Charge Trapping Phenomena in MOSFETs: From Noise to Bias Temperature Instability

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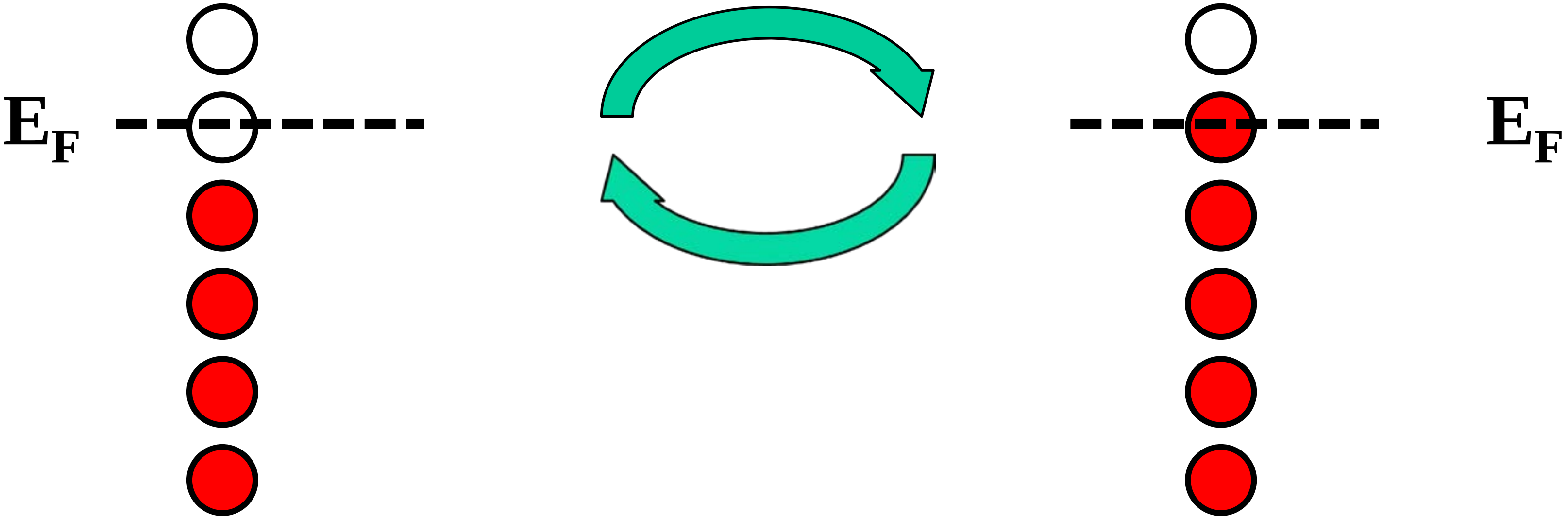
Outline

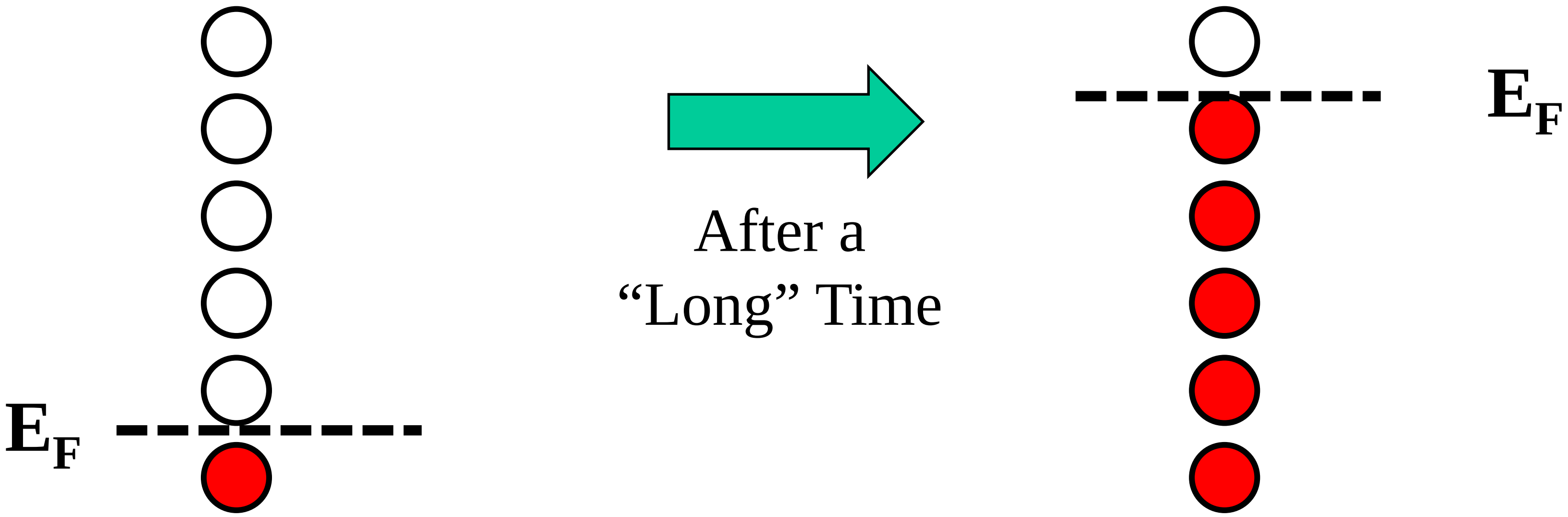
- Our Modeling Approach for Charge Trapping
- Low-Frequency Noise:
  - Frequency Domain Models (DC and AC Large Signal)
  - Time Domain Analysis and Simulation
- NBTI: Charge Trapping Component
- Amplitude of the ΔV_T Induced by a Trap
- Conclusion

Low-Frequency Noise



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

Charge Trapping Component of BTI



Transistor Off

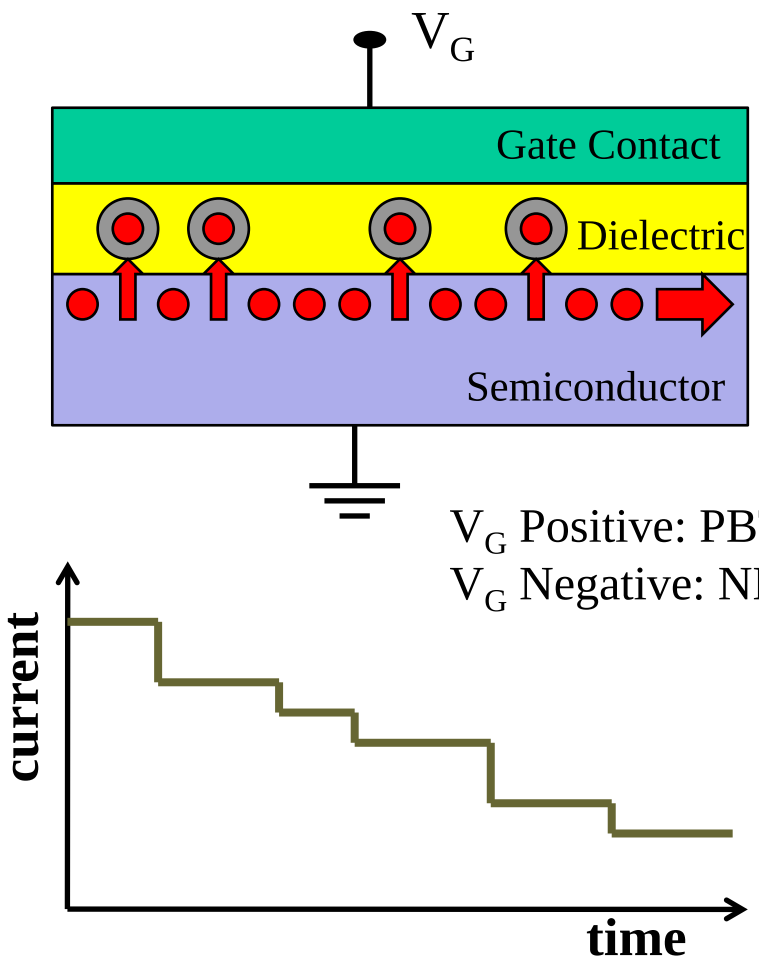
After a
“Long” Time

Transistor On

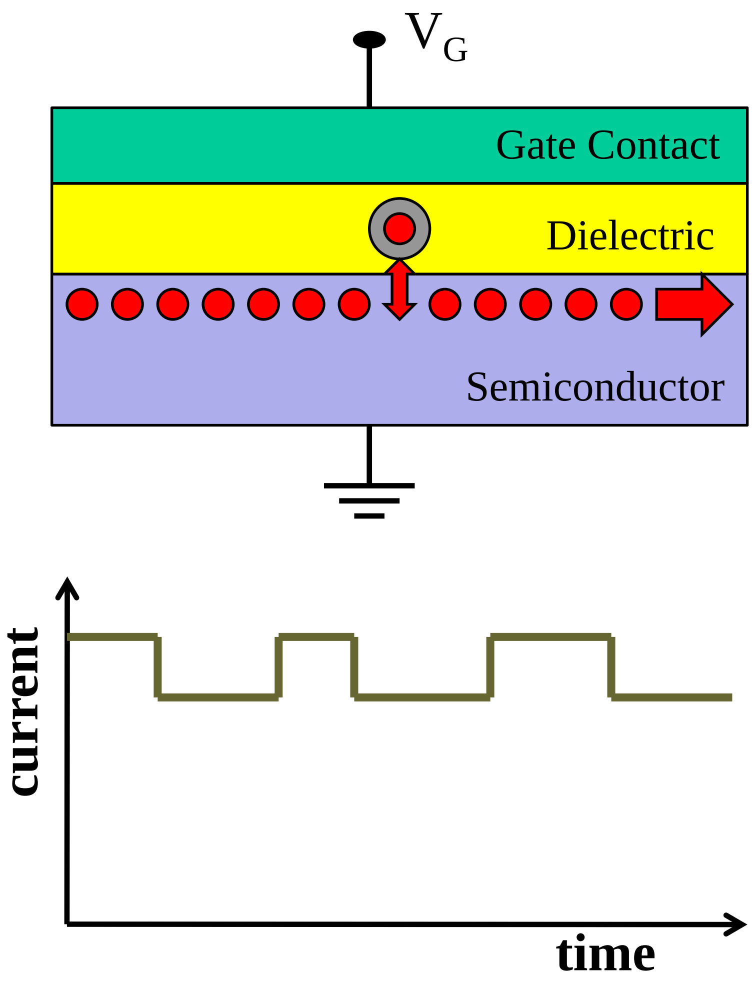
Traps Mostly Empty

Traps Mostly Occupied

BTI x RTS



V_G Positive: PBTI
V_G Negative: NBTI



BTI x RTS

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.**
4. **Trap energy distribution is assumed to be U shaped (key to explain the AC behavior).**

Some Advantages of our Approach

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).**
4. **Can be Applied to Different Phenomena where Charge Trapping Plays a Role, such as Noise and NBTI.**

