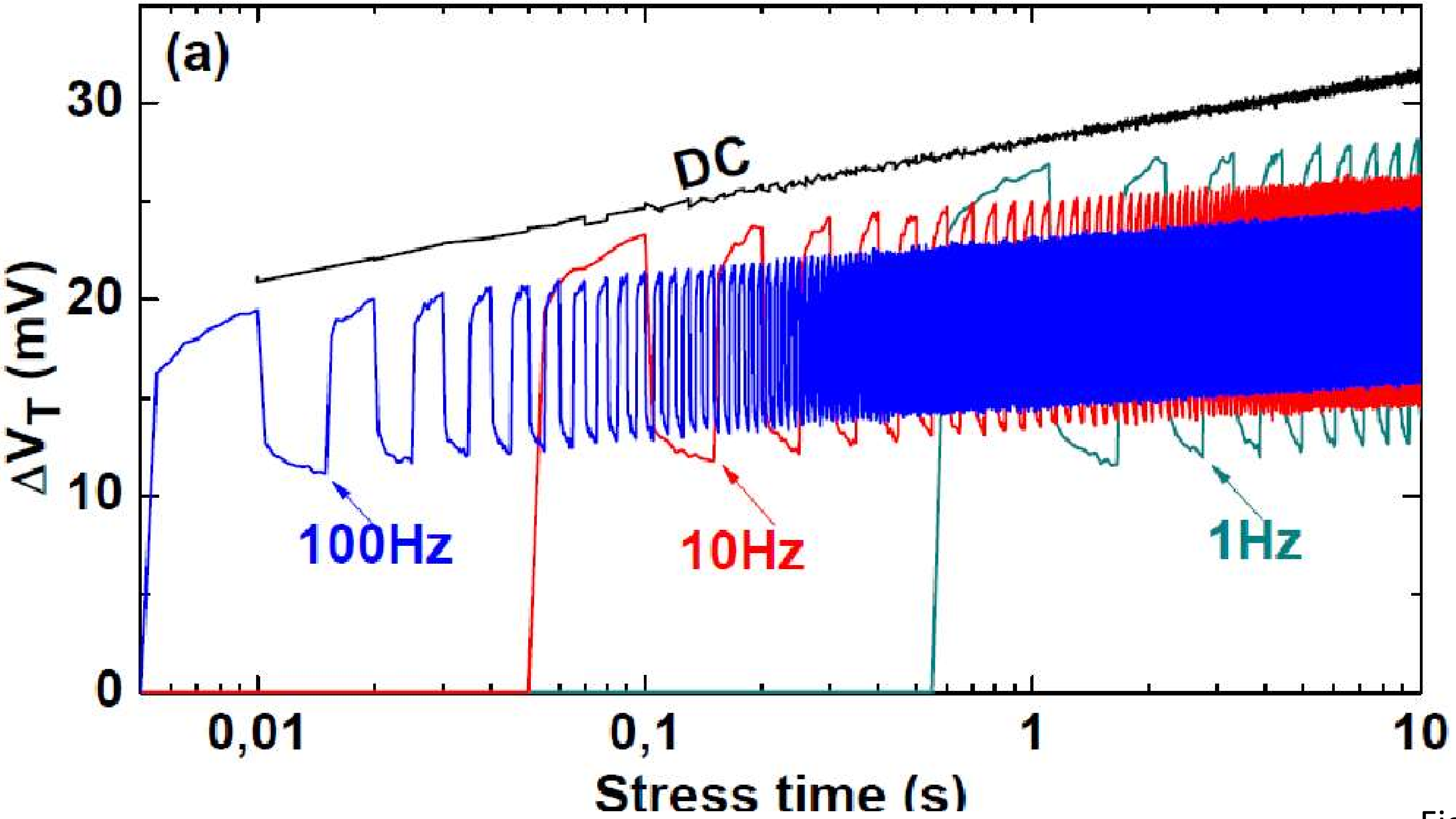


Figure from
J. Martin-Martinez et al., IRPS 2011

$$\Delta V_{T,Fast} = [k_C + k_F \log(T_S)] * [(\log(\alpha + k_A) + \log(1 - \alpha + k_A)]$$

Fast Traps

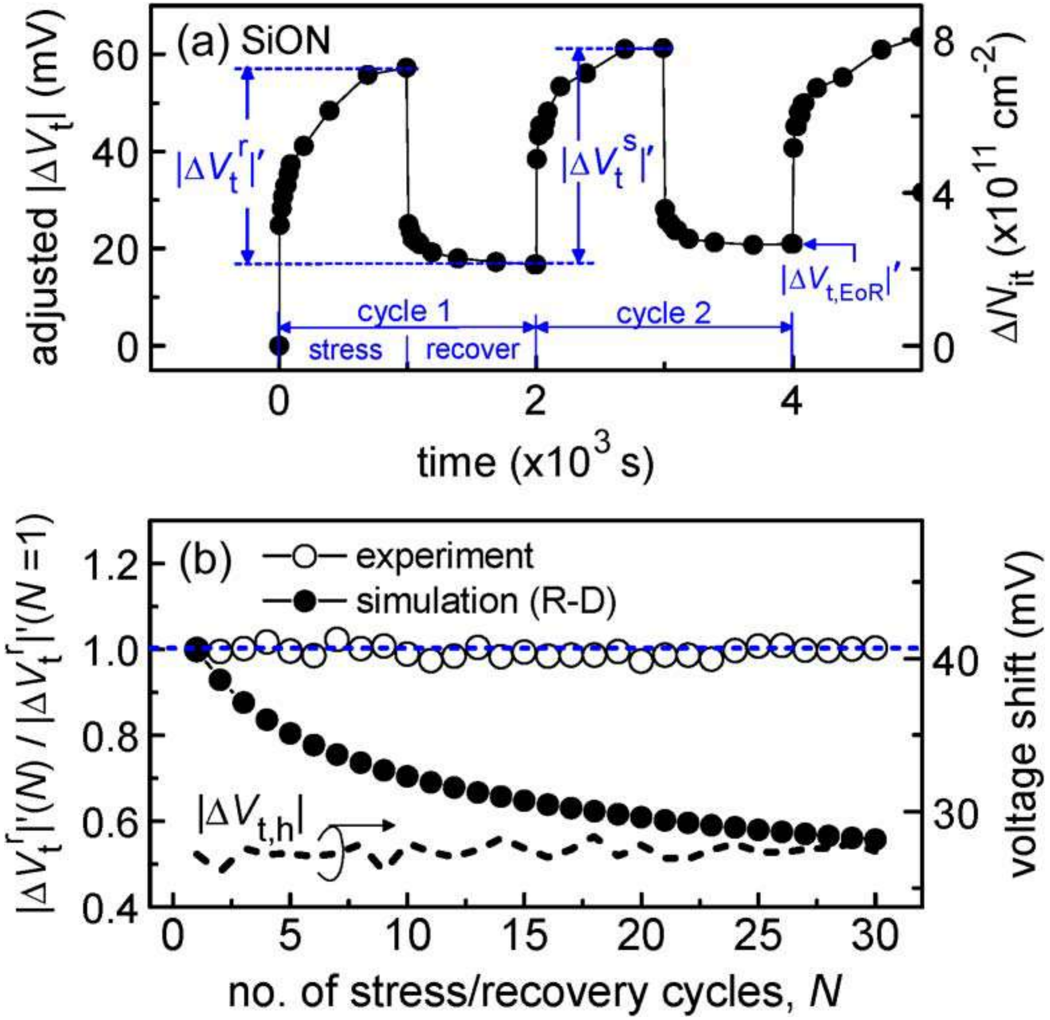
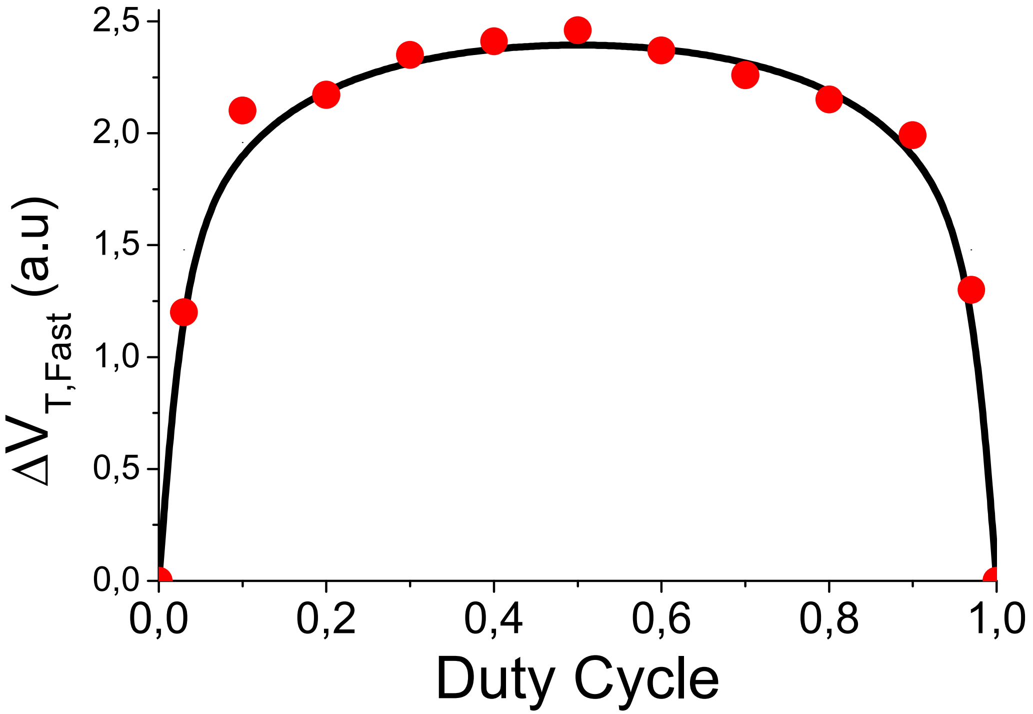


