Unifying the Modeling of Charge Trapping in RTN, 1/f Noise and BTI

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Motivation

- **“Traditional / Ideal” MOSFET**
  - **Deterministic Behavior**
  - **Distributed quantities (densities)**

- **“Real” MOSFET:**
  - **Discrete Quantities (electrons, dopants …)**
  - **Stochastic Behavior / Variability**

- **<u>Time Dependent Variability</u>**

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].

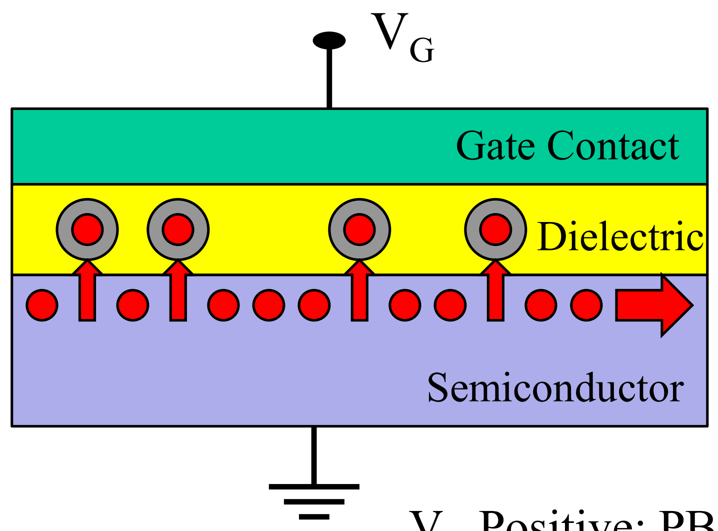
$$\Delta V_{th} = q / C_{ox} \quad with \quad C_{ox} = \varepsilon \times A / tox$$

Modeling Approach

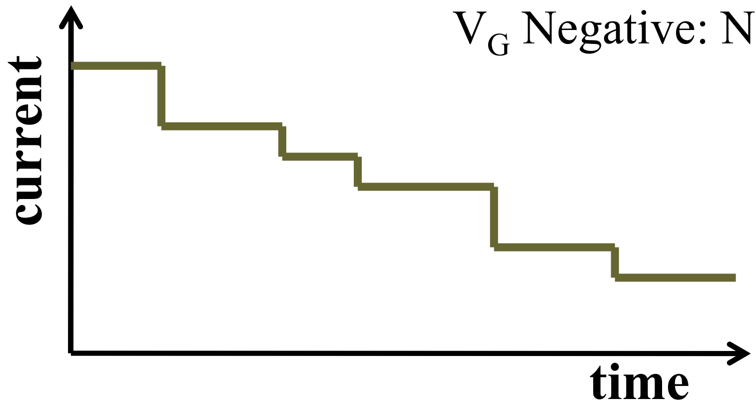
Based on Microscopic (Random) Quantities, instead of distributed (homogeneous) quantities.

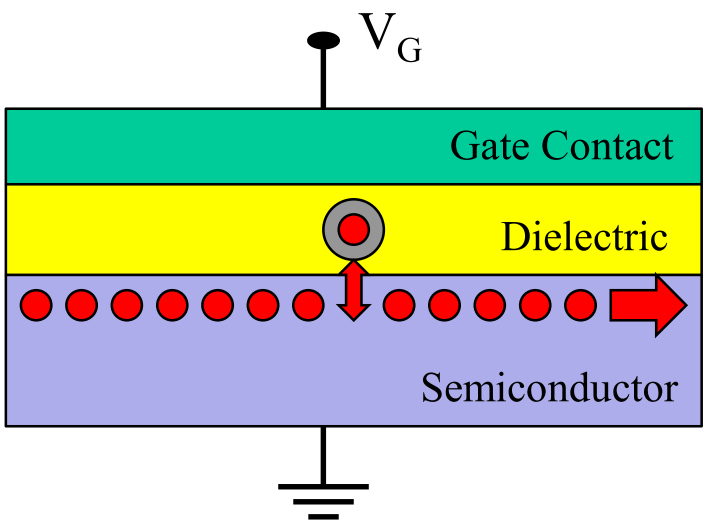
1. **Charge trapping and de-trapping are stochastic events governed by characteristic time constants, which are uniformly distributed on a log scale.**
2. **Number of traps is assumed to be Poisson distributed.**
3. **Amplitude of the fluctuation induced by a single trap is a random variable. If needed, exponential distribution assumed.**