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 Many Traps

- Average Value

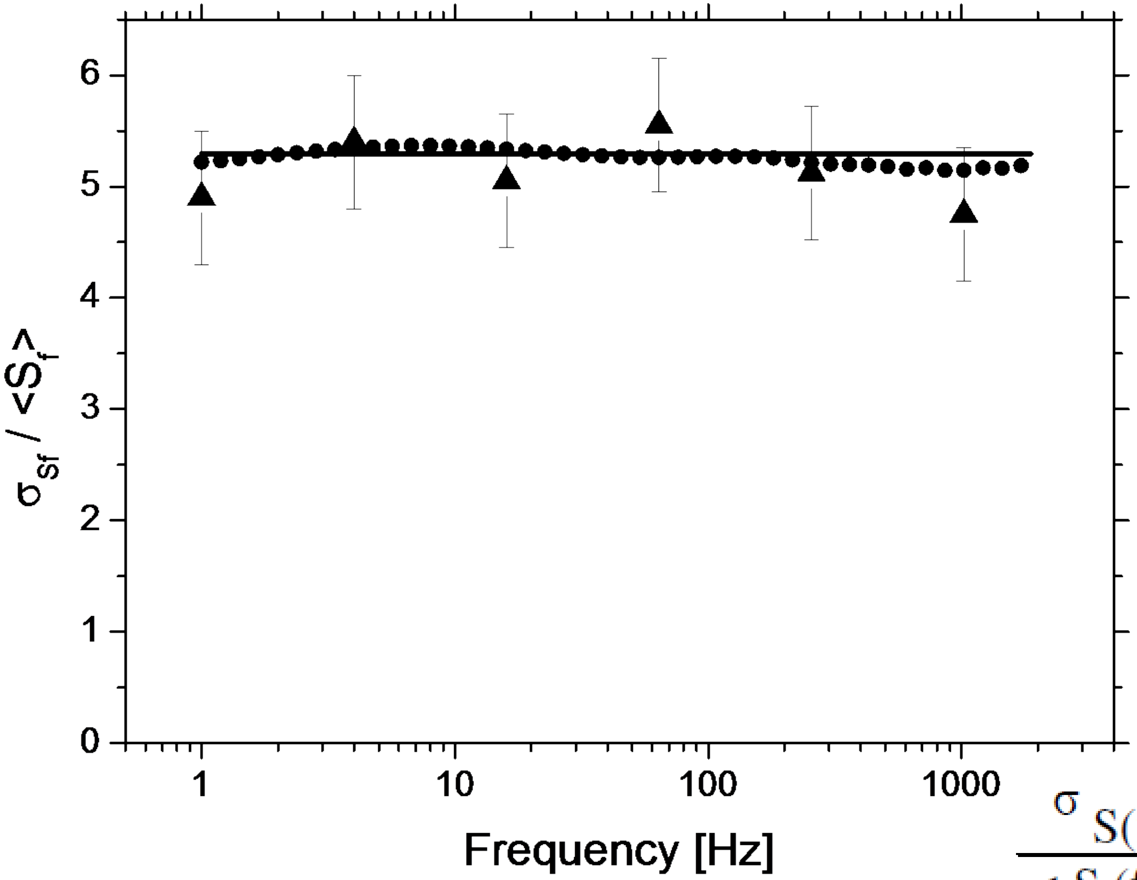
$$< S(f) > = \frac{<A^2> N_{dec} WL}{f} \frac{\pi}{2}$$

- 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

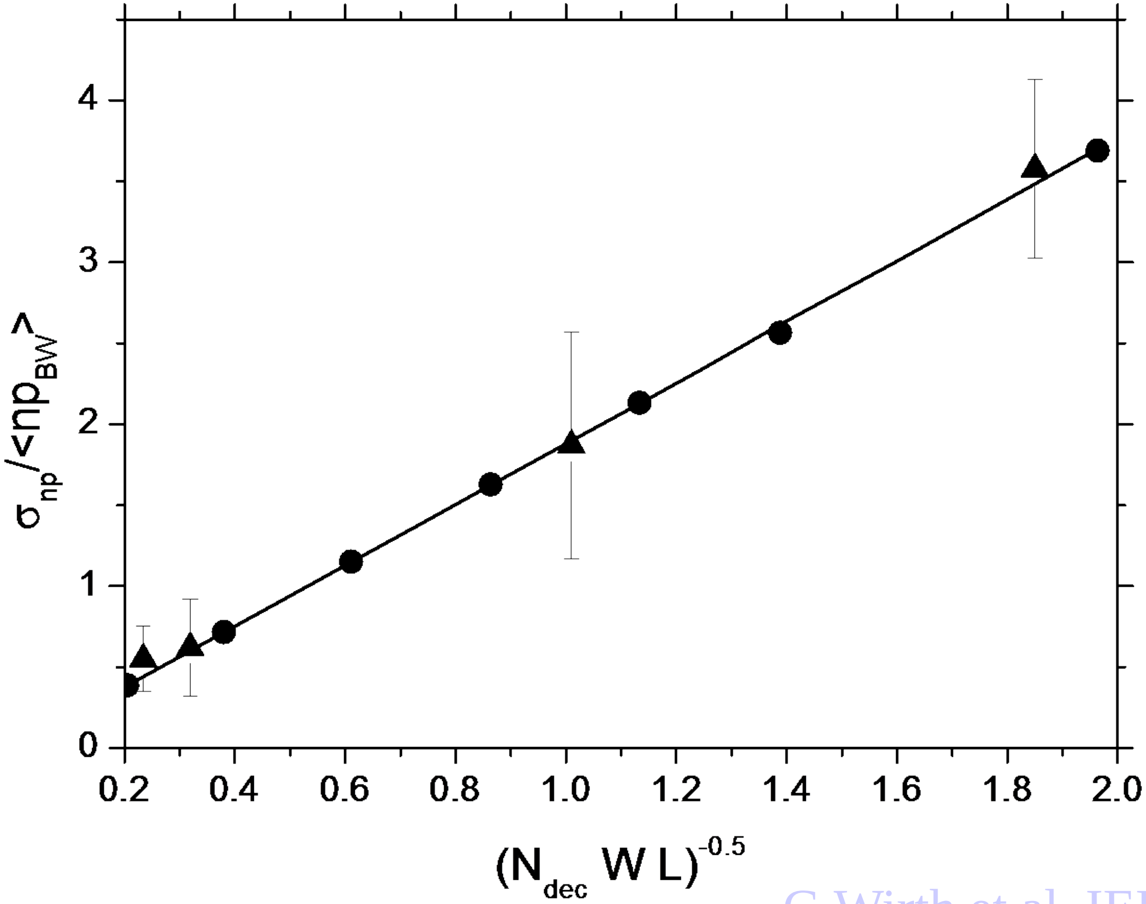
Variability: Dependency on Frequency



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

G Wirth et al. IEEE Trans Electron Dev, 2007

Variability Scaling



Triangles: Measurement
Dots: Monte Carlo Simulation
Line: Model

G Wirth et al. IEEE Trans Electron Dev, 2005

Low-Frequency Noise

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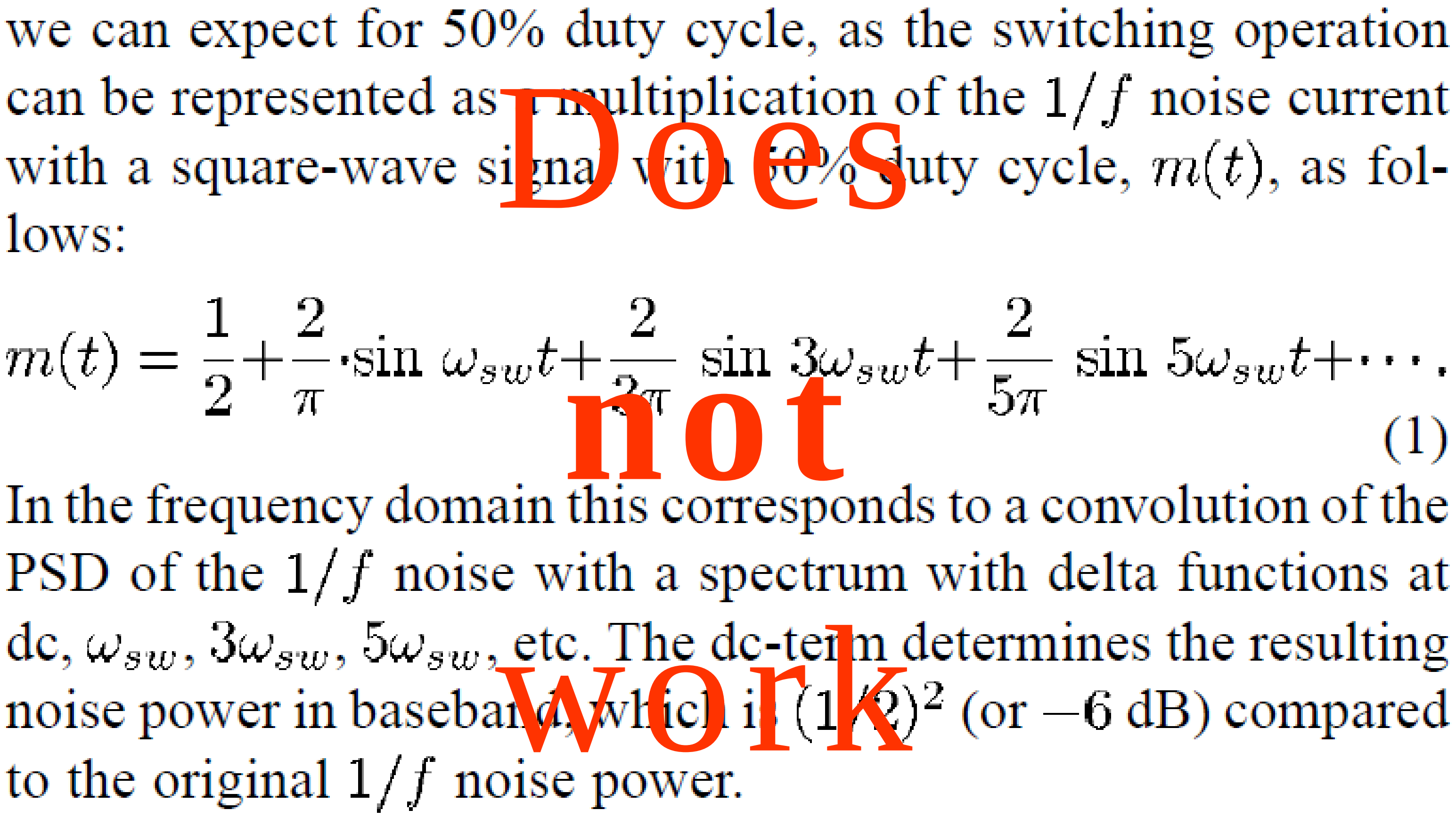
Switched Bias: Modulaton Theory