Figure from
D S Ang et al
IEEE TDMR
pp.19, March 2011

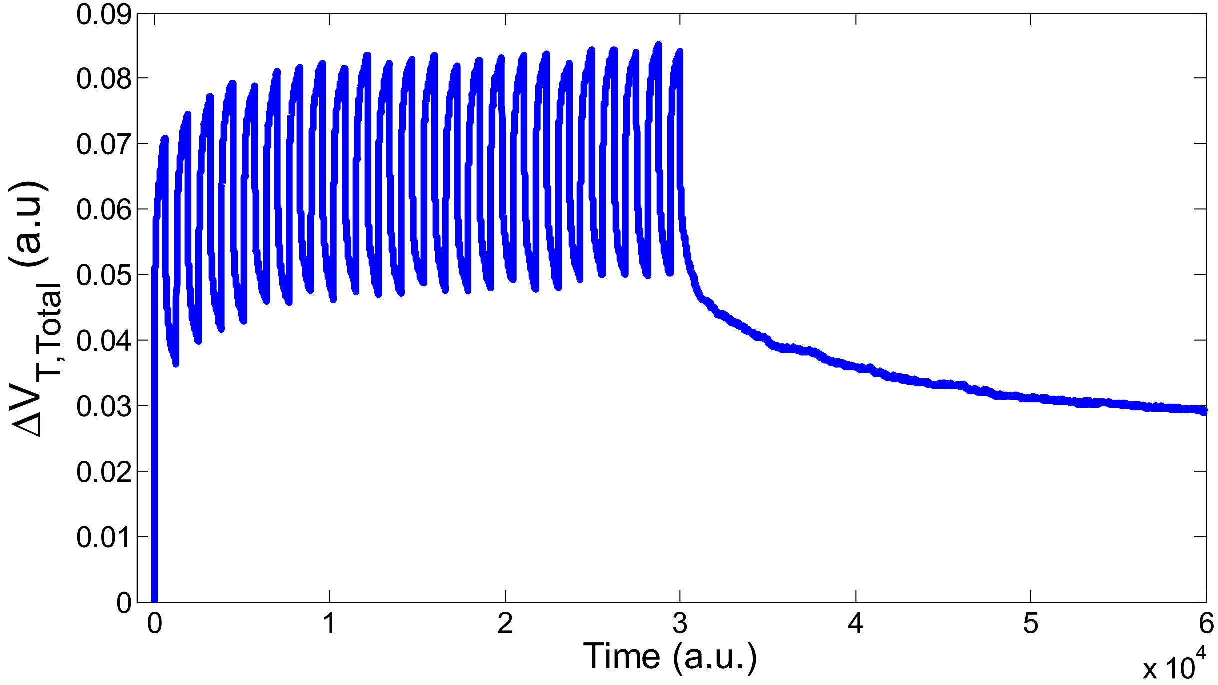
$$\Delta V_{T,Fast} = [k_C + k_F \log(T_S)] * [(\log(\alpha + k_A) + \log(1 - \alpha + k_A)]$$

Fast Traps



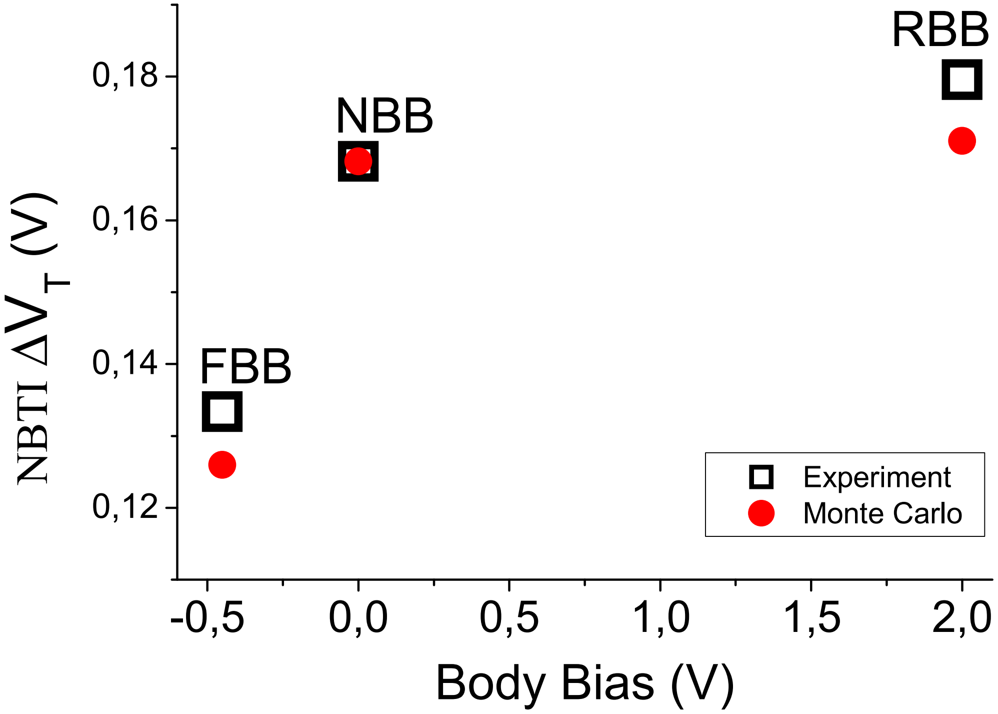
$$\Delta V_{T,Fast} = [k_C + k_F \log(T_S)] * [(\log(\alpha + k_A) + \log(1 - \alpha + k_A)]$$