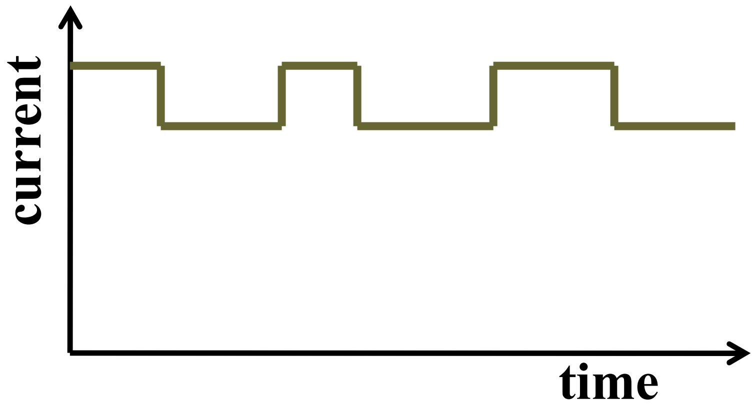
BTI x RTN



V_G Positive: PBTI
V_G Negative: NBTI







BTI x RTN

Traps that contribute to noise are the ones with

$$\tau_{C} \cong \tau_{E}$$

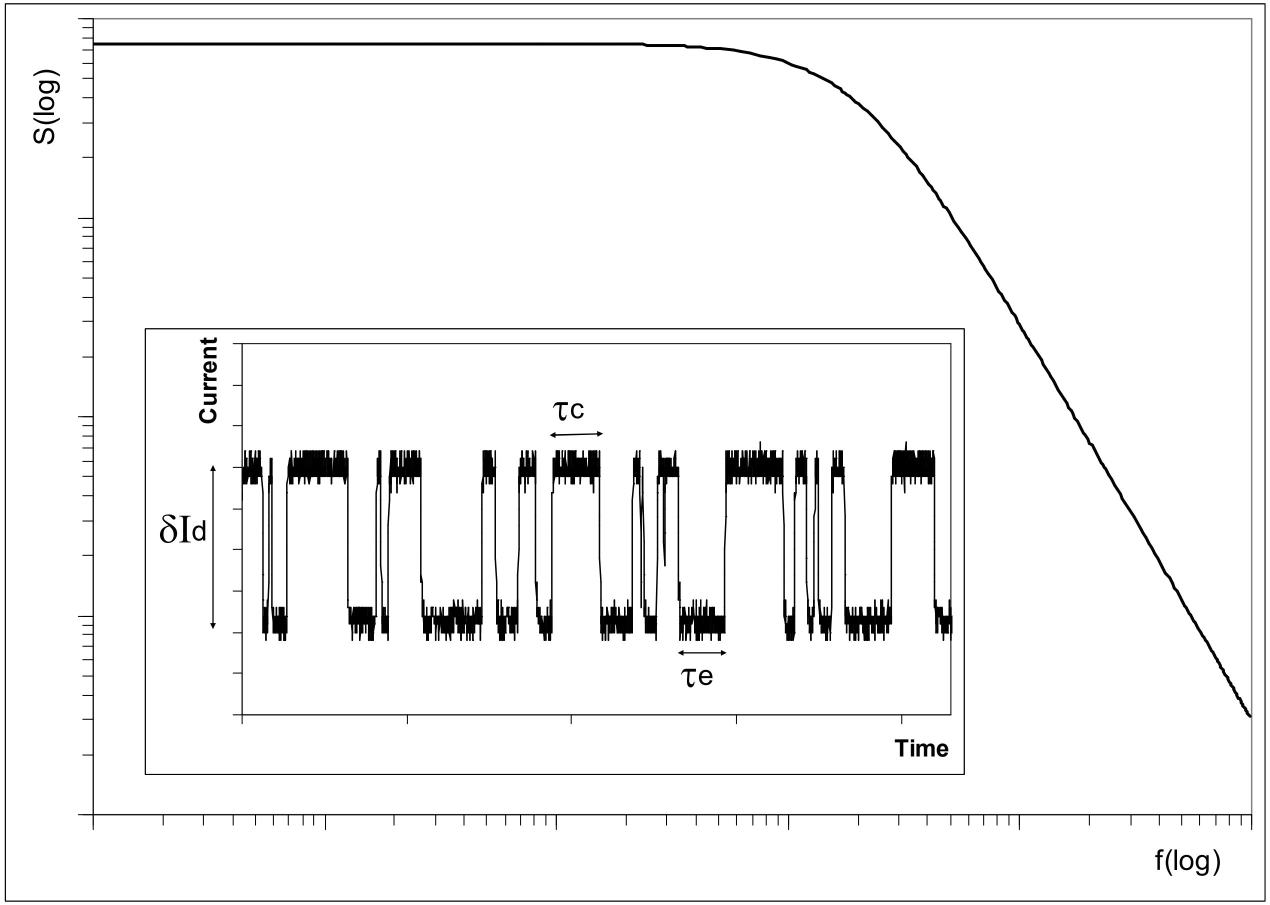
i.e., traps that keep switching state

Traps that contribute to NBTI are the ones with

$$\tau_{C} < \tau_{E}$$

i.e, traps that become occupied

Time x Frequency Domain



Time x Frequency Domain

RTN and BTI:

$$\Delta V_T(t) = \sum_{i=1}^{Ntr} \delta V_{Ti}\, S_i(t)$$

$S_i(t)$ is related to the state of the *ith* trap, which may be empty or occupied and depends on τ_{Ci} and τ_{Ei}

1/f Noise:

$$S(f) = \sum_{i=1}^{Ntr} \delta V_{Ti}{}^2 \cdot \frac{\beta_i}{(1+\beta_i)^2} \frac{2}{\pi f_i} \frac{1}{1+\left(\frac{f}{f_i}\right)^2}$$

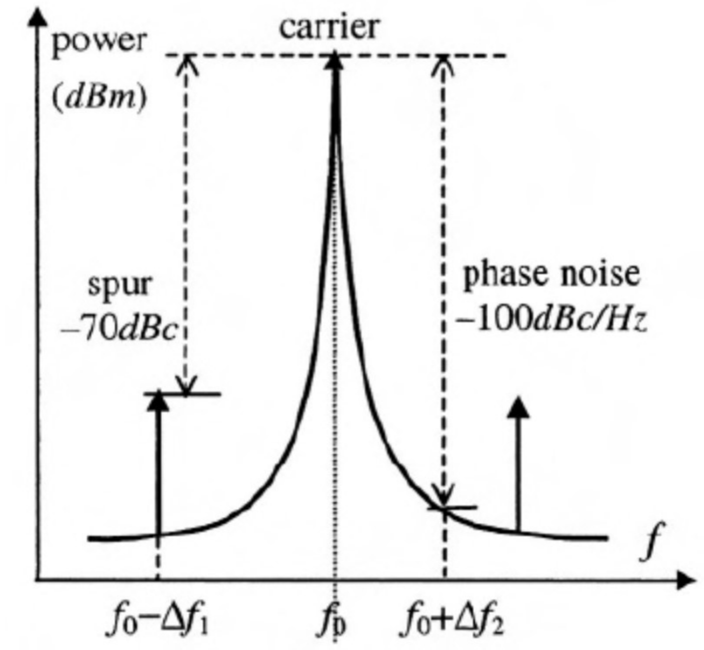
$$A_i{}^2 = \delta V_{Ti}{}^2 . \frac{\beta_i}{(1+\beta_i)^2}$$

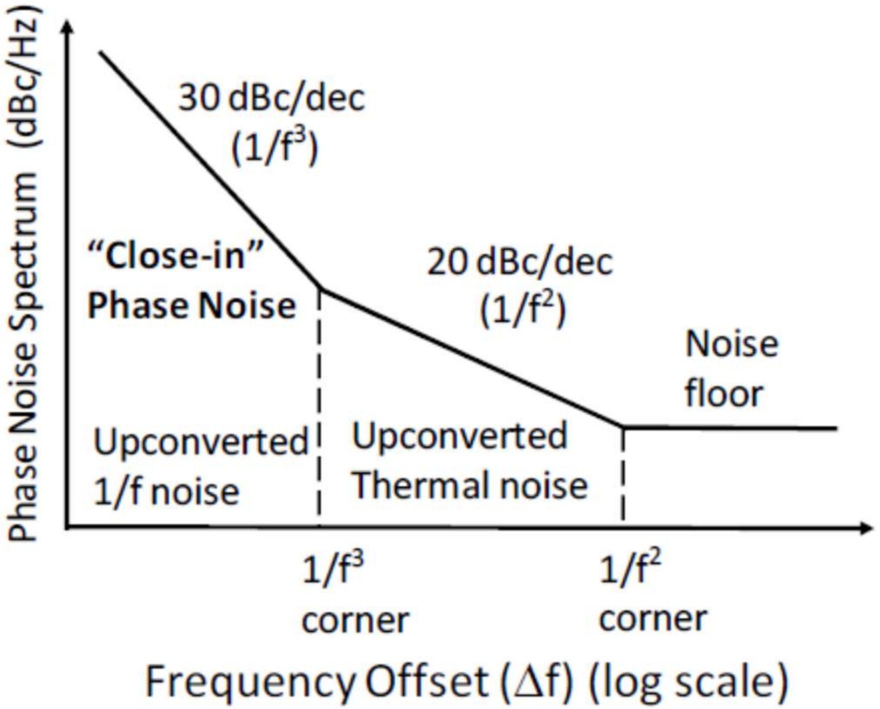
$$N_{tr} = N_{dec} WL \ln(10) \log\left(\frac{f_{max}}{f_{min}}\right)$$