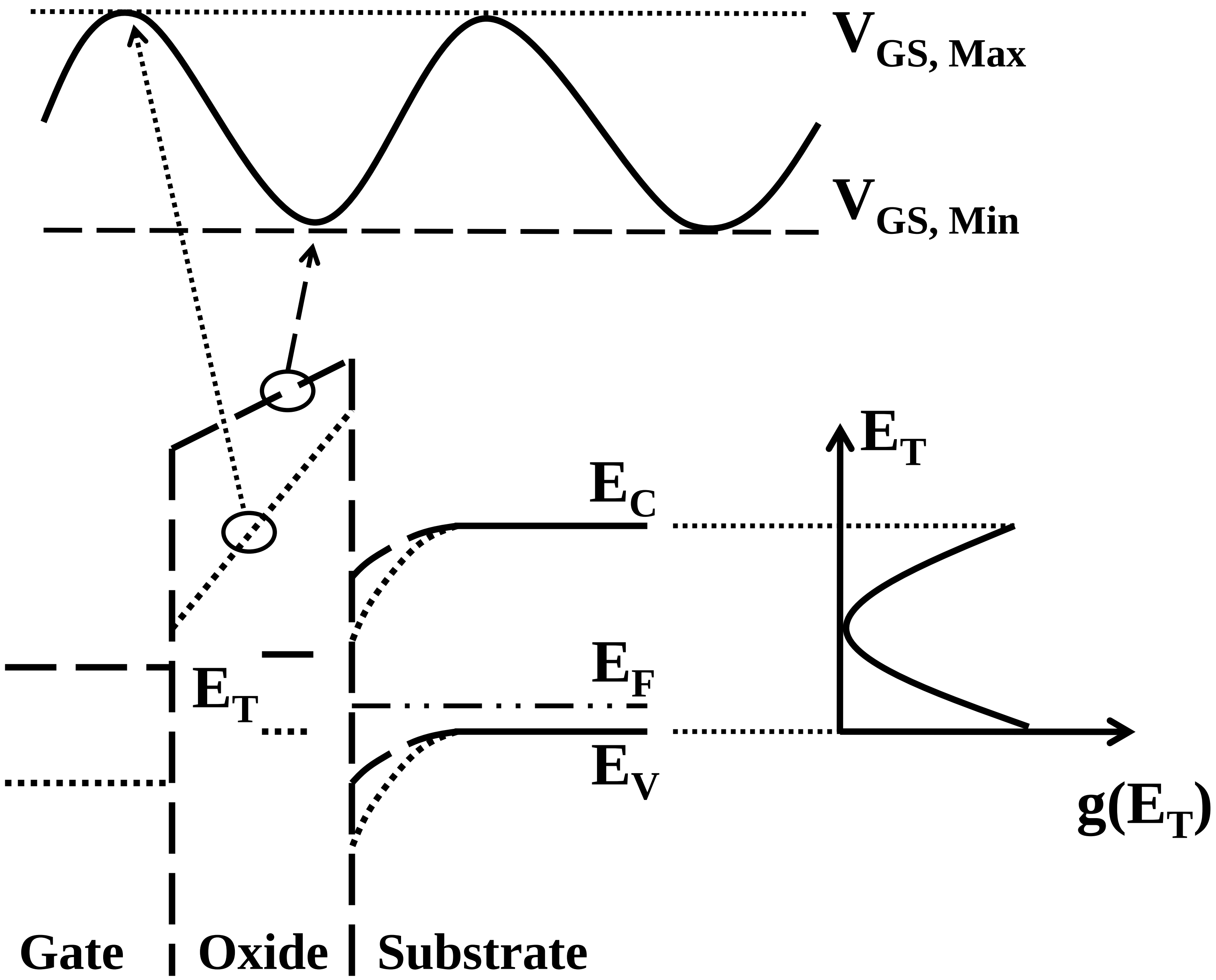
we can expect for 50% duty cycle, as the switching operation can be represented as a multiplication of the $1/f$ noise current with a square-wave signal with 50% duty cycle, $m(t)$, as follows:

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

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.

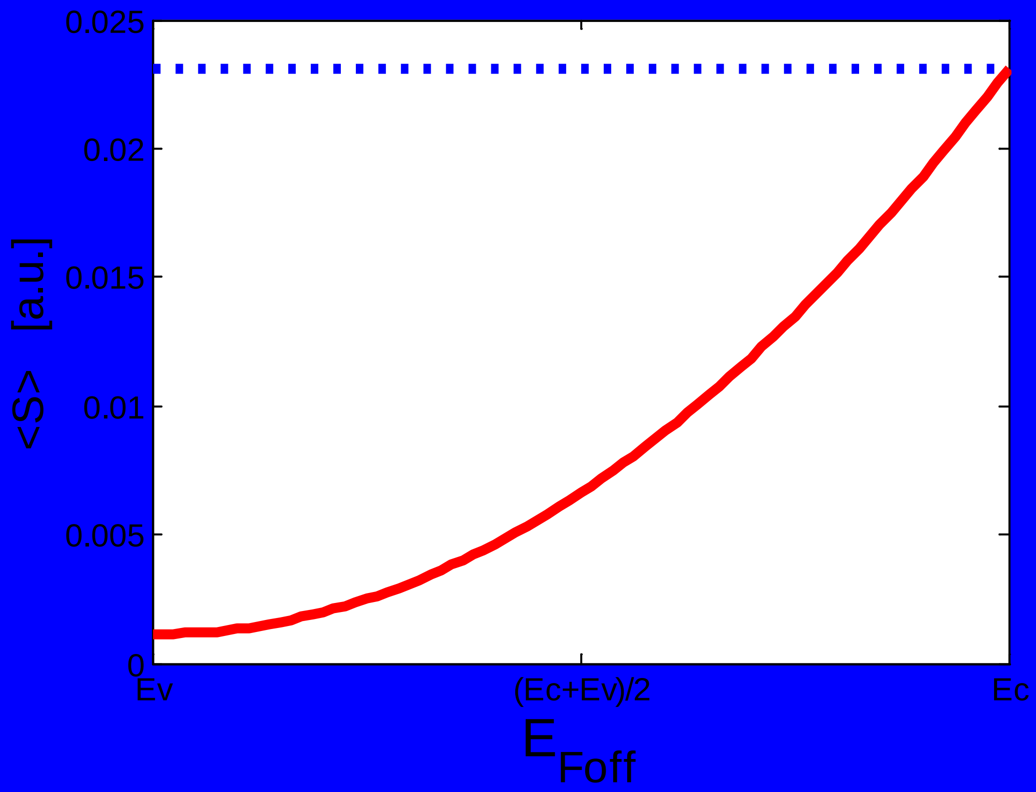
Does not work

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


$V_{GS,\ Max}$
$V_{GS,\ Min}$
E_T
E_C
E_F
E_V
E_T
$g(E_T)$
Gate
Oxide
Substrate

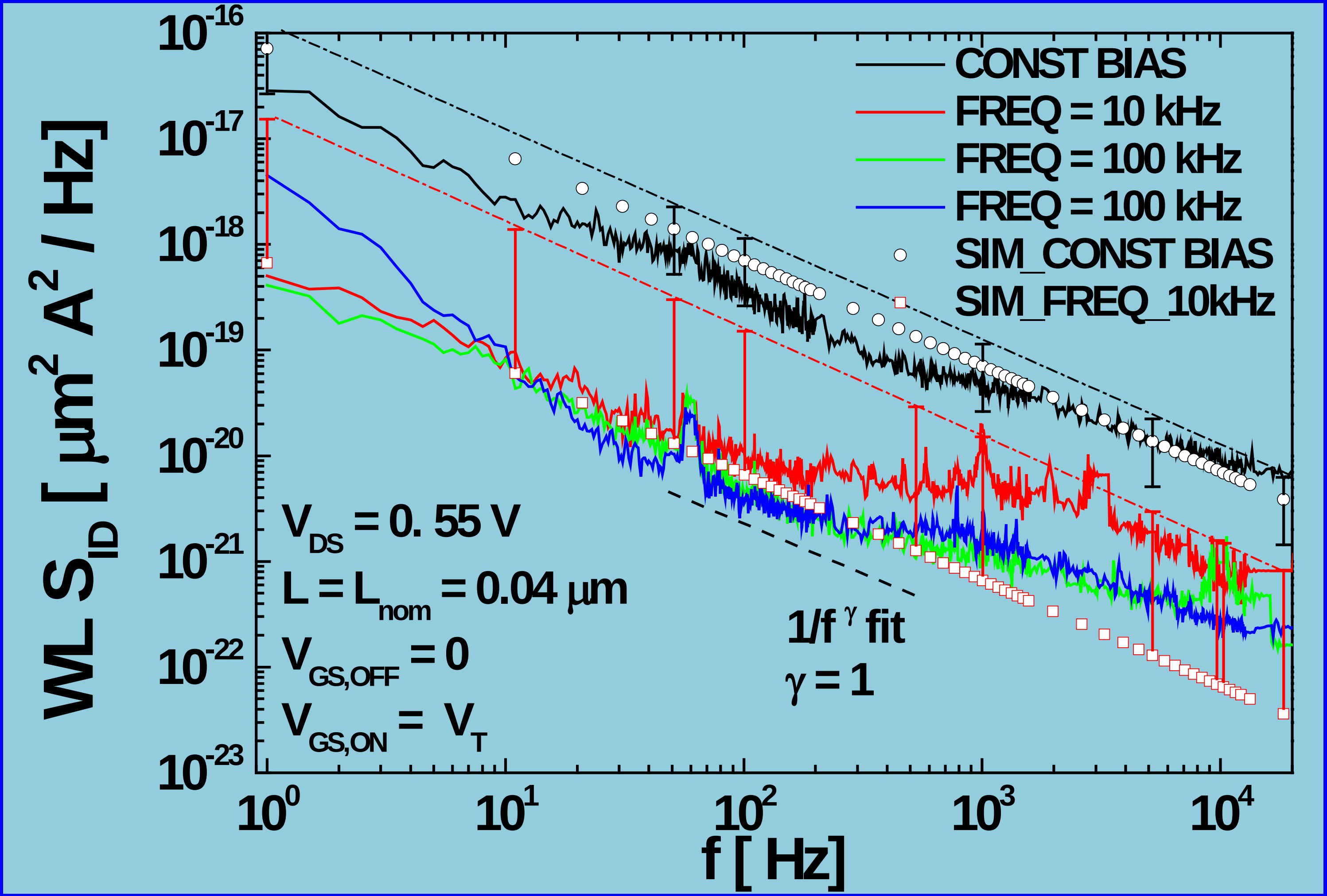
Switched Bias: Noise Mean Value Decreases

Noise power as a function of the Fermi level in the off phase



Noise power as a function of the Fermi level in the off phase. In the on phase of the device, the Fermi level is assumed to be fixed, close to the conduction band. The blue dotted line shows the behavior as predicted by standard models used today (e.g. BSIM). The red solid line shows the behavior as predicted by the model here presented.

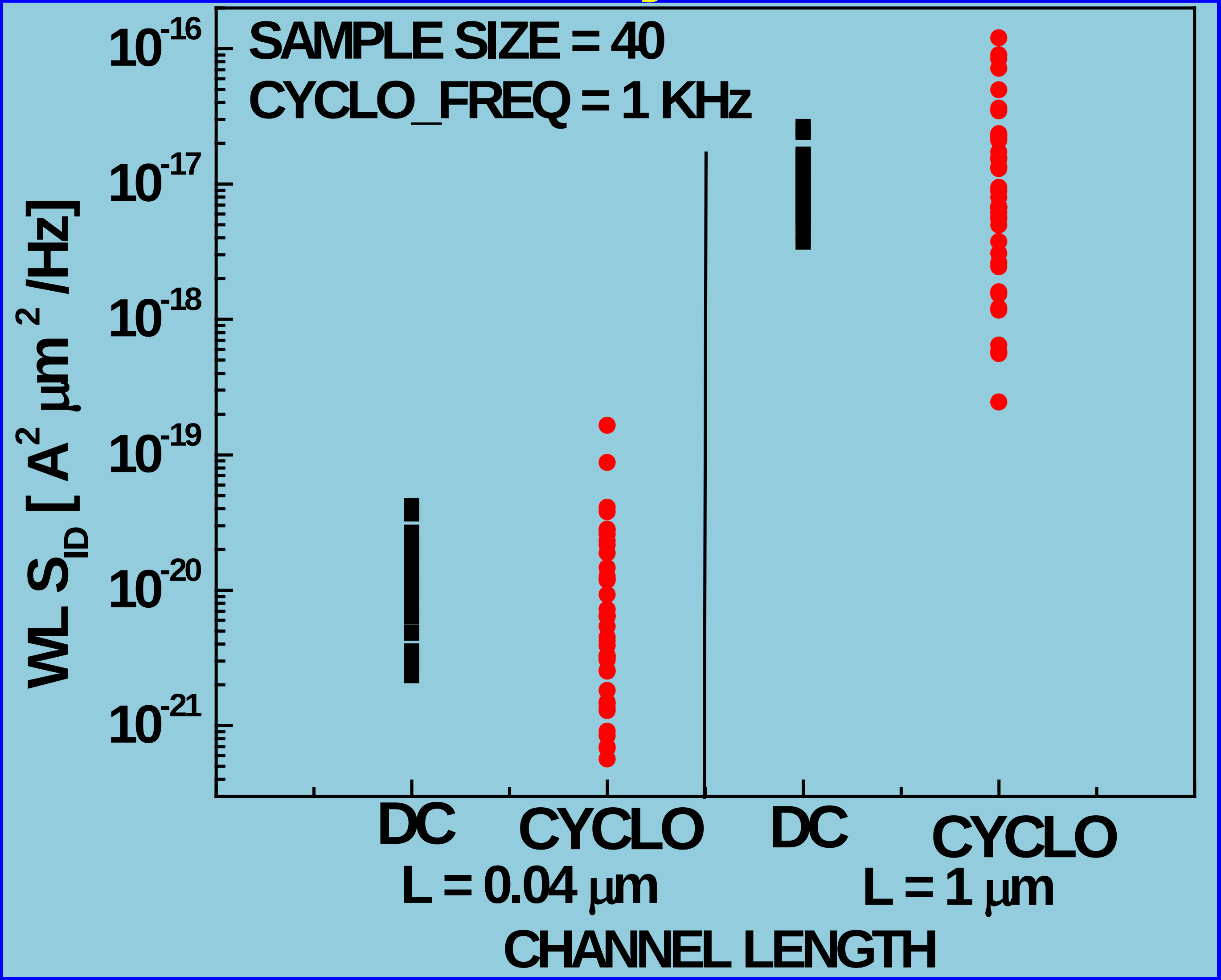
Noise Reduction under Cyclo-Operation



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

G Wirth et al. iedm 2009

Normalized Variability of Noise Behavior



Variability is seen to increase under Cyclo-Stationary Operation.