ΔV_T Total

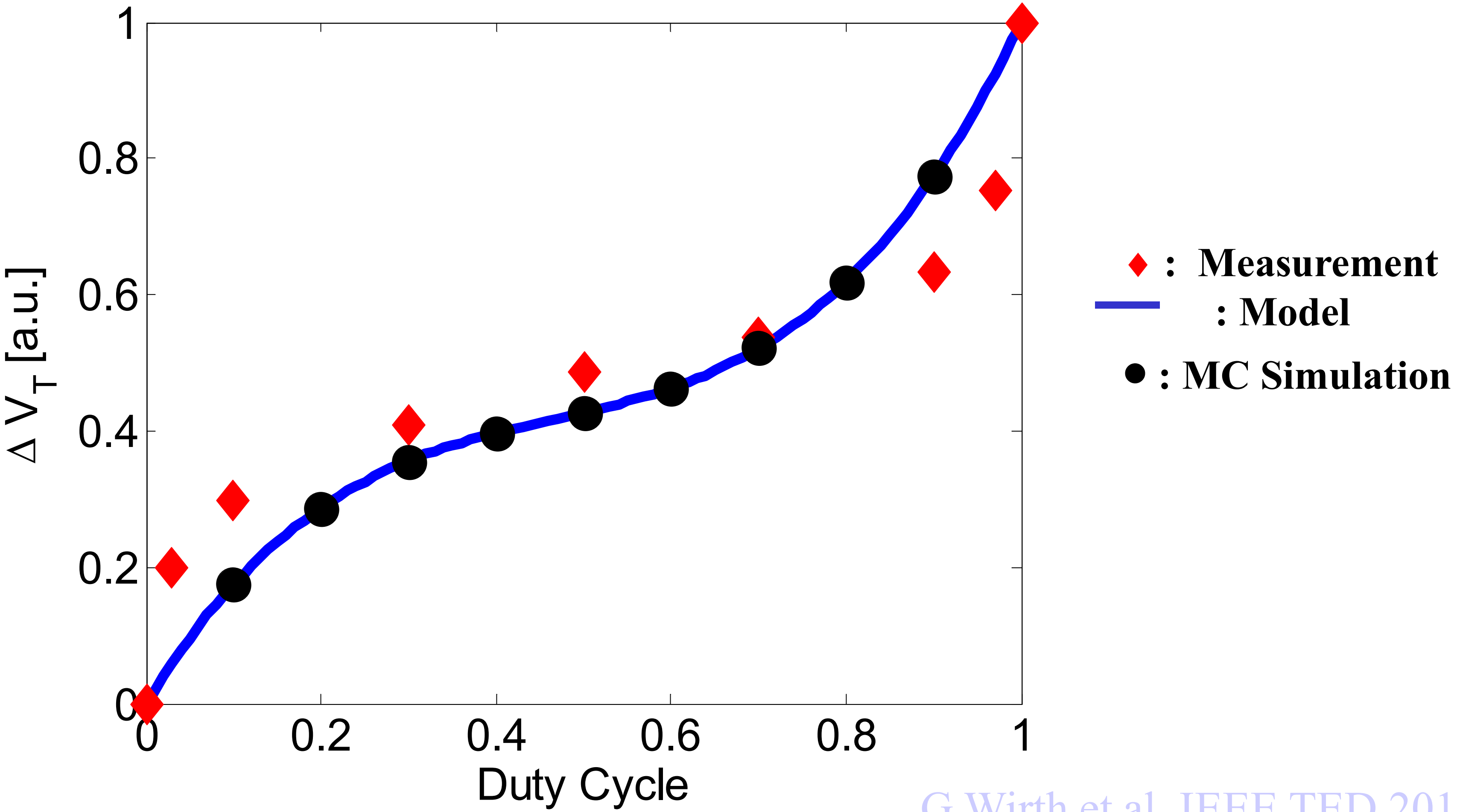


Monte Carlo Simulation: “Permanent” component

Body Biasing

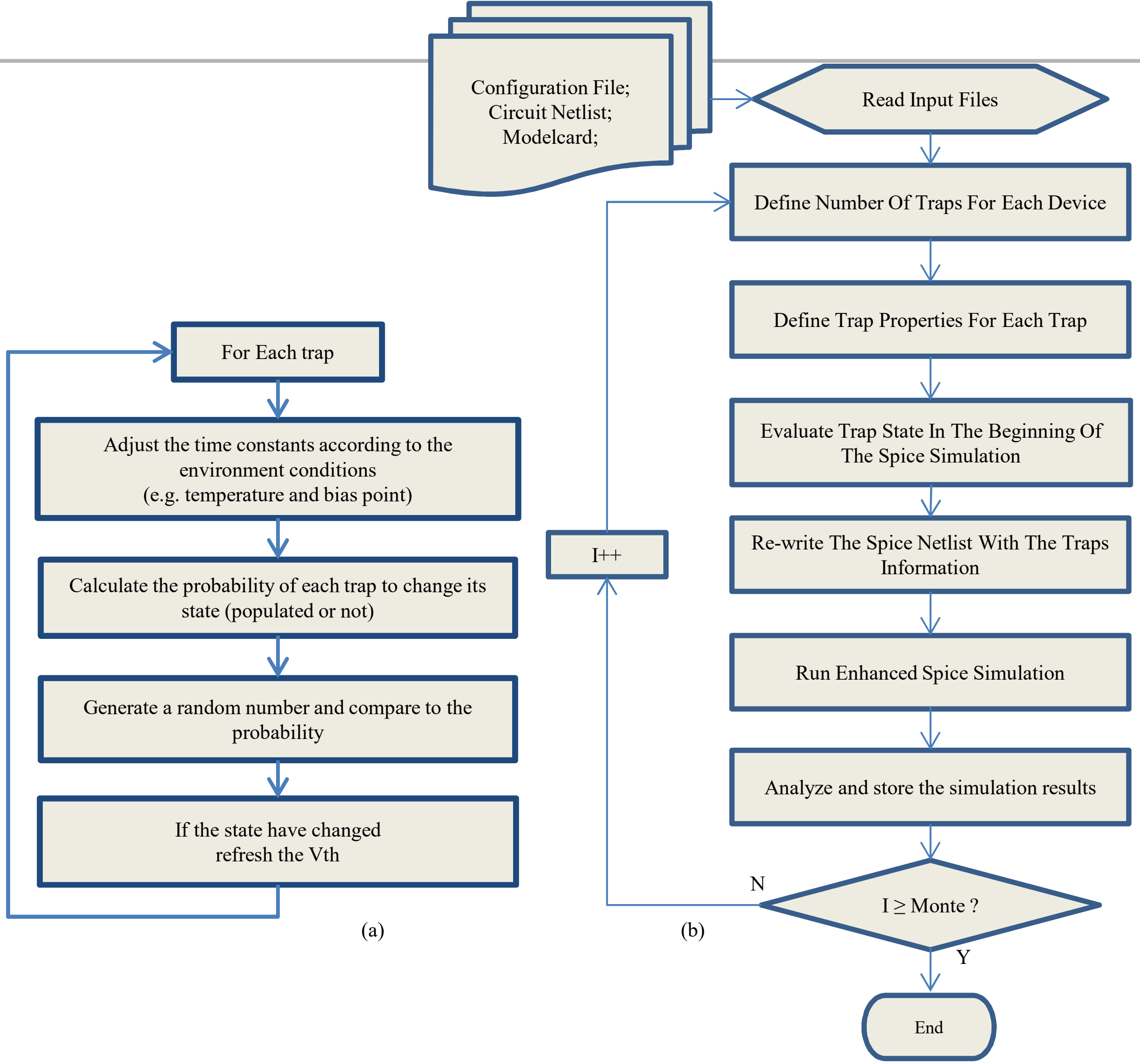


Circuit Activity (Duty Cycle) Dependence



G Wirth et al, IEEE TED 2011

Simulation of Both RTN and BTI



Configuration File;
Circuit Netlist;
Modelcard;

Read Input Files

Define Number Of Traps For Each Device

Define Trap Properties For Each Trap

Evaluate Trap State In The Beginning Of The Spice Simulation

Re-write The Spice Netlist With The Traps Information

Run Enhanced Spice Simulation

Analyze and store the simulation results

I ≥ Monte ?

N

Y

I++

End

(b)

For Each trap

Adjust the time constants according to the environment conditions
(e.g. temperature and bias point)

Calculate the probability of each trap to change its state (populated or not)

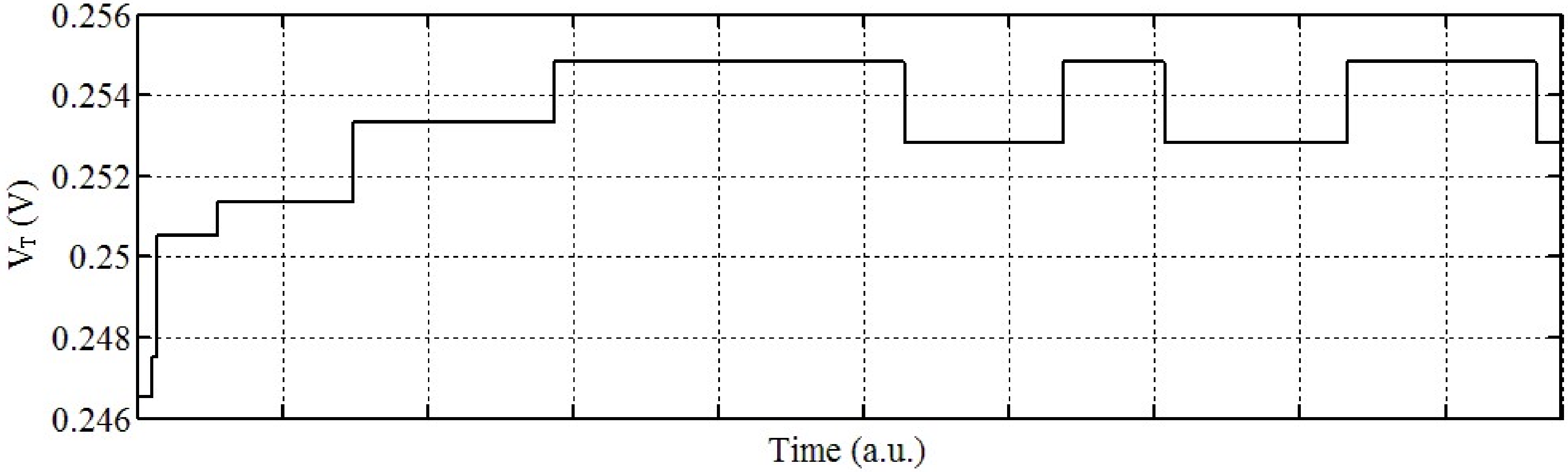
Generate a random number and compare to the probability