$\beta_i = \tau_{Ci}/\tau_{Ei}$

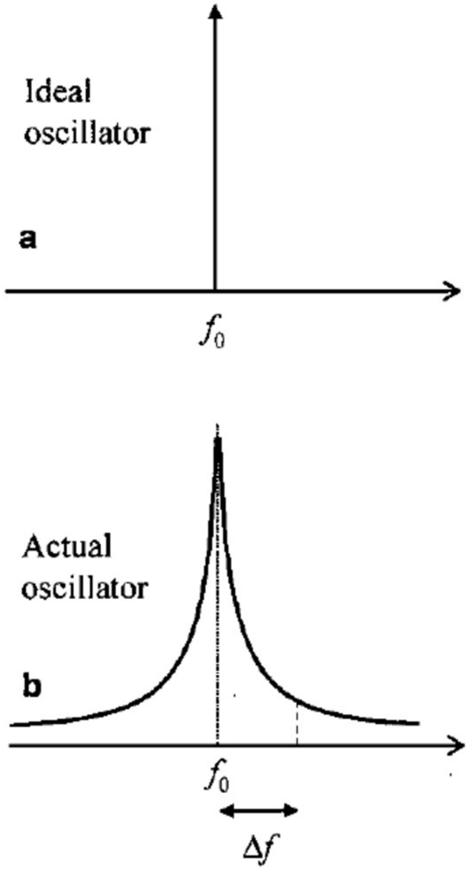
$$N_{tr} = N_{dec} WL \ln(10) \log\left(\frac{t_{max}}{t_{min}}\right)$$