G Wirth et al. iedm 2009

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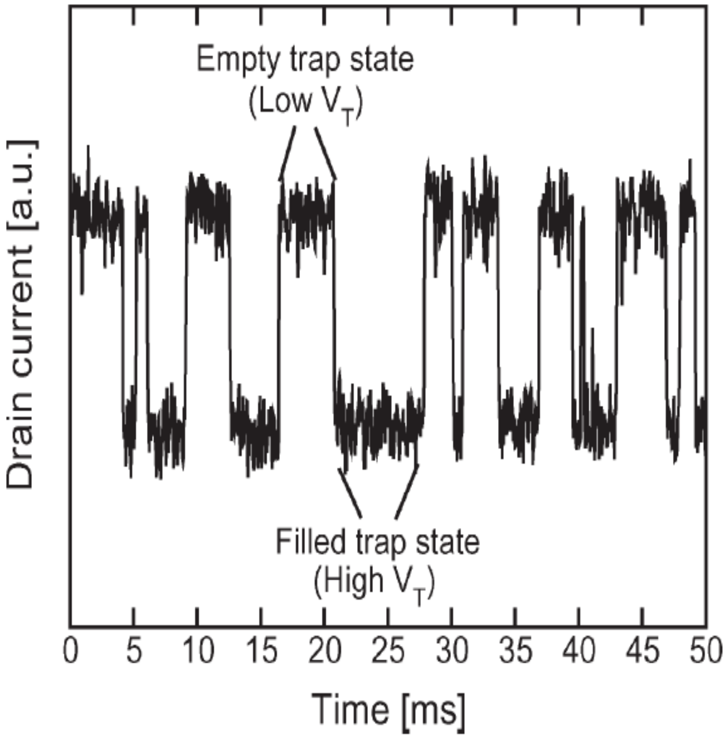
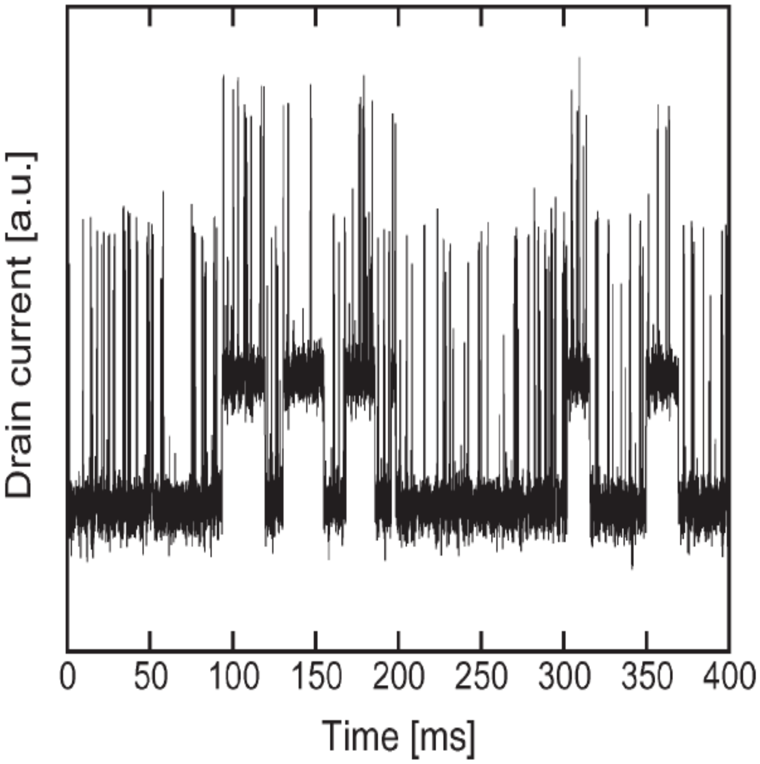
- Time Domain (Transient) Analysis and Simulation

RTS and Time Domain

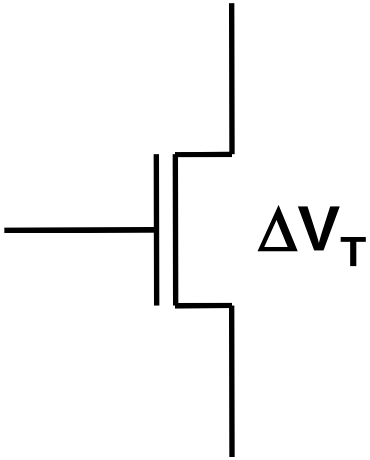




V_T Fluctuations

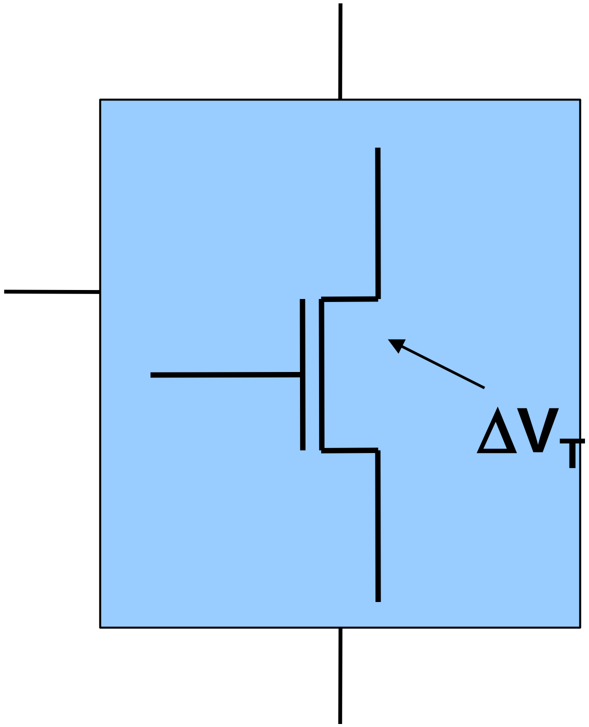
Possible Simulation Methodologies

Static

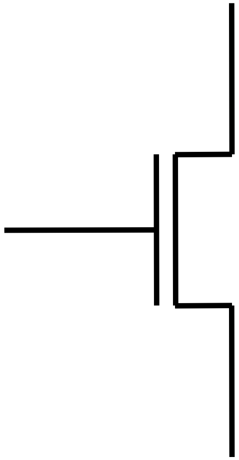


Change dVt at instantiation

Dynamic



Verilog-A wrapper to Trans. model



Ids = … + f(delvto(t))

Change transistor Model equations

RTS: Transient Simulation (1)

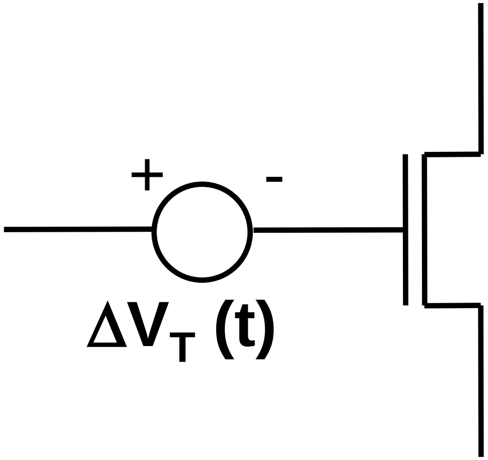
- Charge trapping and de-trapping are stochastic events, governed by capture and emission time constants, $\boldsymbol{\tau_c}$ and $\boldsymbol{\tau_e}$, which are uniformly distributed on a log-scale;
- the number of traps ($\boldsymbol{N_{tr}}$) is assumed to be Poisson distributed, and the average number of traps (parameter of the Poisson) is assumed to be proportional to the channel area;
- trap energy distribution, $\boldsymbol{g(E_T)}$, 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.

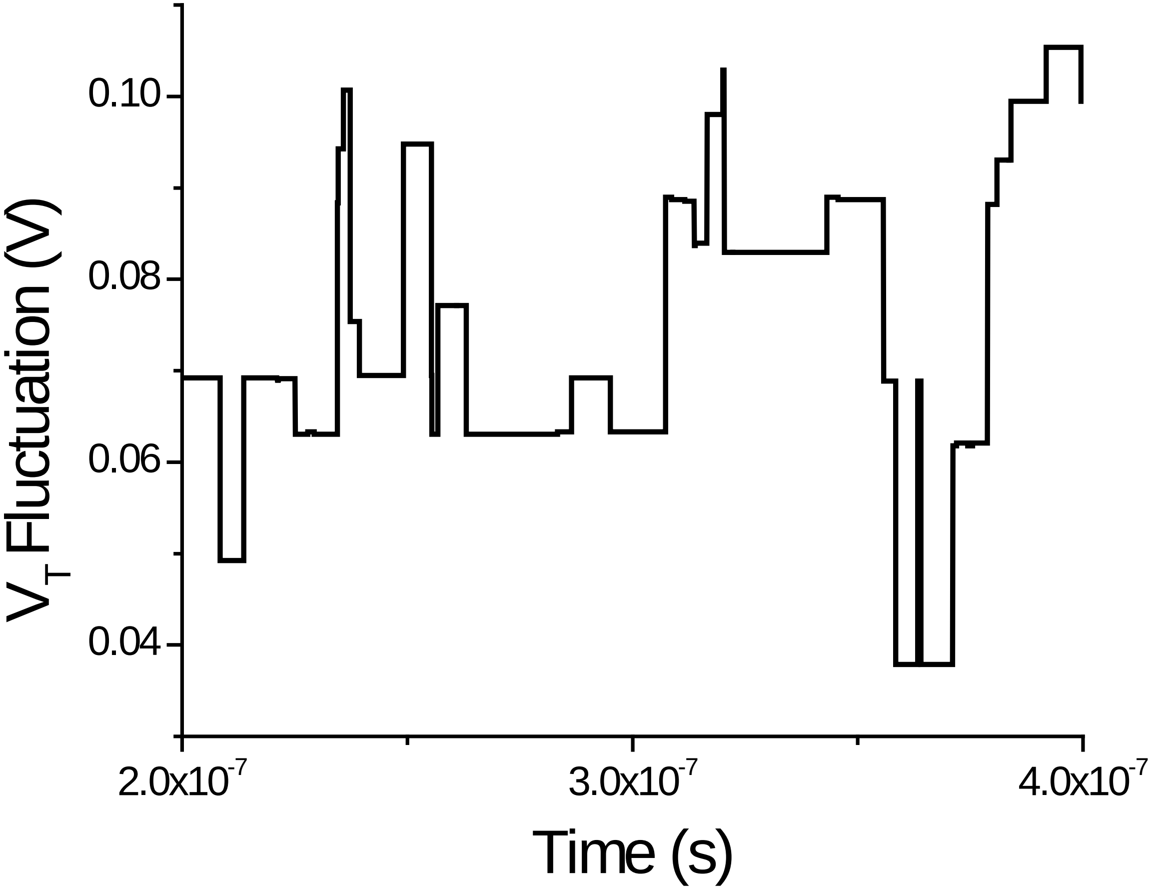
RTS: Transient Simulation (2)

- 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.