If the state have changed refresh the Vth

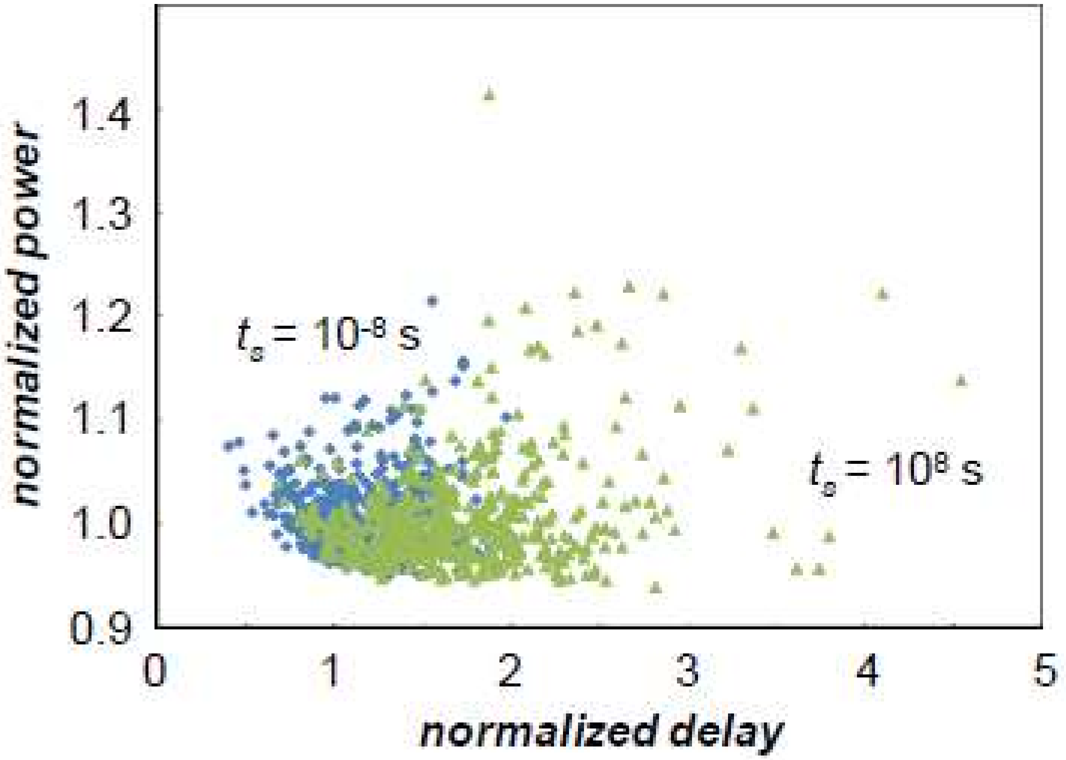
(a)

UFRGS

Simulation of Both RTN and BTI

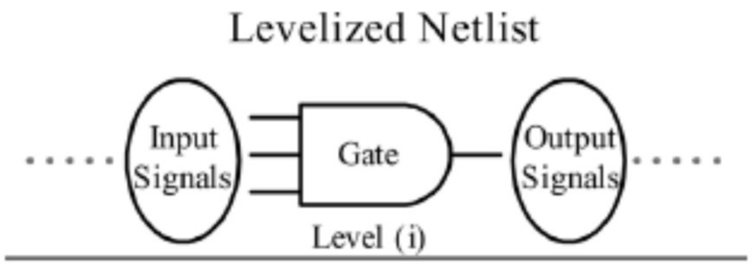


Simulation of Both RTN and BTI



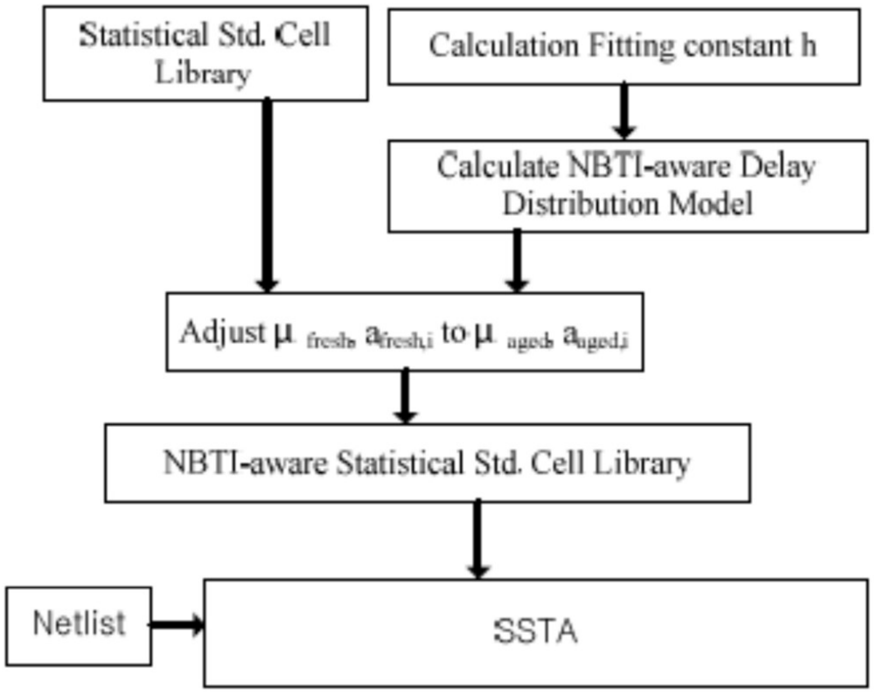
Inverter power and delay after 10^{-8}s and 10^{8}s of stress (250 MHz clock)

Simulation of Both RTN and BTI at System Level



NBTI timing degradation analysis algorithm:
Input: circuit netlist, input signal probability, slew rate
Output: Delay

```
FOR each gate in level i
    identify input signals
    load signal information: duty cycle , slew rate
    identify gate fanouts
    calculate gate load capacitance
    calculate gate intrinsic delay
    calculate gate delay degradation caused by NBTI
    calculate duty cycle for output signals
    calculate slew rate for output signals
    update information for output signals
    set output signals as inputs for level (i+1)
END FOR
```


Statistical Std. Cell Library

Calculation Fitting constant h

Calculate NBTI-aware Delay Distribution Model

Adjust μ_{fresh}, $a_{fresh,i}$ to μ_{aged}, $a_{aged,i}$

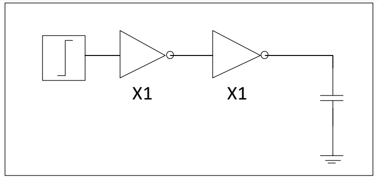
NBTI-aware Statistical Std. Cell Library