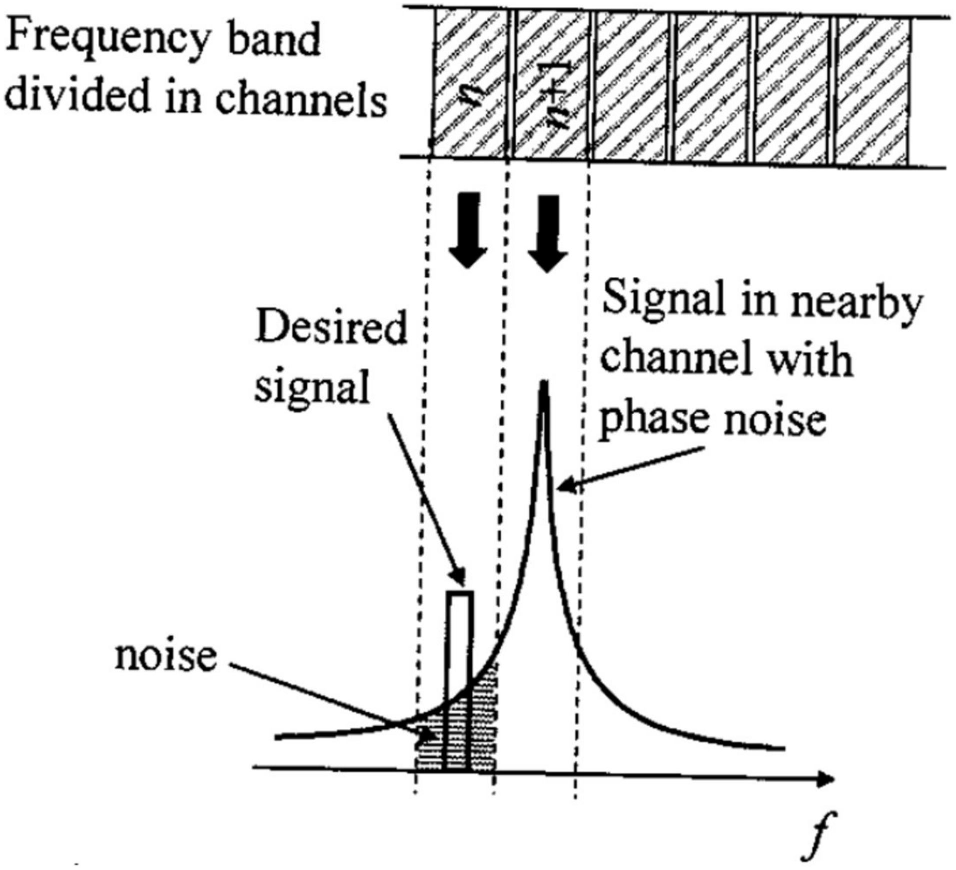
Phase Noise: Up-converted 1/f Noise





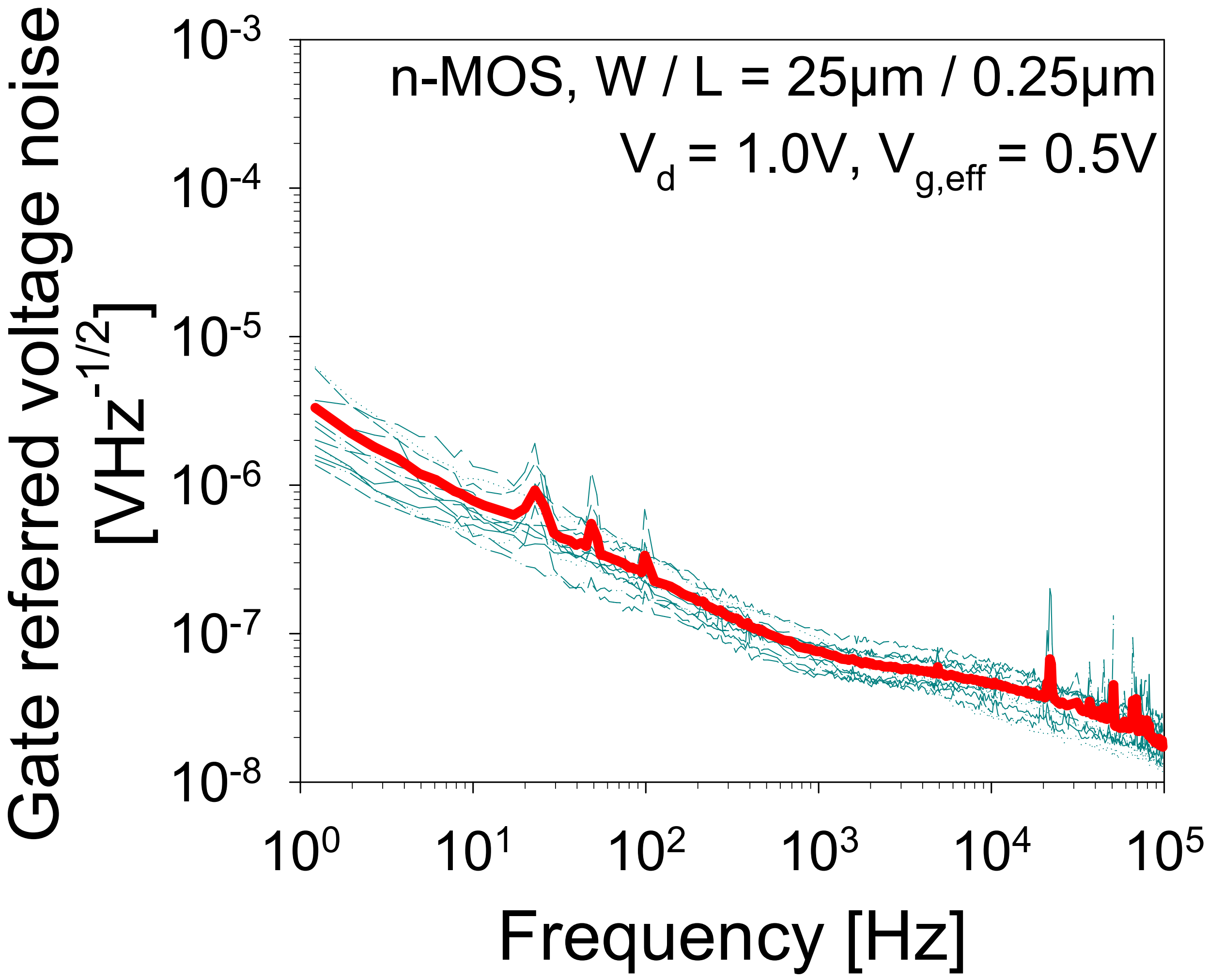
Phase Noise: Up-converted 1/f Noise



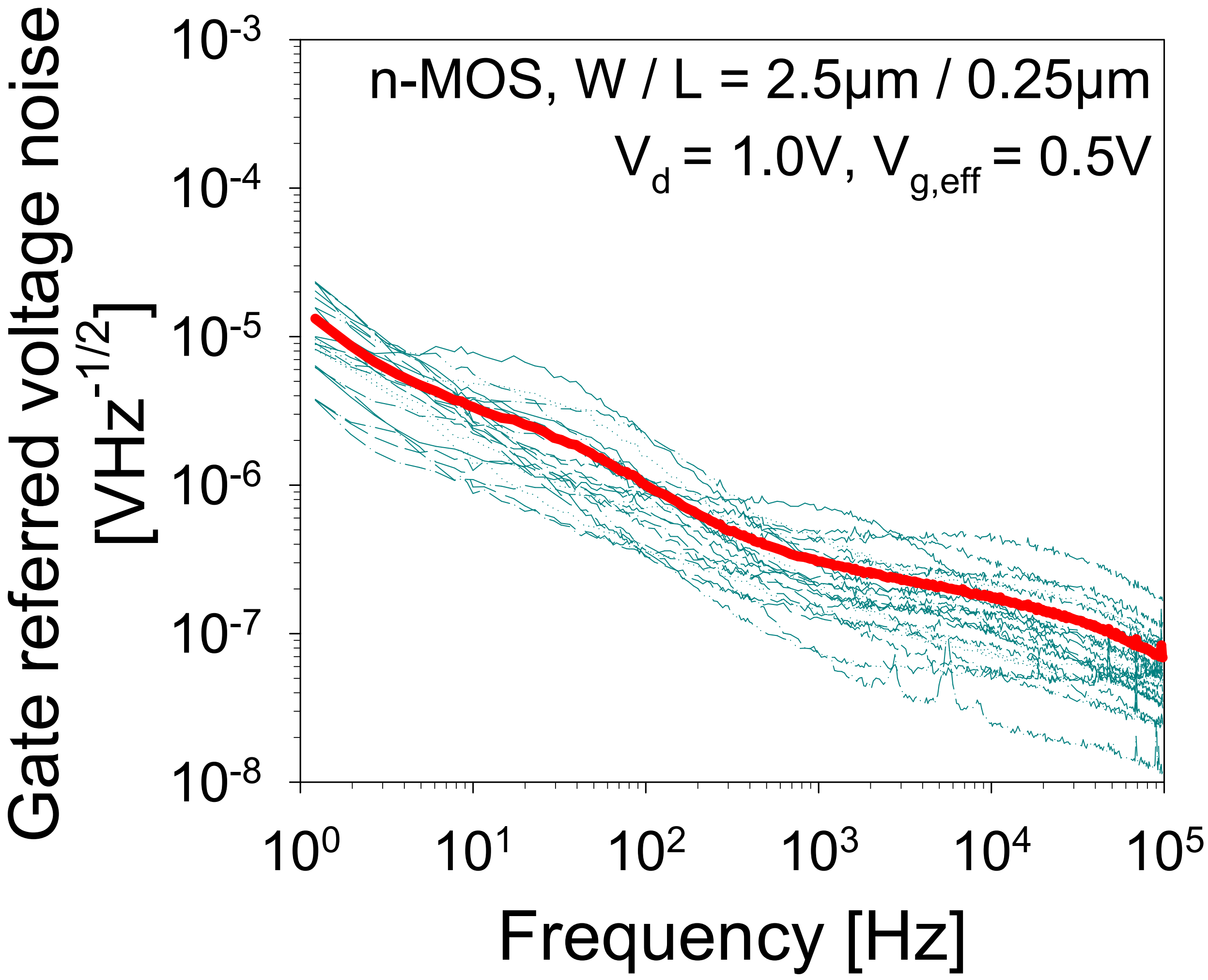


Haartman and Oestling

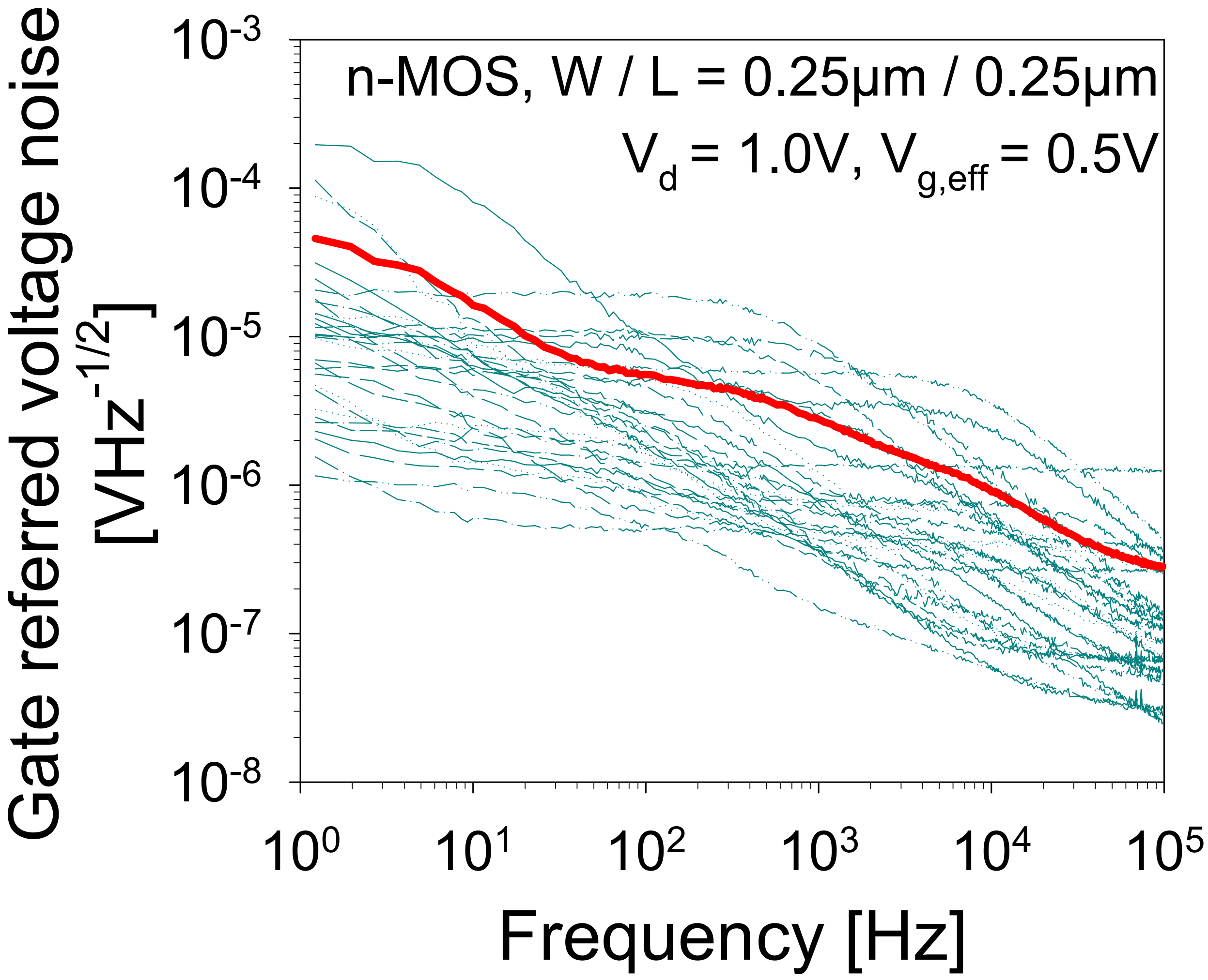
Average Value and Variability