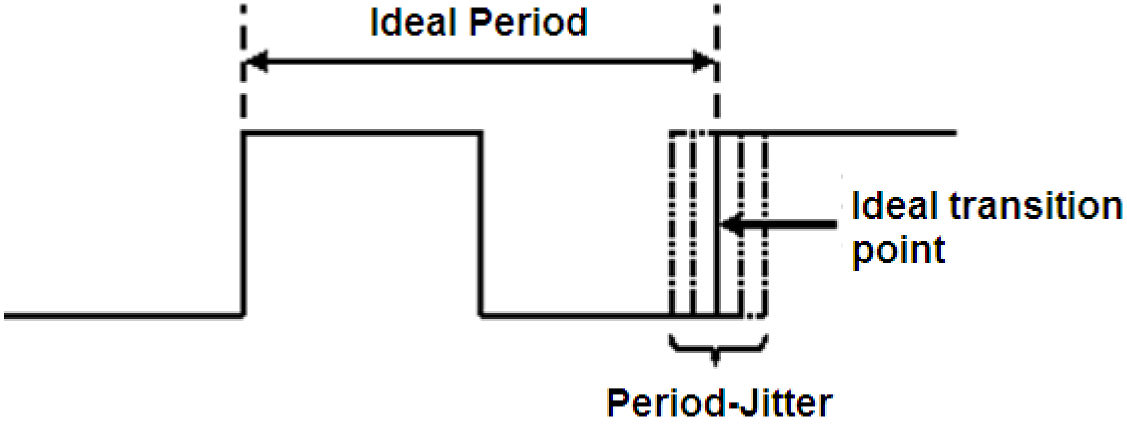
V_T Fluctuates Over Time



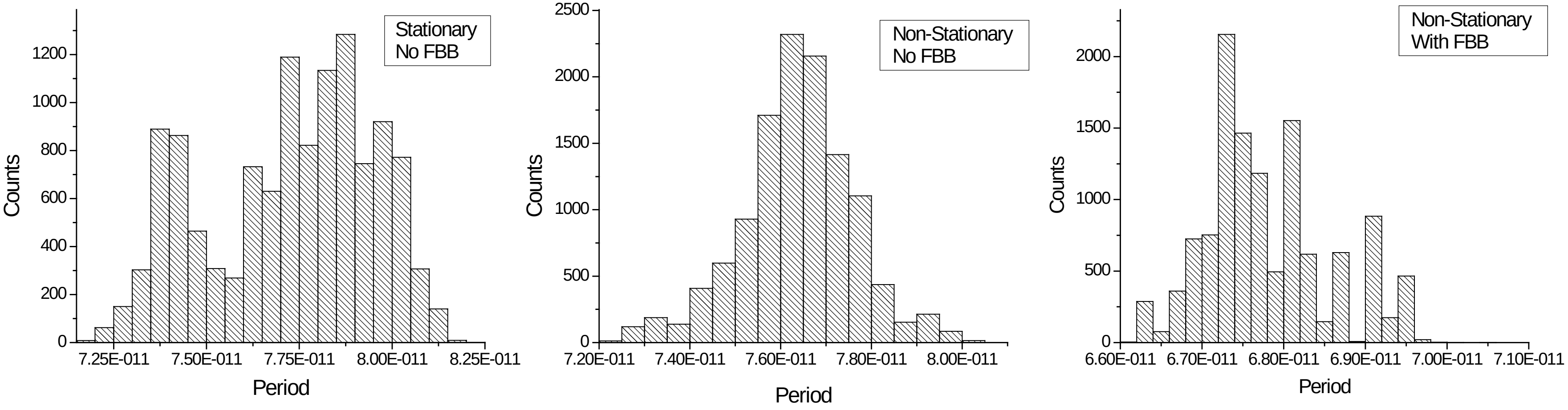


Ring Osc Period Jitter

- **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).



Transient Simulation of a Ring Oscillator



(a) (b) (c)

Histogram of oscillation period:

(a) stationary DC noise analysis,

(b) and (c) non-stationary simulation methodology here proposed.

Case (c) is for the oscillator under forward body biasing (FBB).

Stationary noise analysis predicts a jitter (σ_T) of 2.2ps, non stationary analysis predicts a 1.3ps jitter. FBB decreases σ_T to 0.8ps.

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.)

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NBTI: Charge Trapping Component

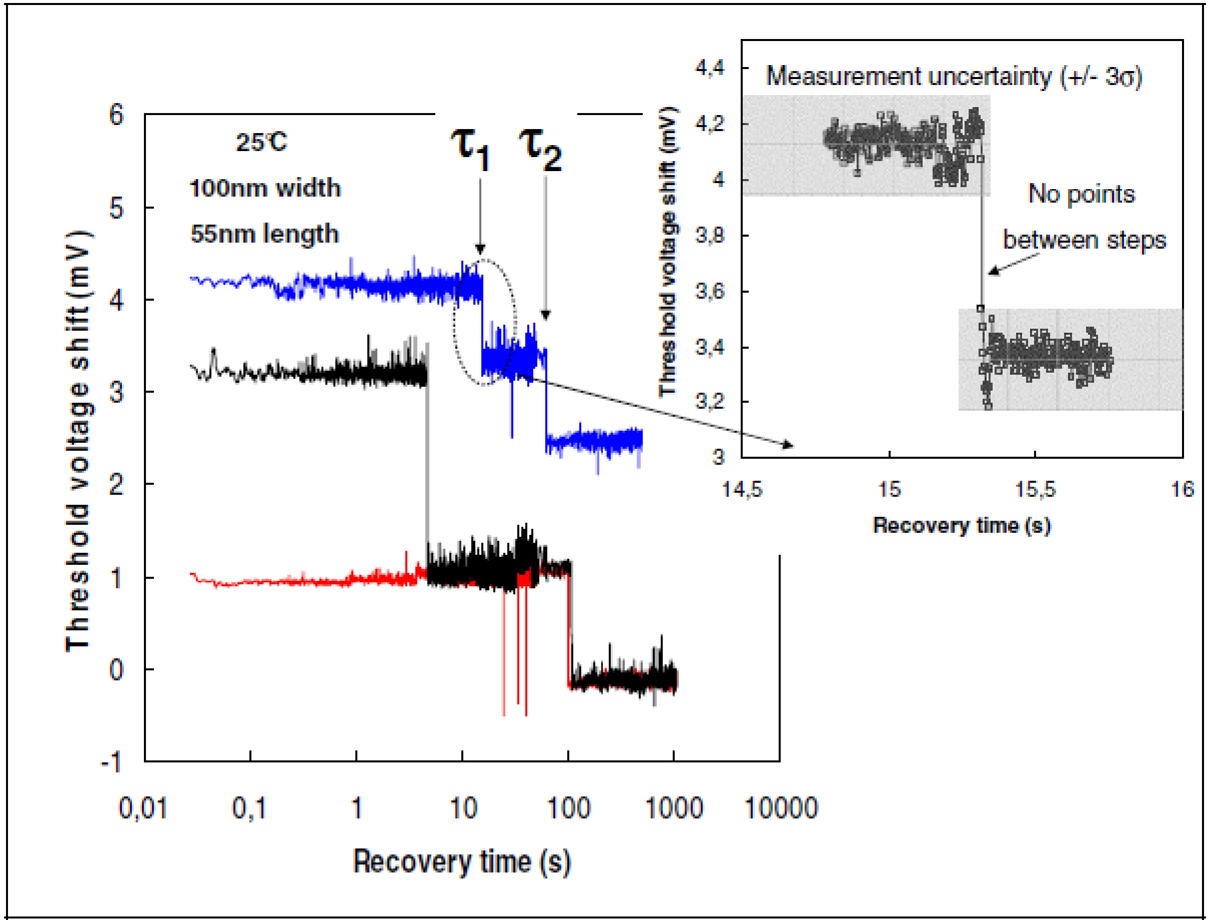
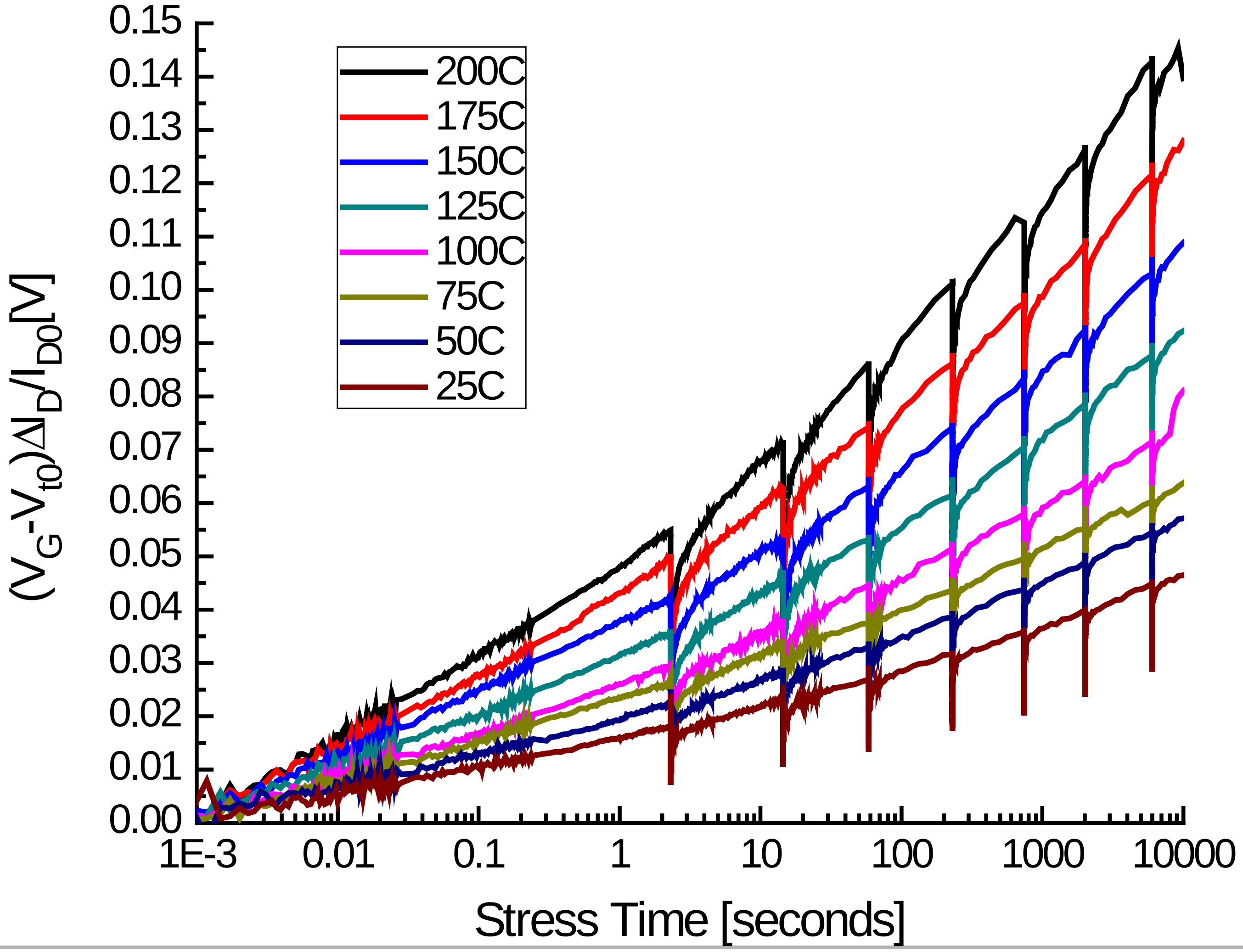