Netlist

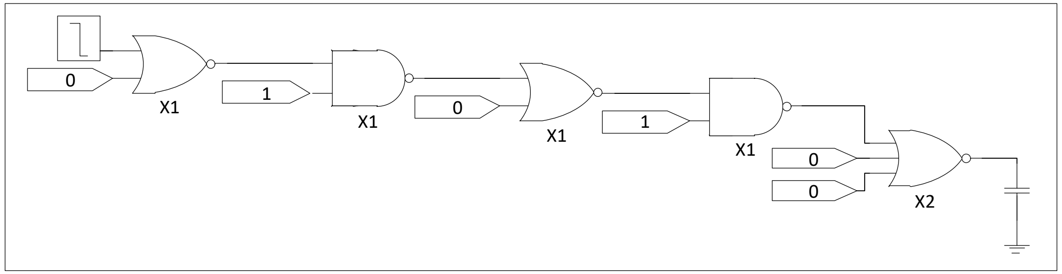
SSTA

Must properly predict duty cycle, etc.
SSTA assumes Gaussian Distributions

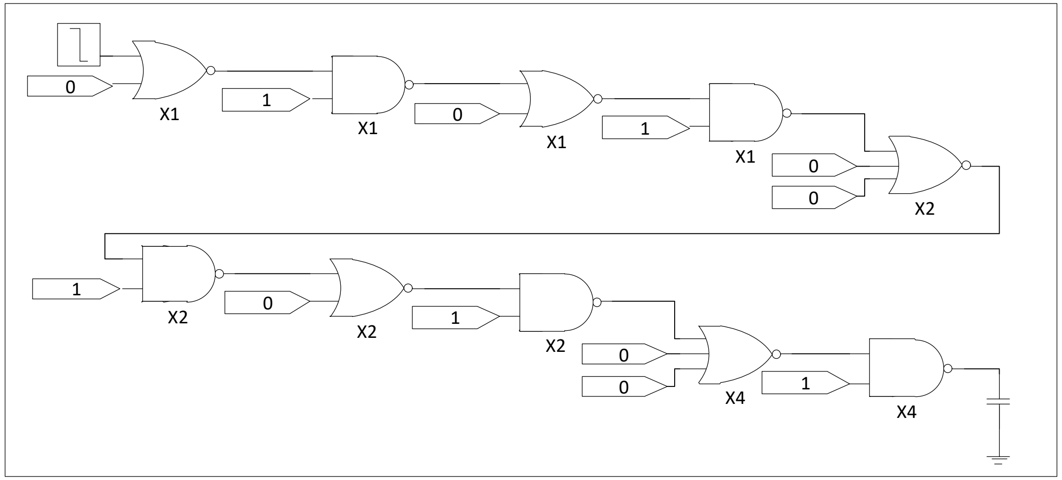
Simulation of Both RTN and BTI at System Level: Case Study



(a)

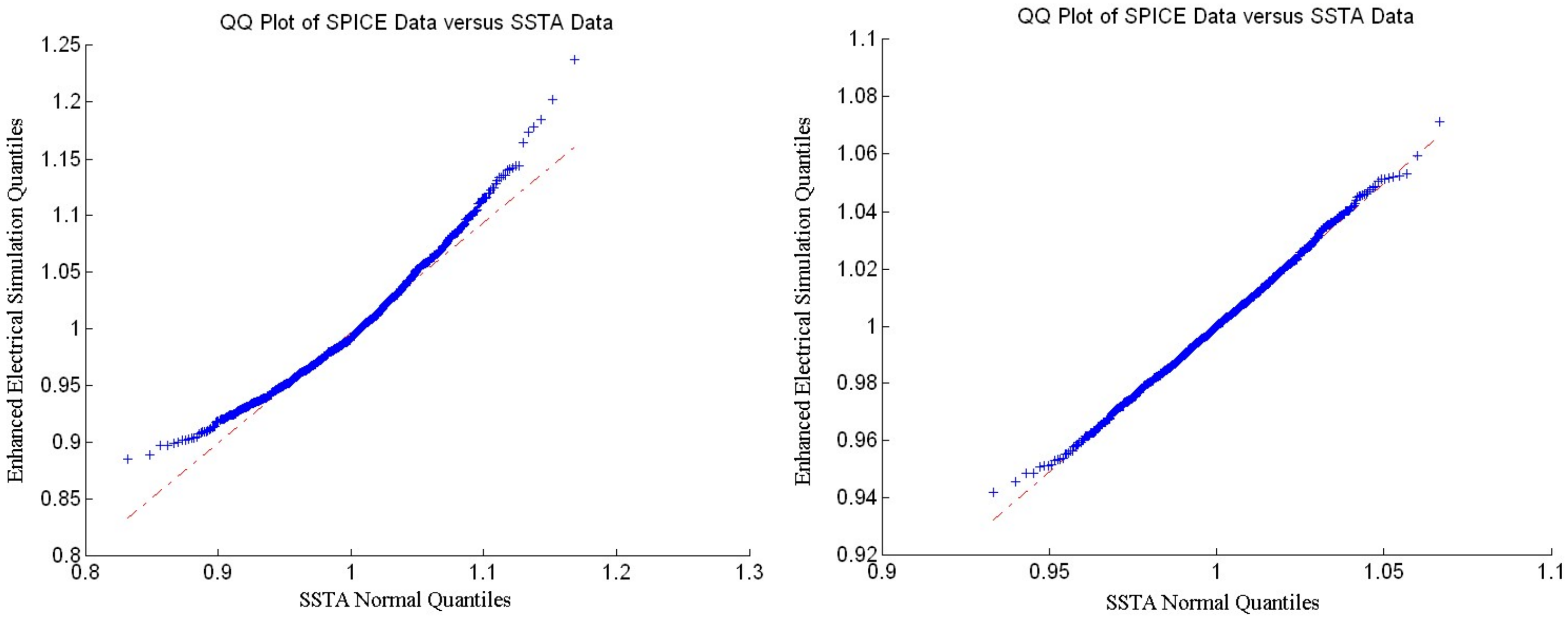


(b)



(c)

Simulation of Both RTN and BTI at System Level: Case Study



(a) (b)

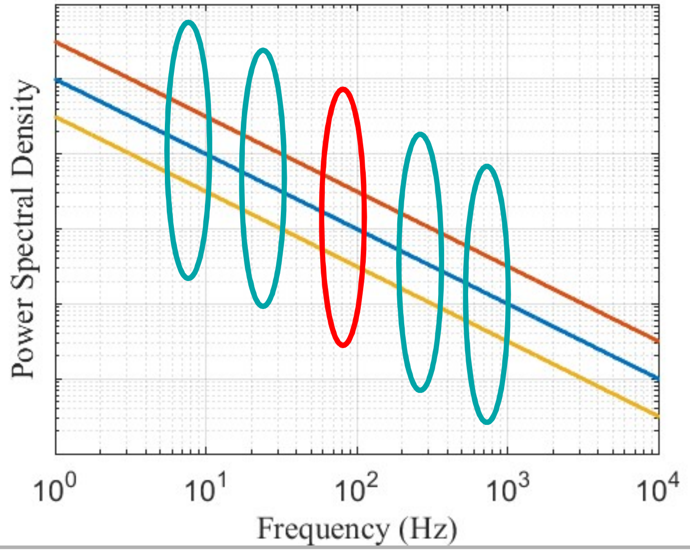
Q-Q plot of normalized delay after 10^4s