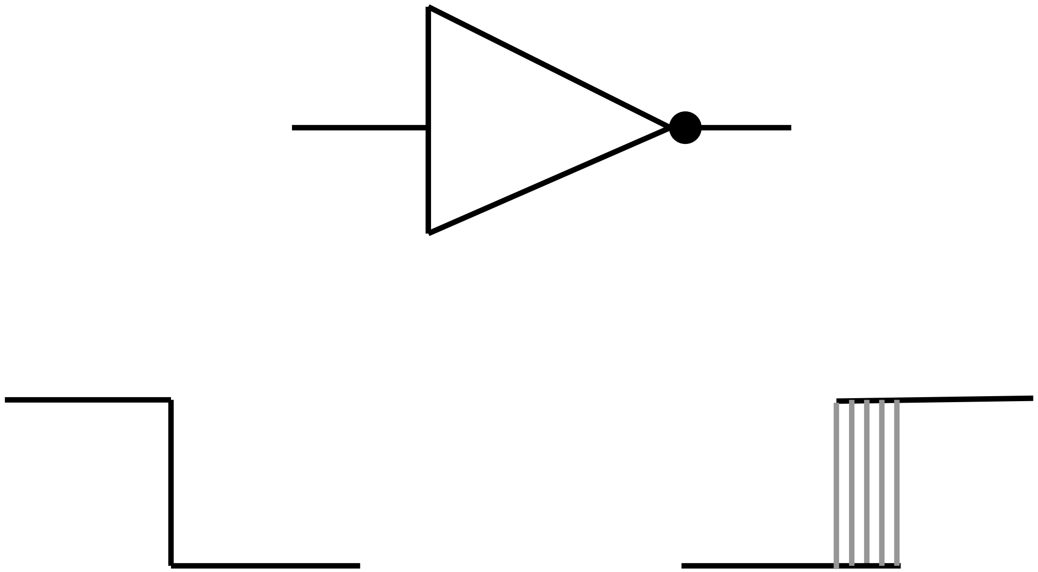
Average Value and Variability



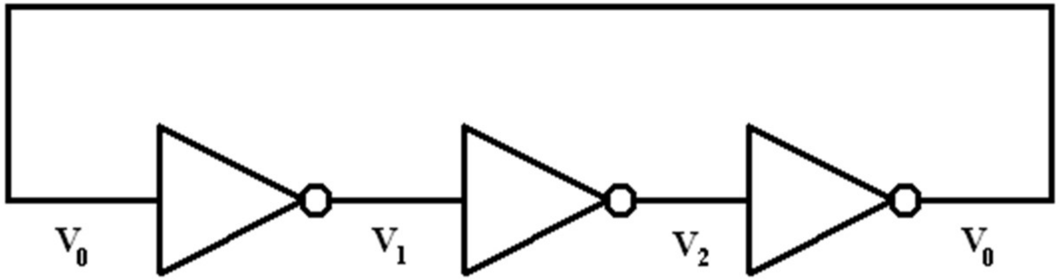
Average Value and Variability

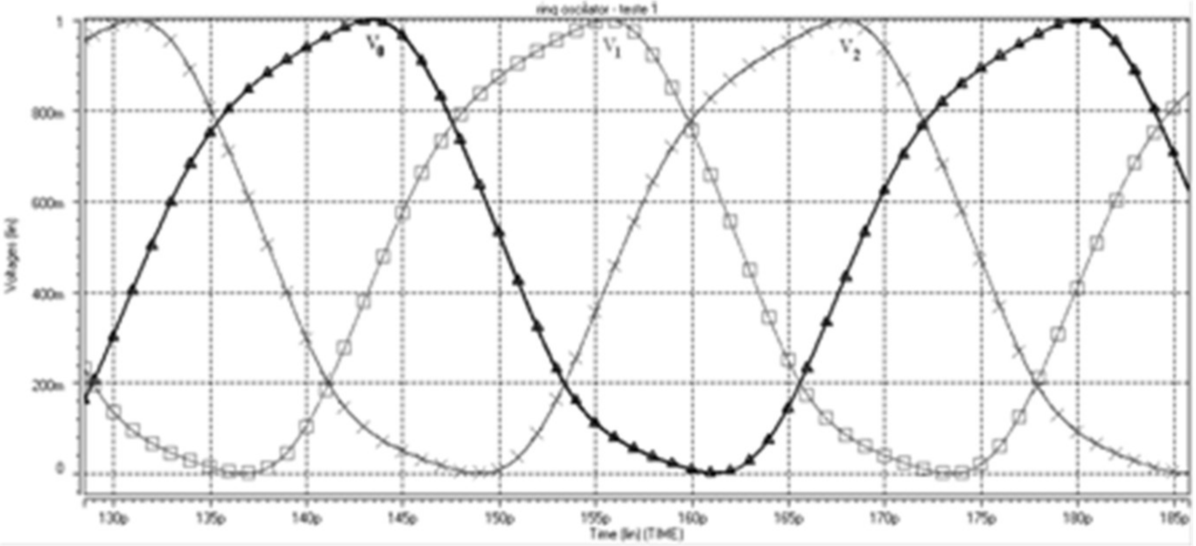


Logic Gate Delay Variability



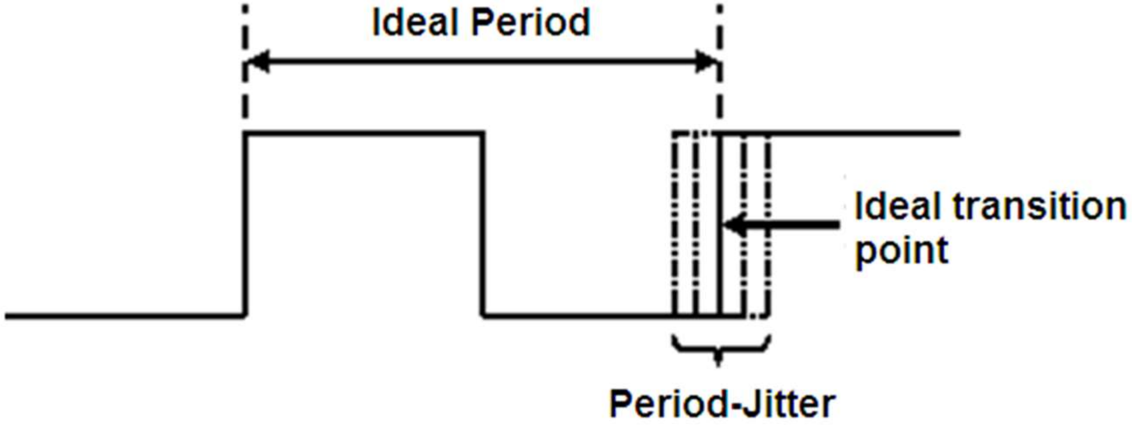
Transient Simulation of Ring Oscillators