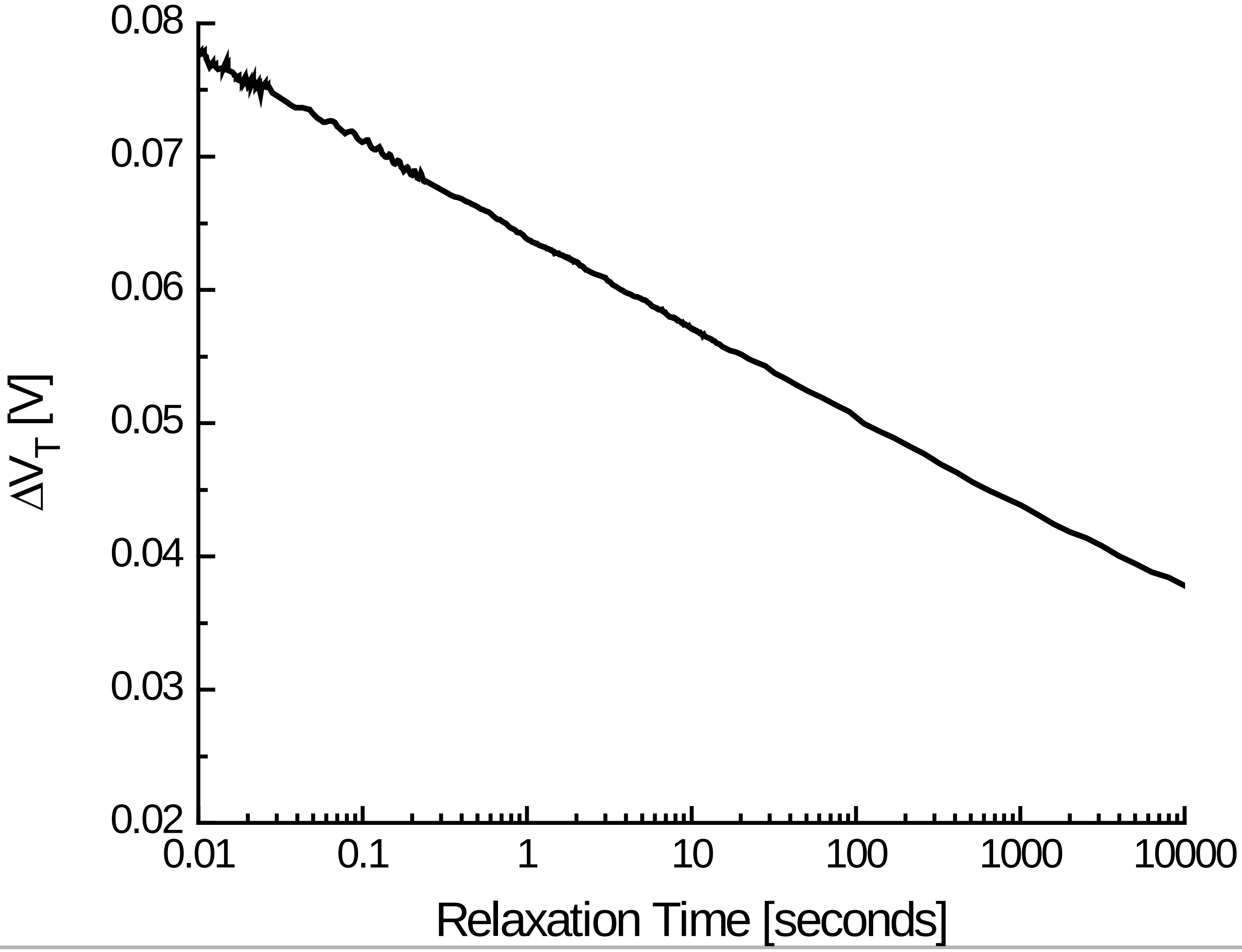
Figure 7: Recovery of V_{TP} shifts for several SRAM-sized devices showing the discrete nature of detrapping events. The inset shows that there are no intermediary values between steps in spite of the small measurement step time (shaded area represents the measurement uncertainty (+/- 3σ).