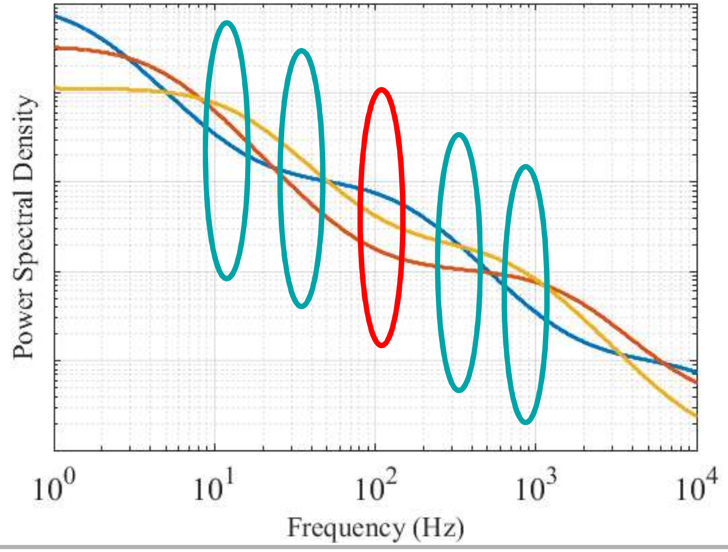
(a) Path 1 (b) Path 2

Considering time zero variability

Autocorrelation Analysis

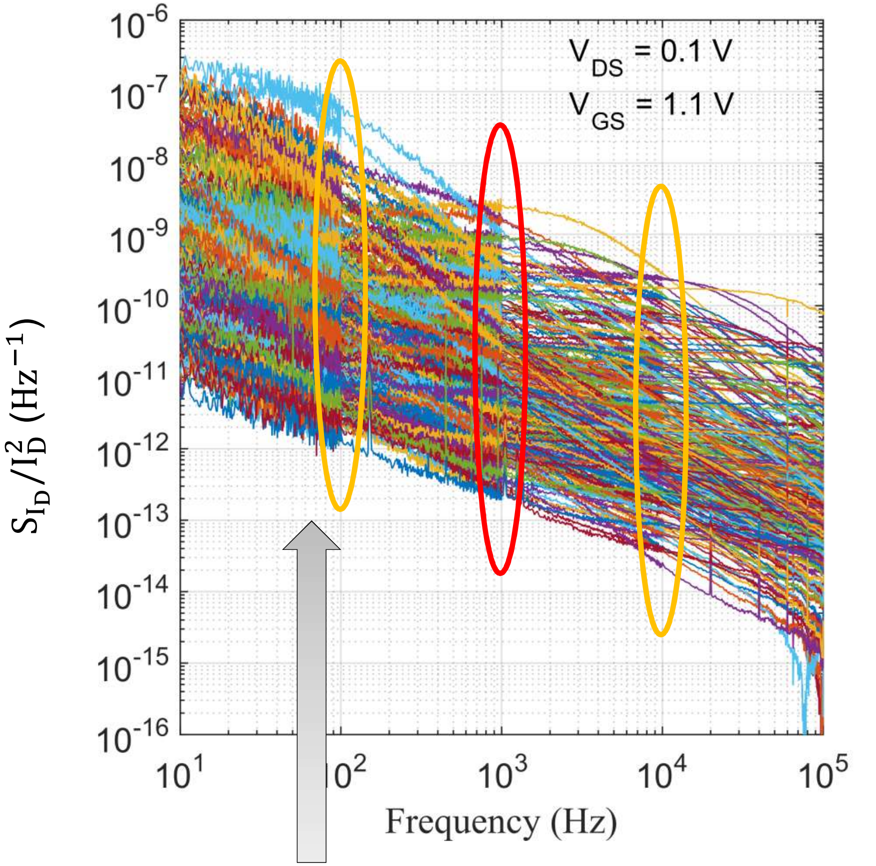
- Calculates how the random variable $S_{I_D}(f)$ relates to the random variable $S_{I_D}(f + \Delta f)$.
- If the noise spectra were perfectly 1/f, then the correlation coefficient would always be equal to 1.
- Sensitive to the frequency dependence of the fundamental noise sources underlying the LFN

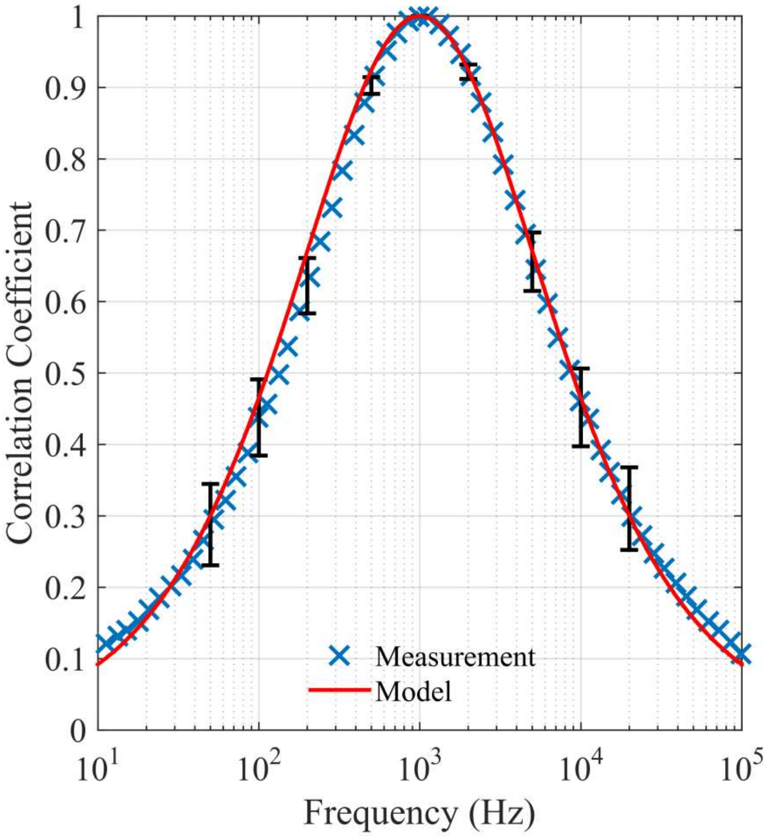




Autocorrelation Analysis

SMALL Area NFET $0.3 \times 0.04 \mu m^2$ (40-nm)



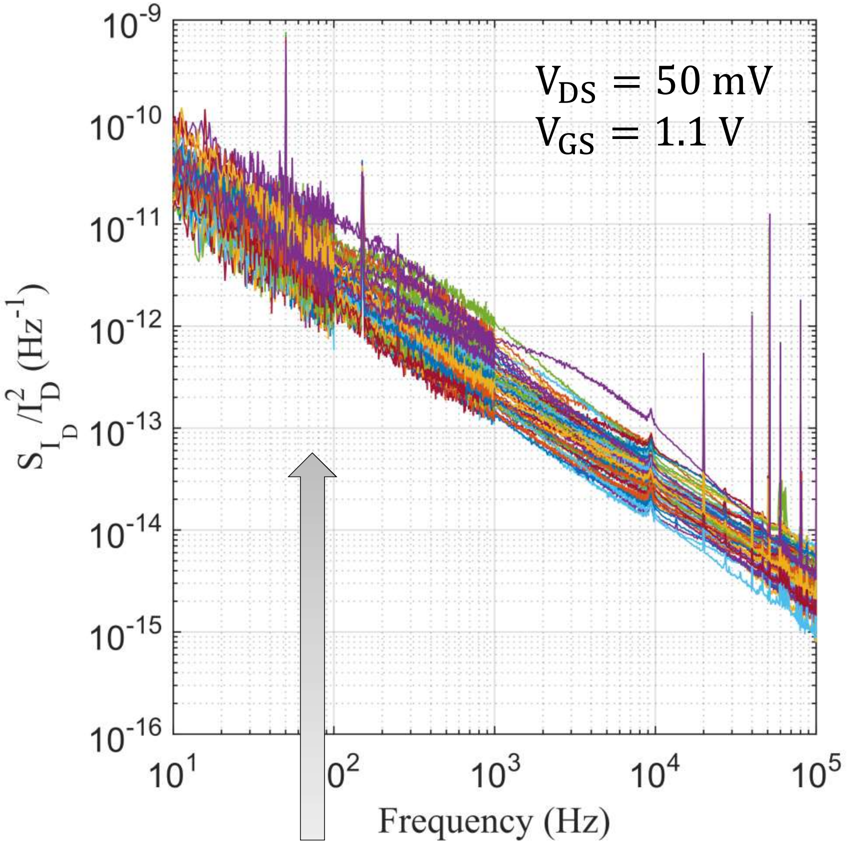


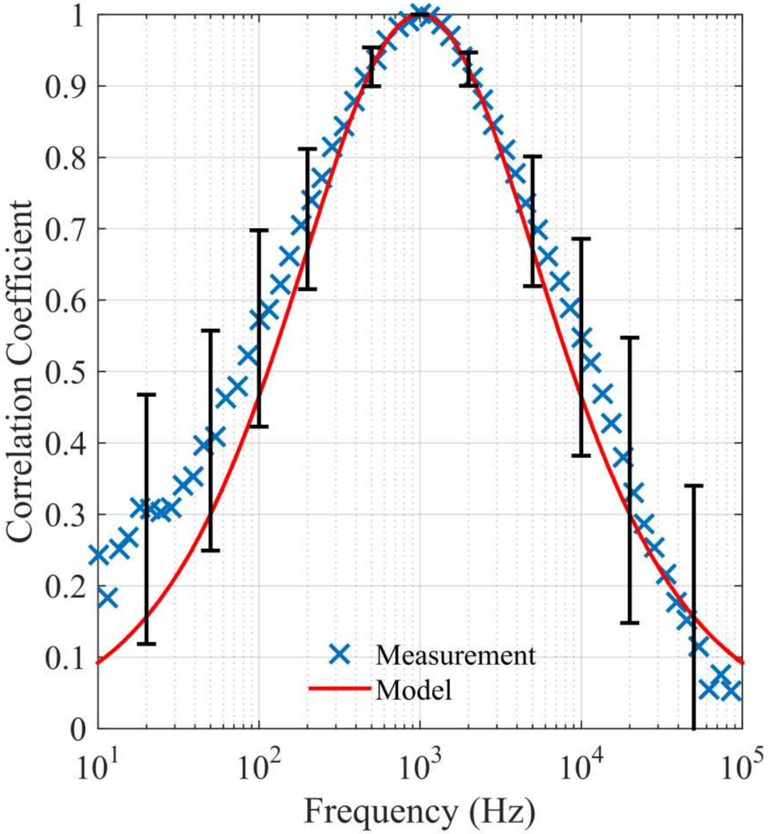
Intertwining! (Shuffling)

$$R[S_{I_D}(f_1), S_{I_D}(f_2)] = \frac{2\ln(f_1/f_2)}{(f_1^2 - f_2^2)} f_1 f_2$$