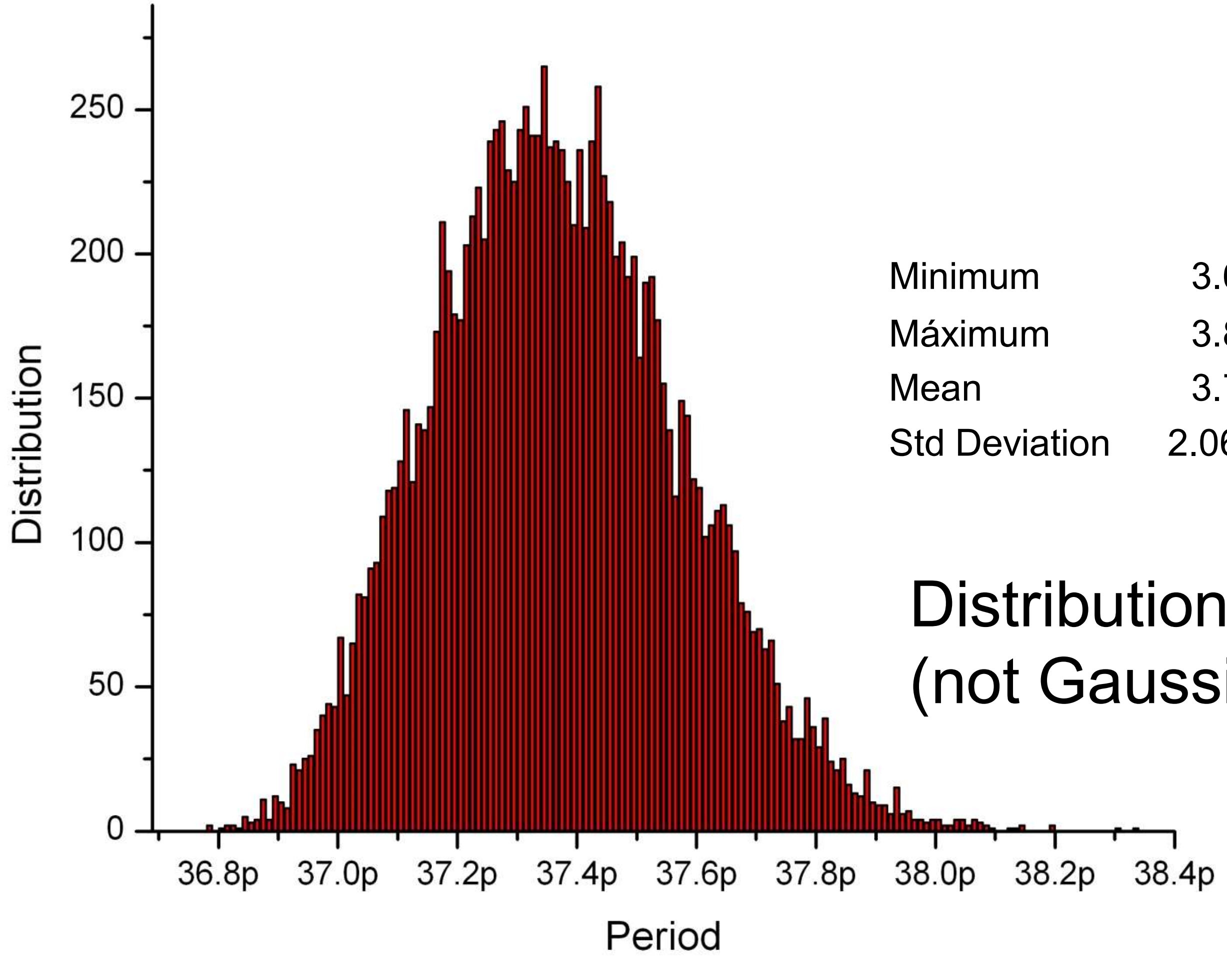


Period Jitter

- **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).