Huard et al.,
IRPS 2008

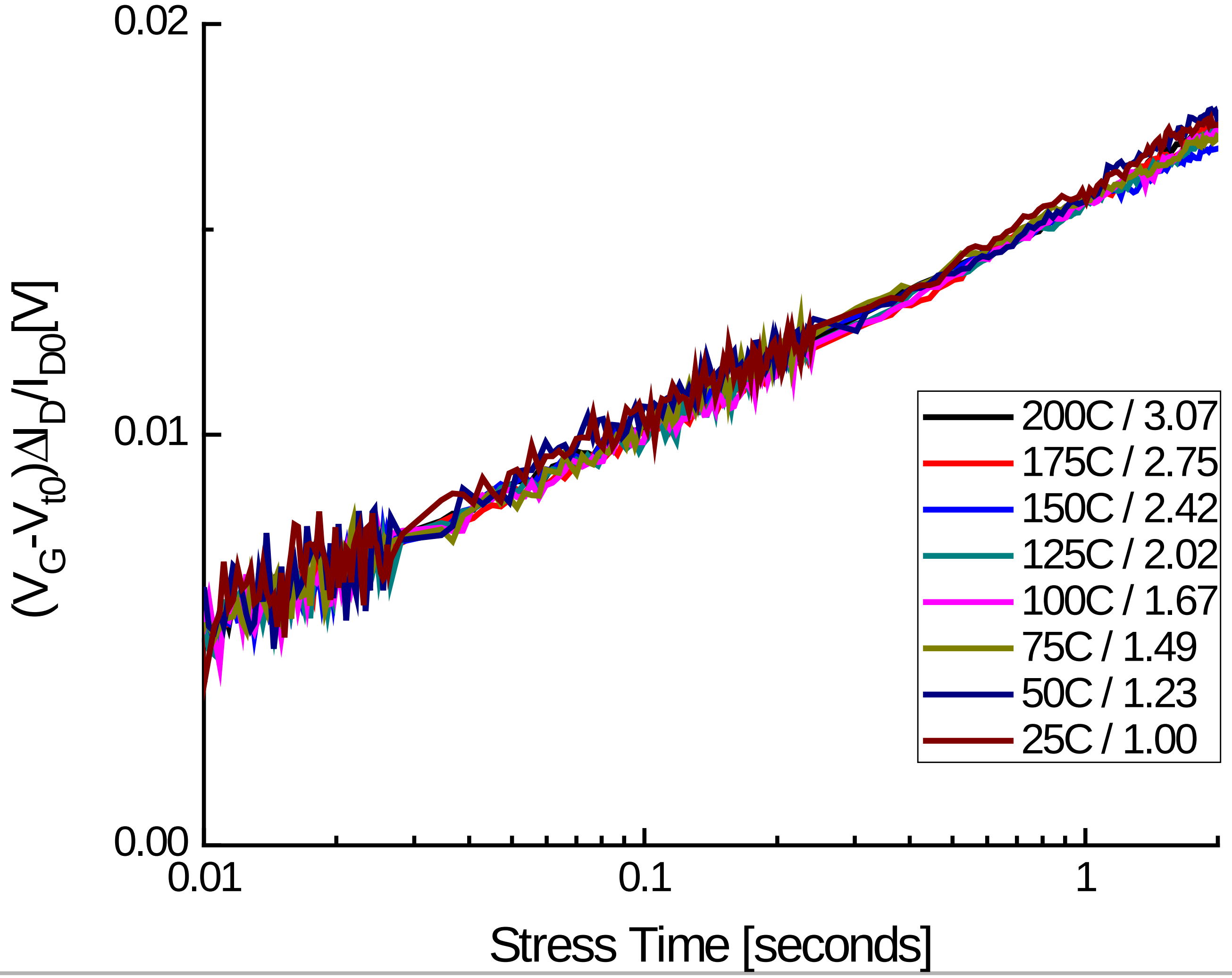
NBTI: Stress Phase



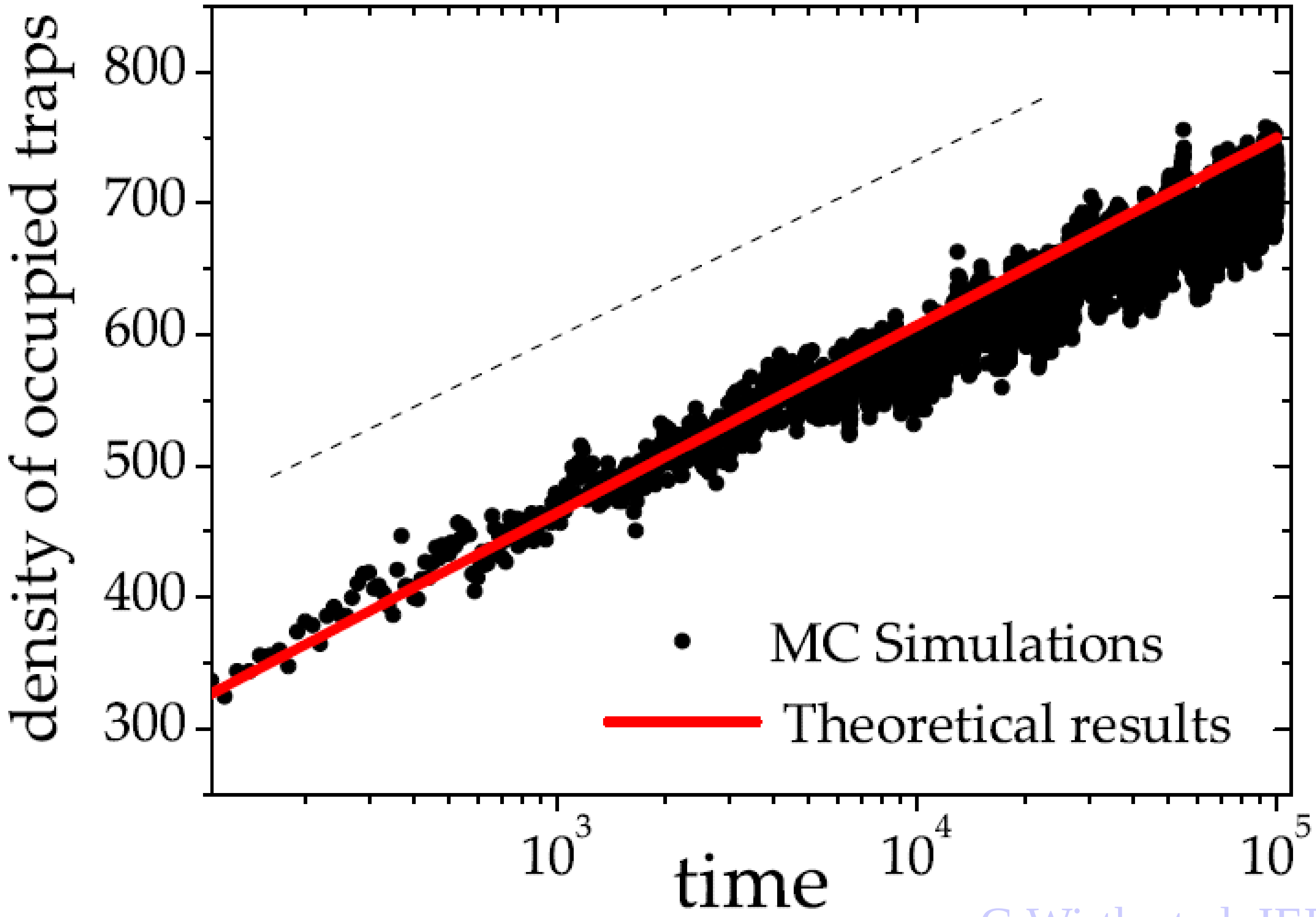
NBTI: Relaxation Phase



NBTI: Temperature Dependence



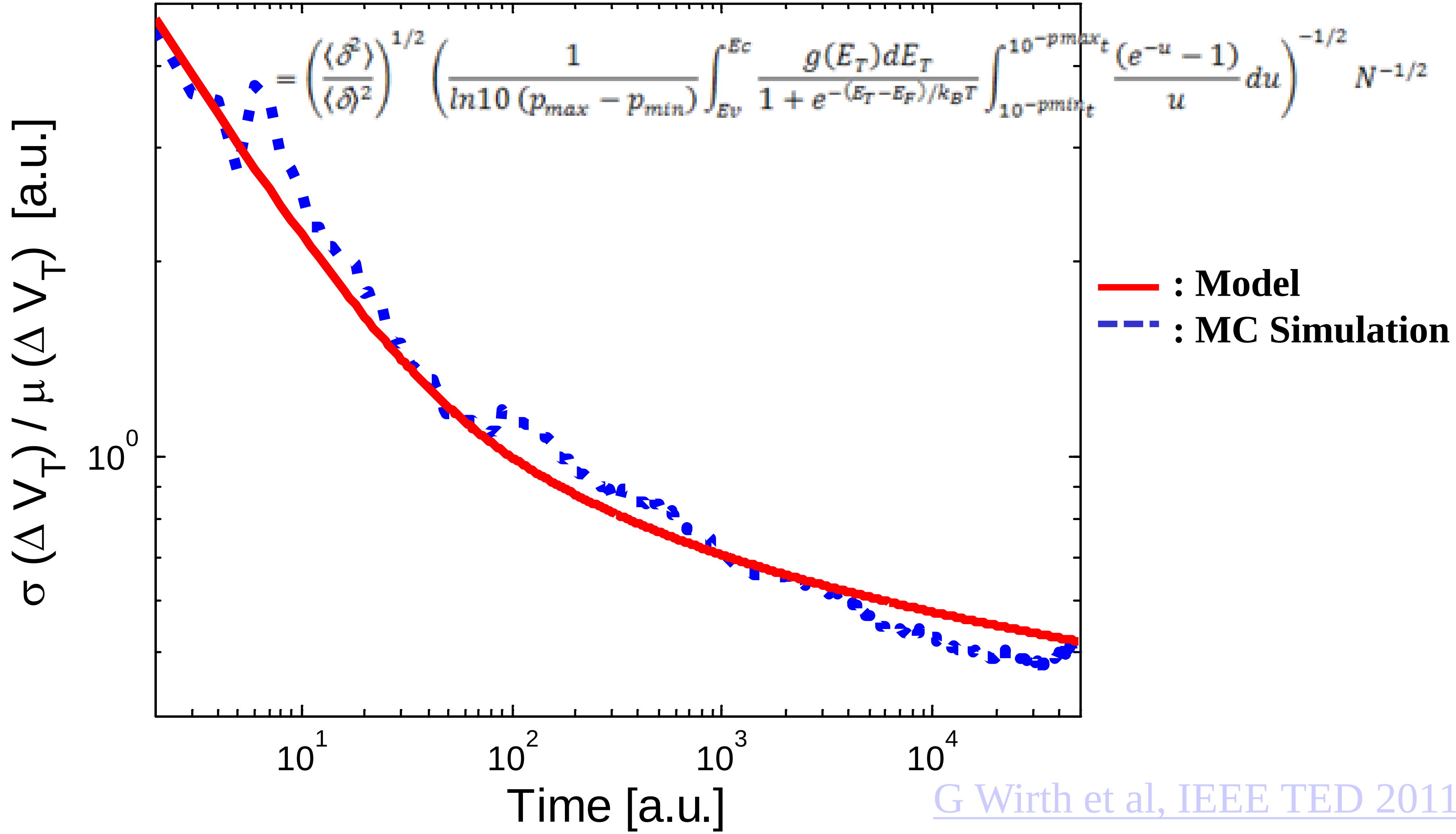
Model for the Charge Trapping Component



G Wirth et al, IEEE TED 2011

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

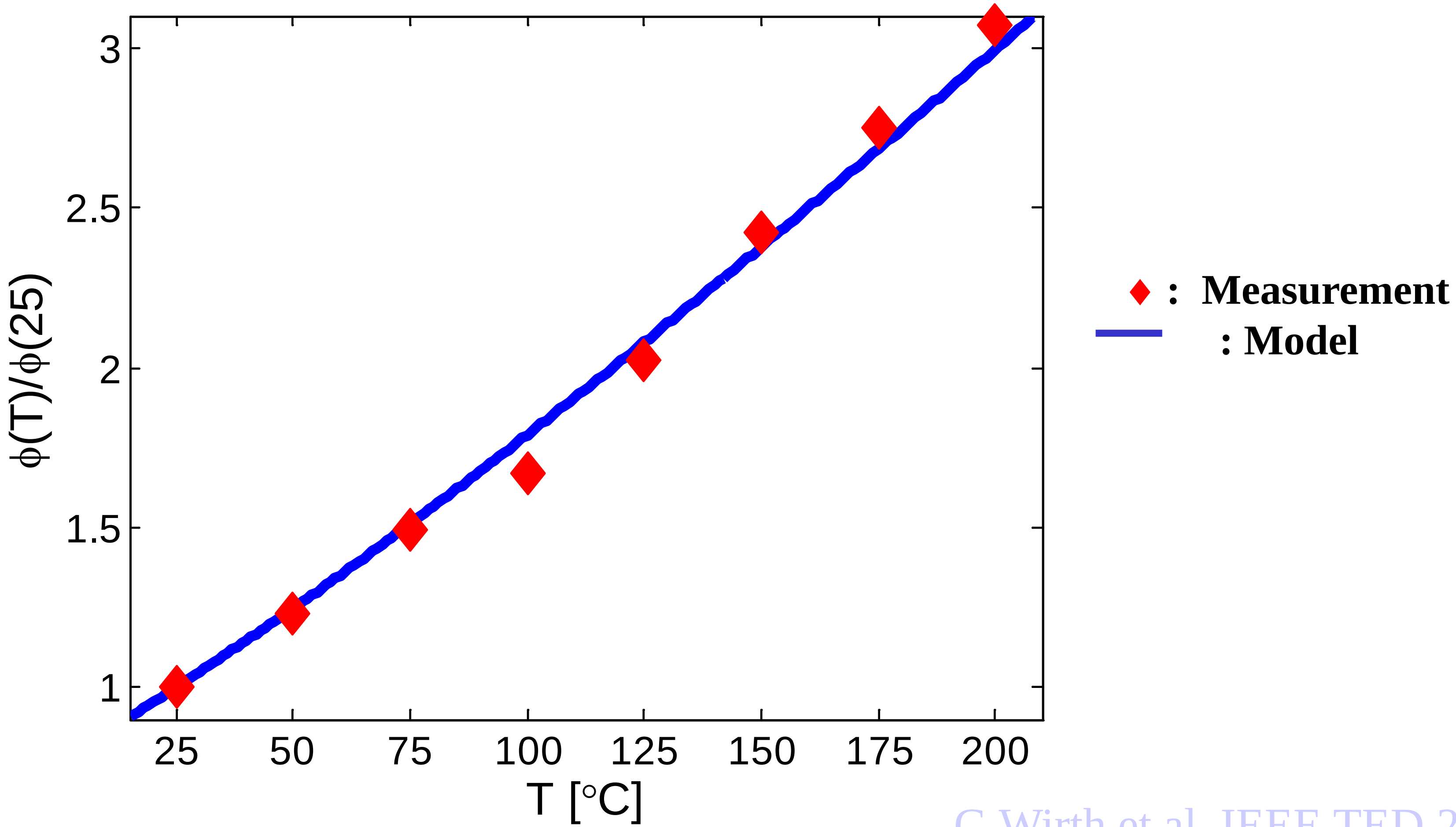
Normalized standard deviation of the BTI induced V_T shift