Autocorrelation Analysis

LARGE Area NFET $16 \times 0.2\mu m^2$(40-nm)

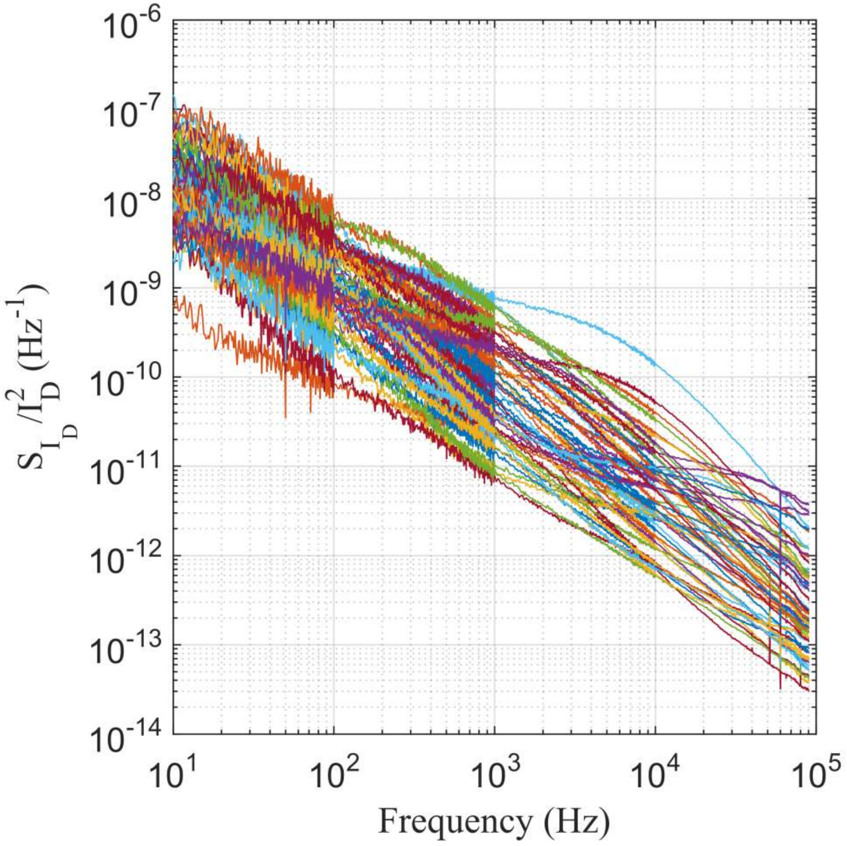


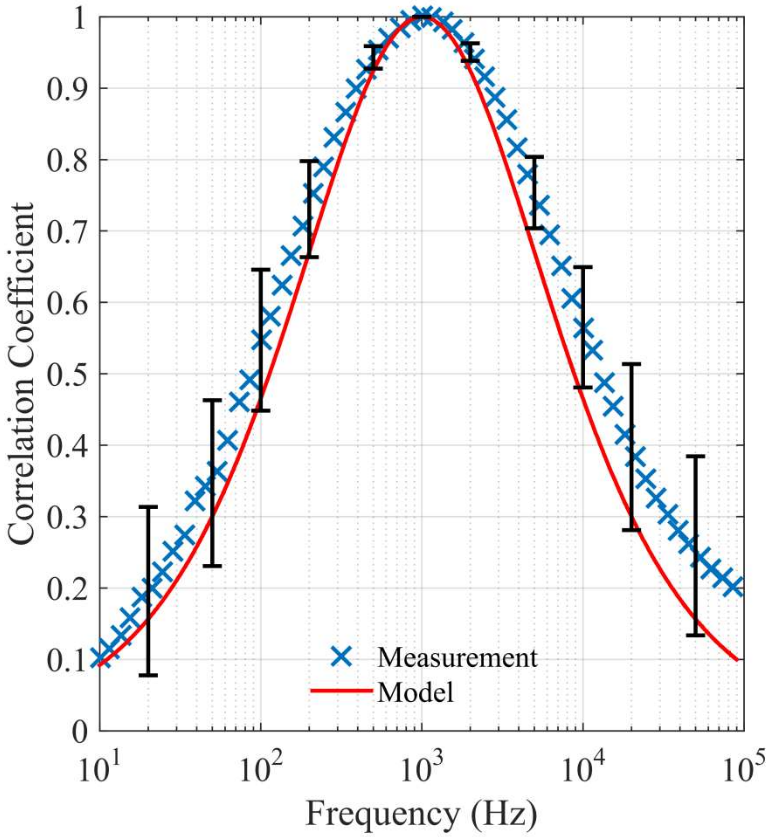


Intertwining! (Shuffling)

Autocorrelation Analysis

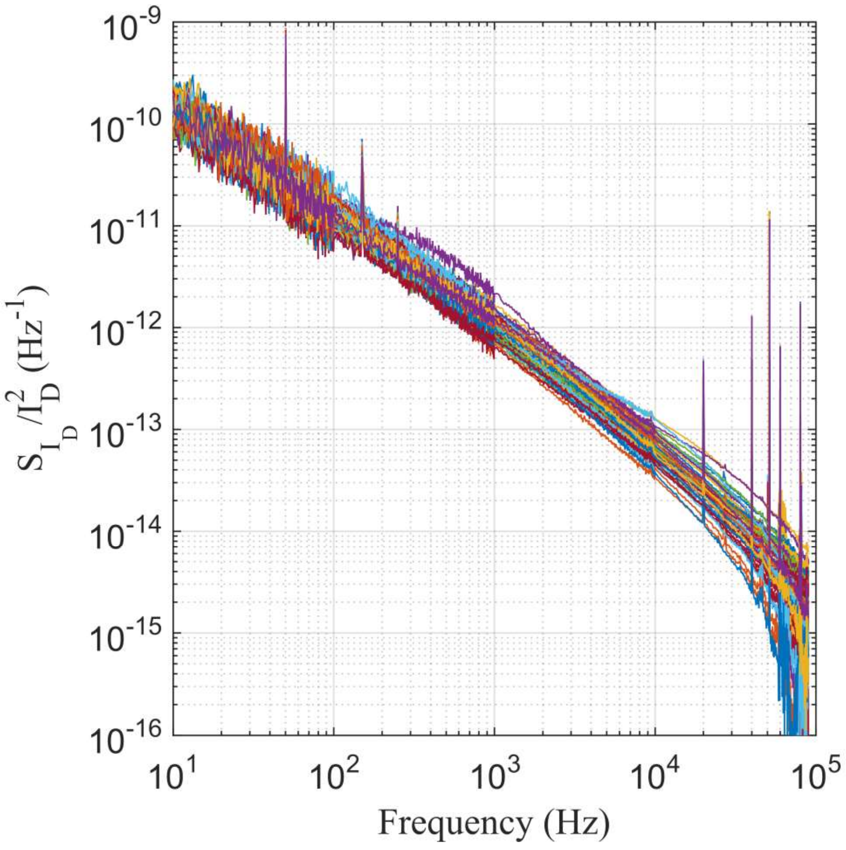
SMALL Area PFET $1 \times 0.04\mu m^2$ (40-nm)