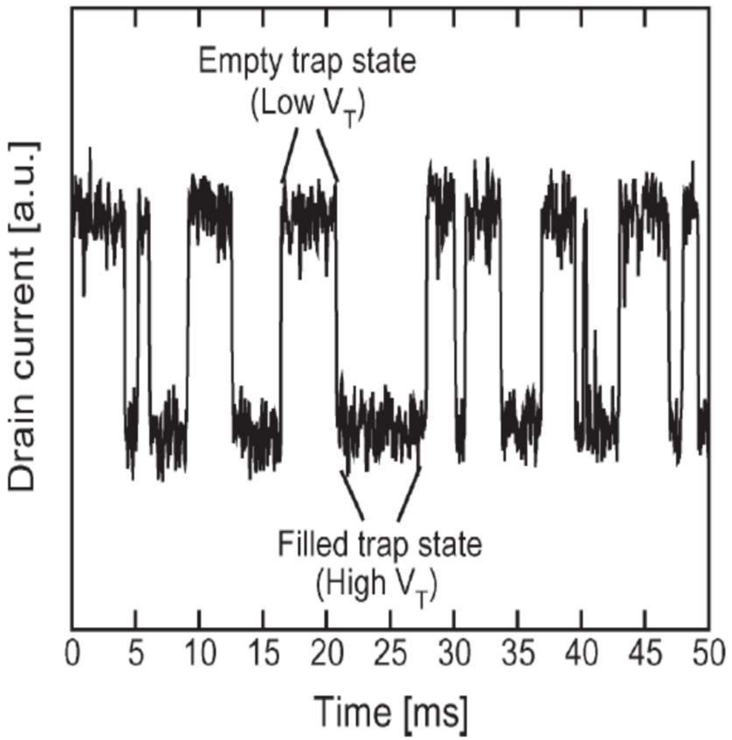
Period of a Single Ring Oscillator

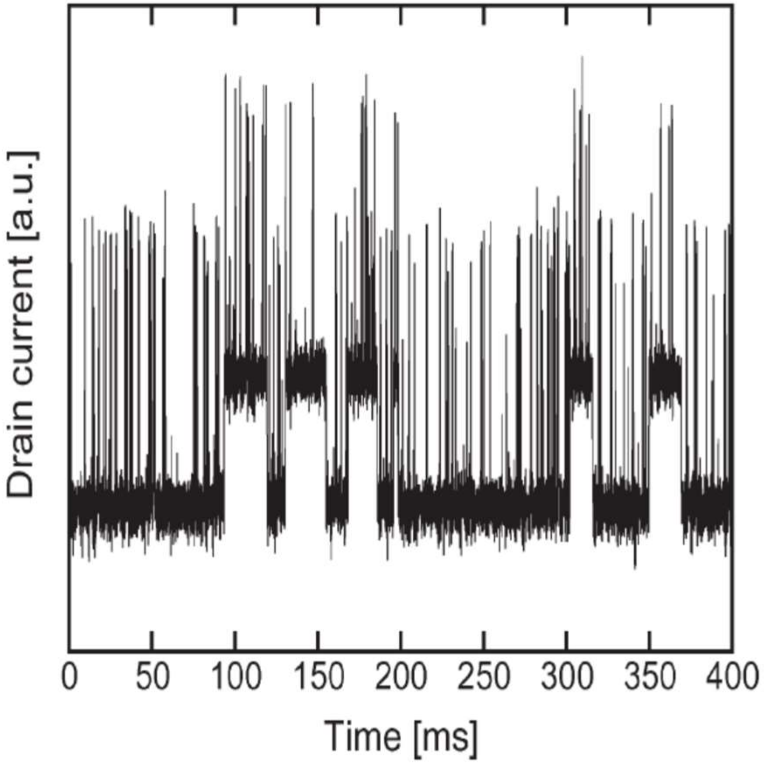


Minimum	3.6784E-11
Máximum	3.8338E-11
Mean	3.7370E-11
Std Deviation	2.06329E-13

Distribution is skewed (not Gaussian)