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

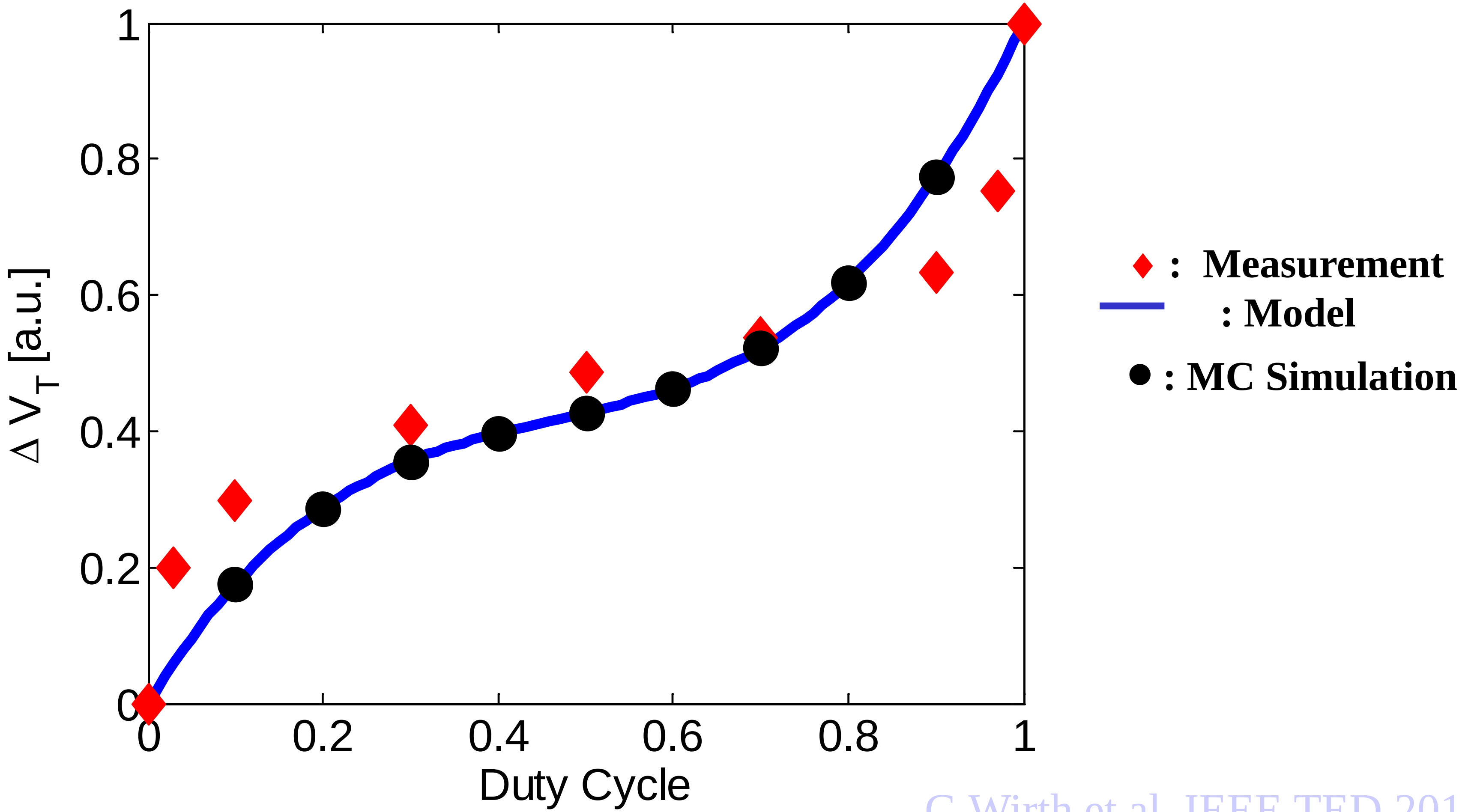
G Wirth et al, IEEE TED 2011

Temperature Dependence



G Wirth et al, IEEE TED 2011

Circuit Activity (Duty Cycle) Dependence



G Wirth et al, IEEE TED 2011

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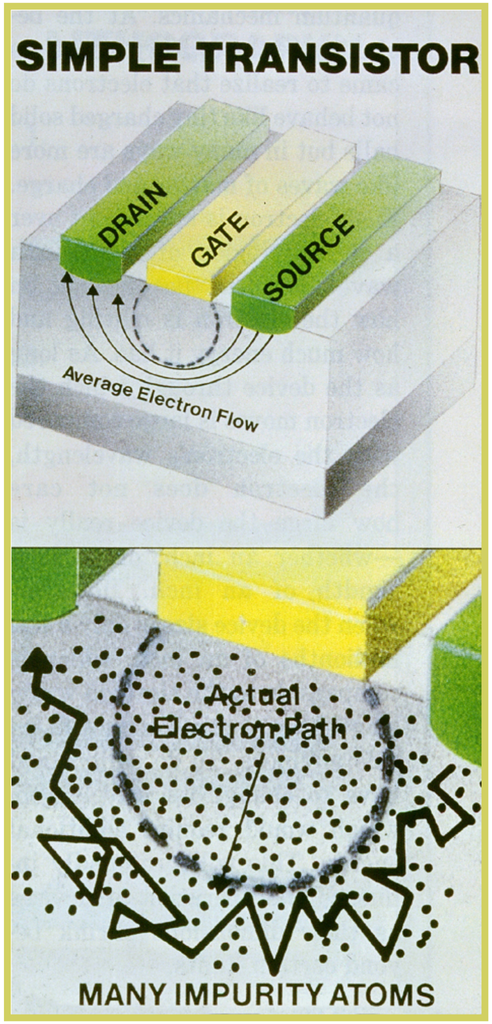
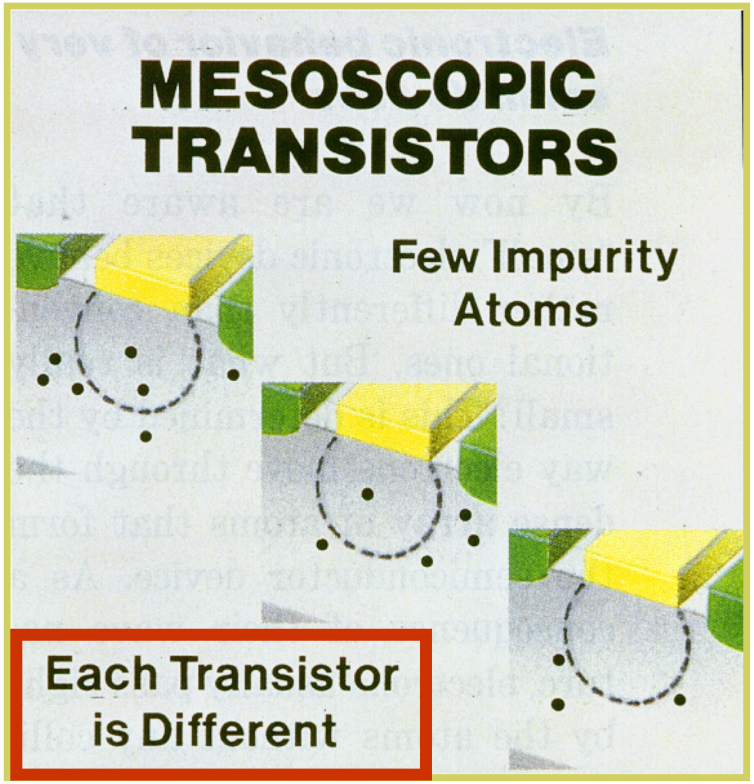
RDF: Random Dopant Fluctuations



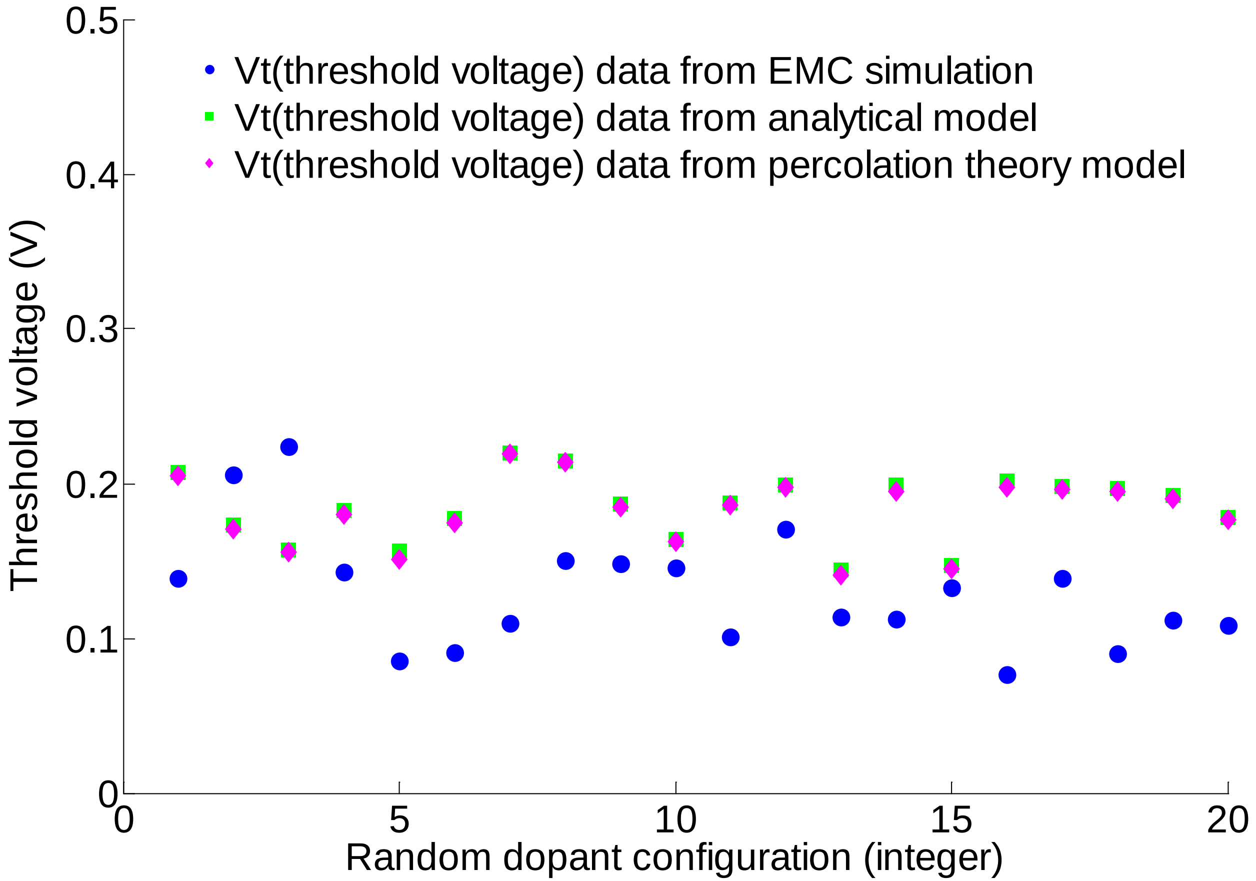
In the **past** all transistors were similar because of *self averaging*

Today, Each Transistor is Different



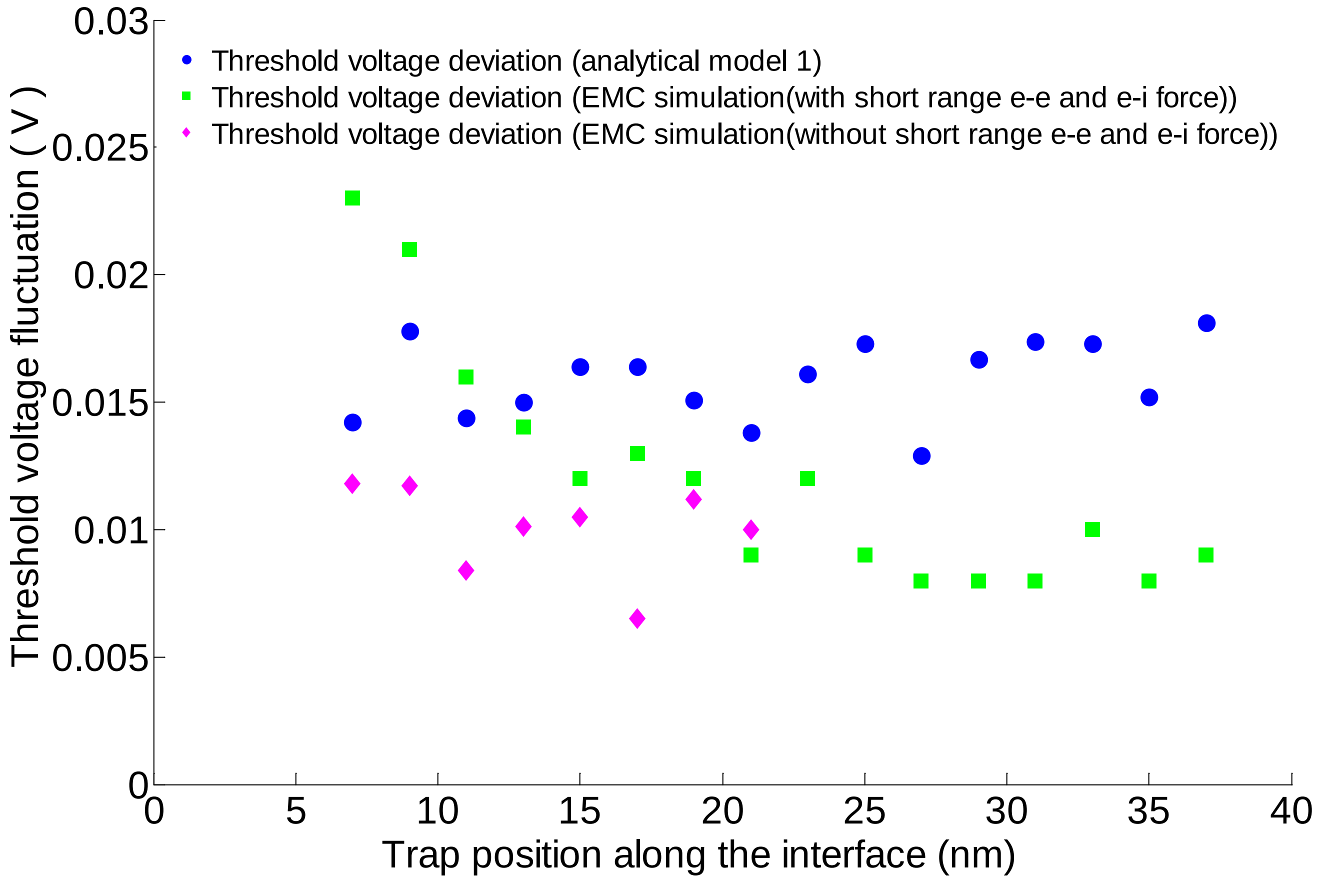
Slide Courtesy Prof Dragica Vasileska, ASU

Threshold Voltage Values For Different RDF Configurations



N Ashraf et al, IEEE EDL 2011

Dependence of V_T Fluctuations on Trap Position Along the Channel



N Ashraf et al, IEEE EDL 2011

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.

Work here presented is due to

- People at UFRGS, Brazil: Roberto da Silva, Lucas Brusamarello, Vinicius Camargo, Mauricio Silva, Gilson Wirth, and many others …
- People at ASU, USA: Dragica Vasileska and Nabil Ashraf.
- People at Texas Instruments: Ralf Brederlow and P Srinivasan (SP).
- People at IMEC, Belgium: Ben Kaczer, Philippe Roussel, Guido Groeseneken, Maria Toledano-Luque, Jacopo Franco, ...
- and many others …