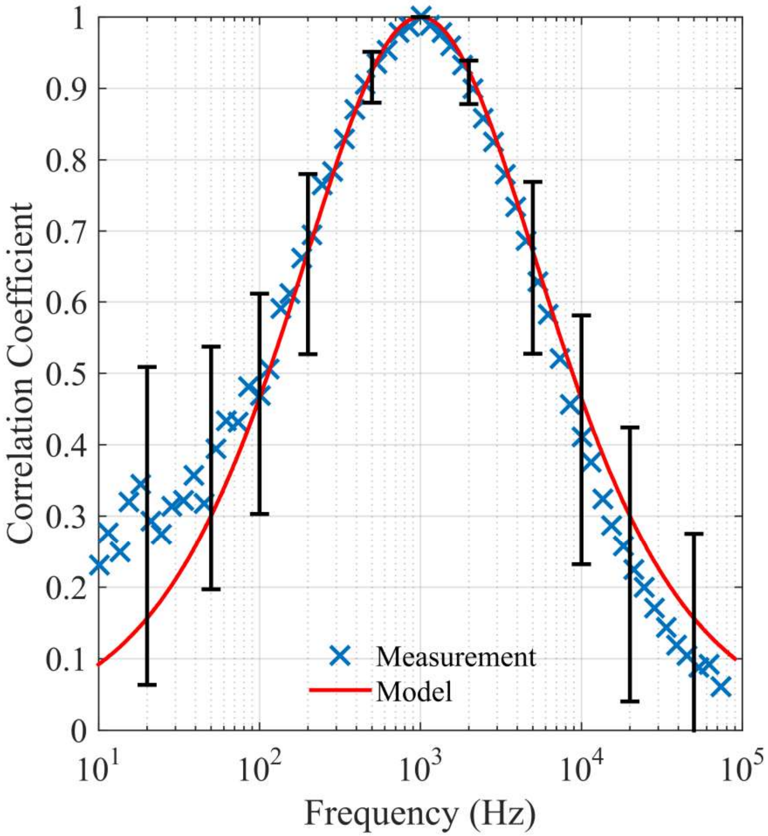




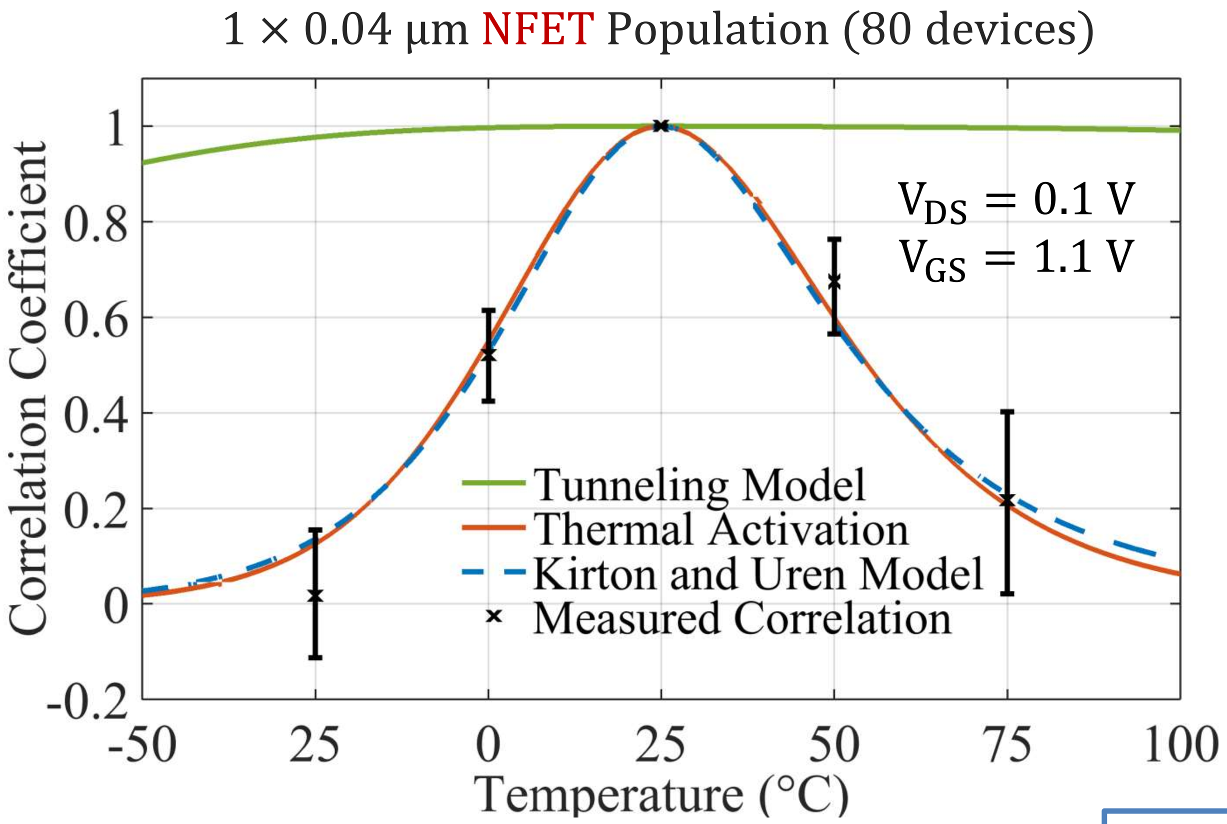
Autocorrelation Analysis

LARGE Area PFET $16 \times 0.2\ \mu m^2$ (40-nm)





Temperature Autocorrelation



Strong temperature dependence indicate thermal activation!

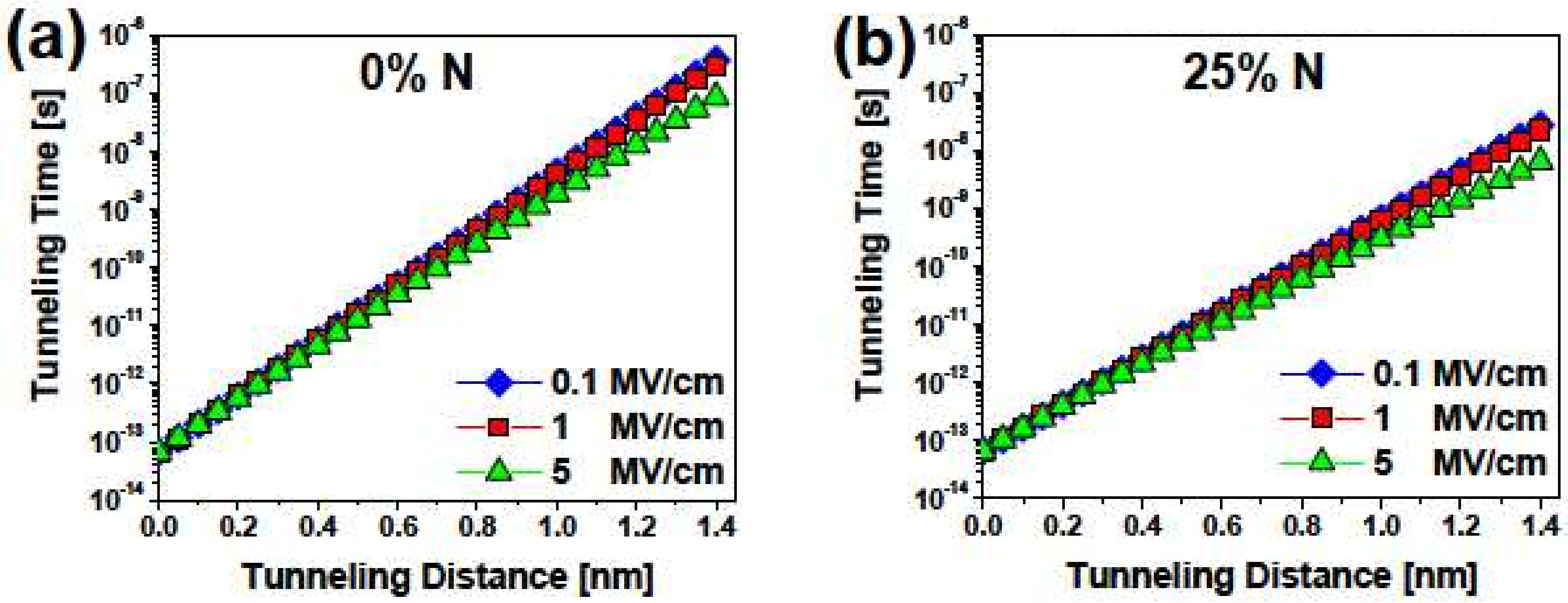
$$\tau = \tau_0 \cdot \exp(z/z_0)$$

$$\tau = \tau_0 \cdot \exp(E_B/kT)$$

$$\tau = \tau_0 \cdot \exp\left(z/z_0 + \frac{E_B}{kT}\right) \cdot \frac{\beta}{1+\beta}$$

Thermal activation fits.

Time Constants and Tunneling



Tunneling front calculations for various dielectric fields and for pure SiO_2 (a) and 25% N SiON (b).

Time constants are inconsistent with elastic tunneling [Campbell et al, 2009].

Conclusion

A microscopic, statistical modeling approach for charge trapping is presented.

It is applied to study the role of charge trapping and de-trapping in Noise and BTI.

Mutual relation between different reliability phenomena (LF noise, BTI and RDF) is discussed.

The modeling approach may be applied for time domain (transient) or frequency domain analysis.

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