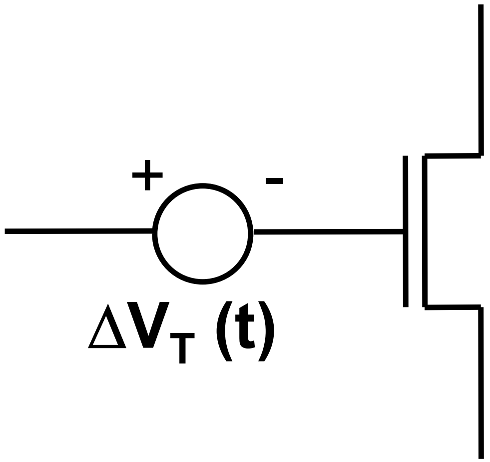
RTN and Time Domain

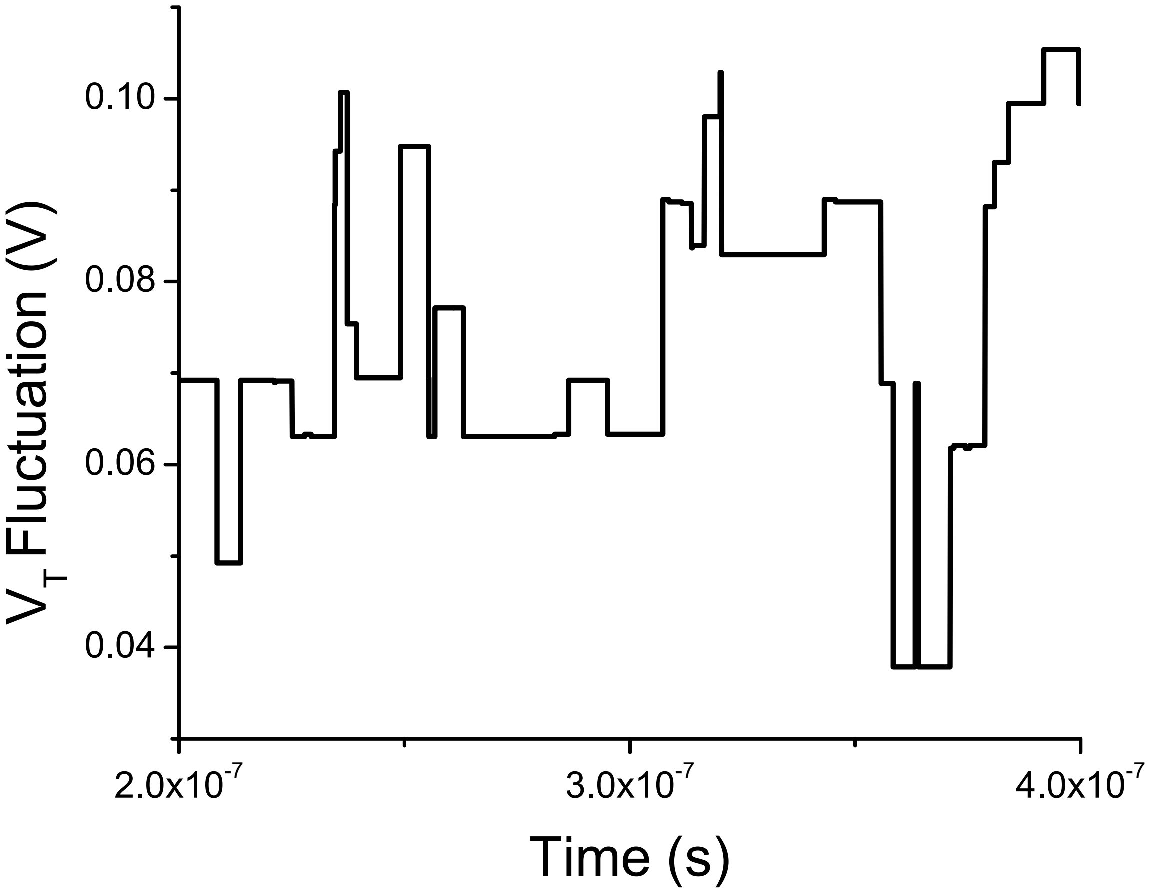




V_T Fluctuations

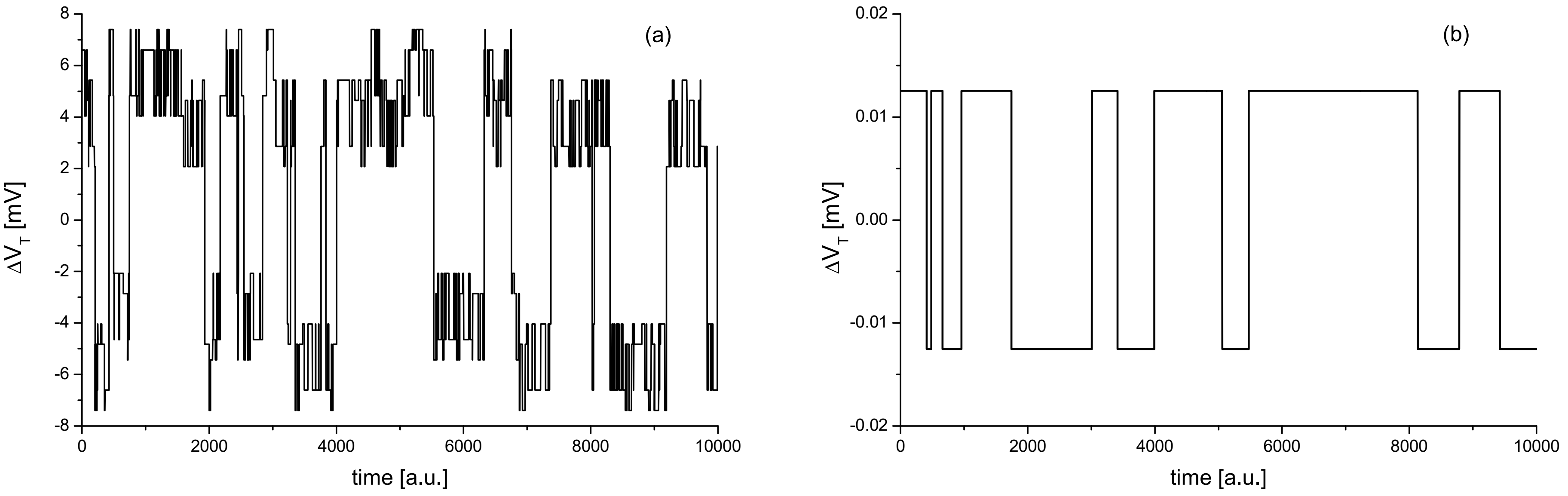
V_T Fluctuates Over Time





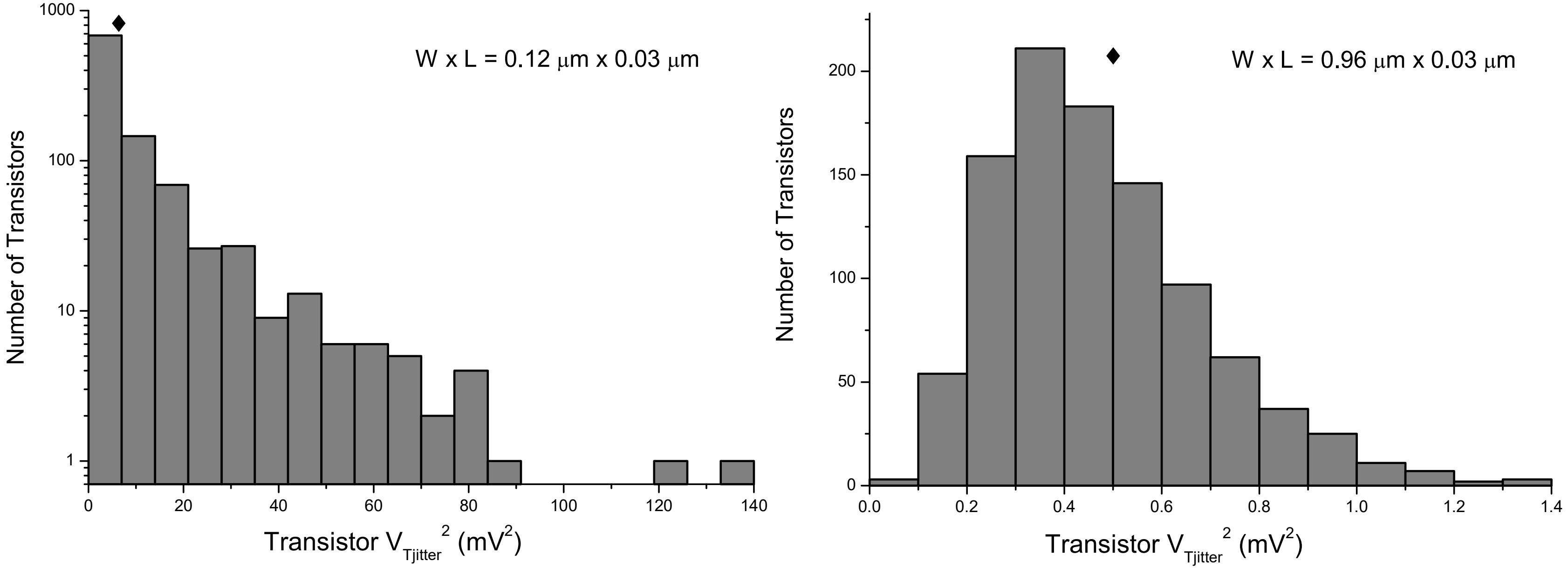
$$E[Var[\Delta V_T(t)]] = E[N_{tr}]E[A_i^2] \equiv E[V_{TJitter}^2]$$

V_T Fluctuates Over Time



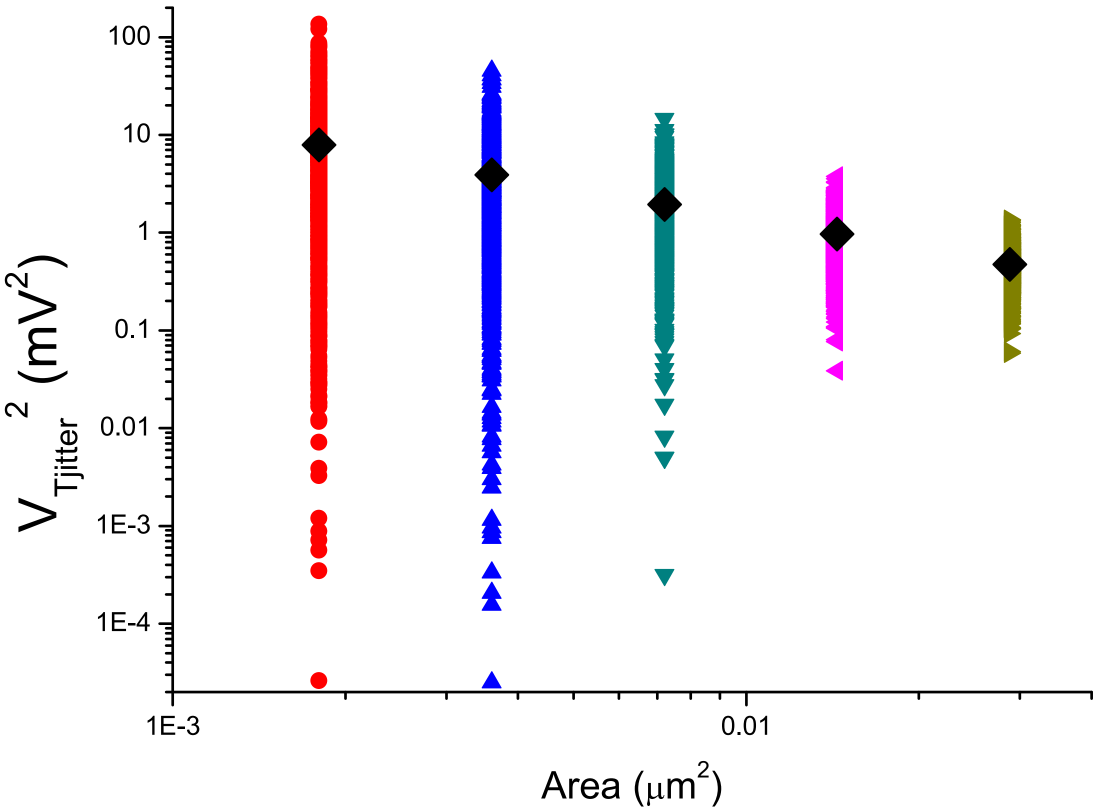
Monte Carlo simulation of V_T variation over time due to RTN. Trap occupancy switching leads to discrete fluctuations in V_T. Two devices of size 0.03μm x 0.12μm are show.

V_T Fluctuates Over Time



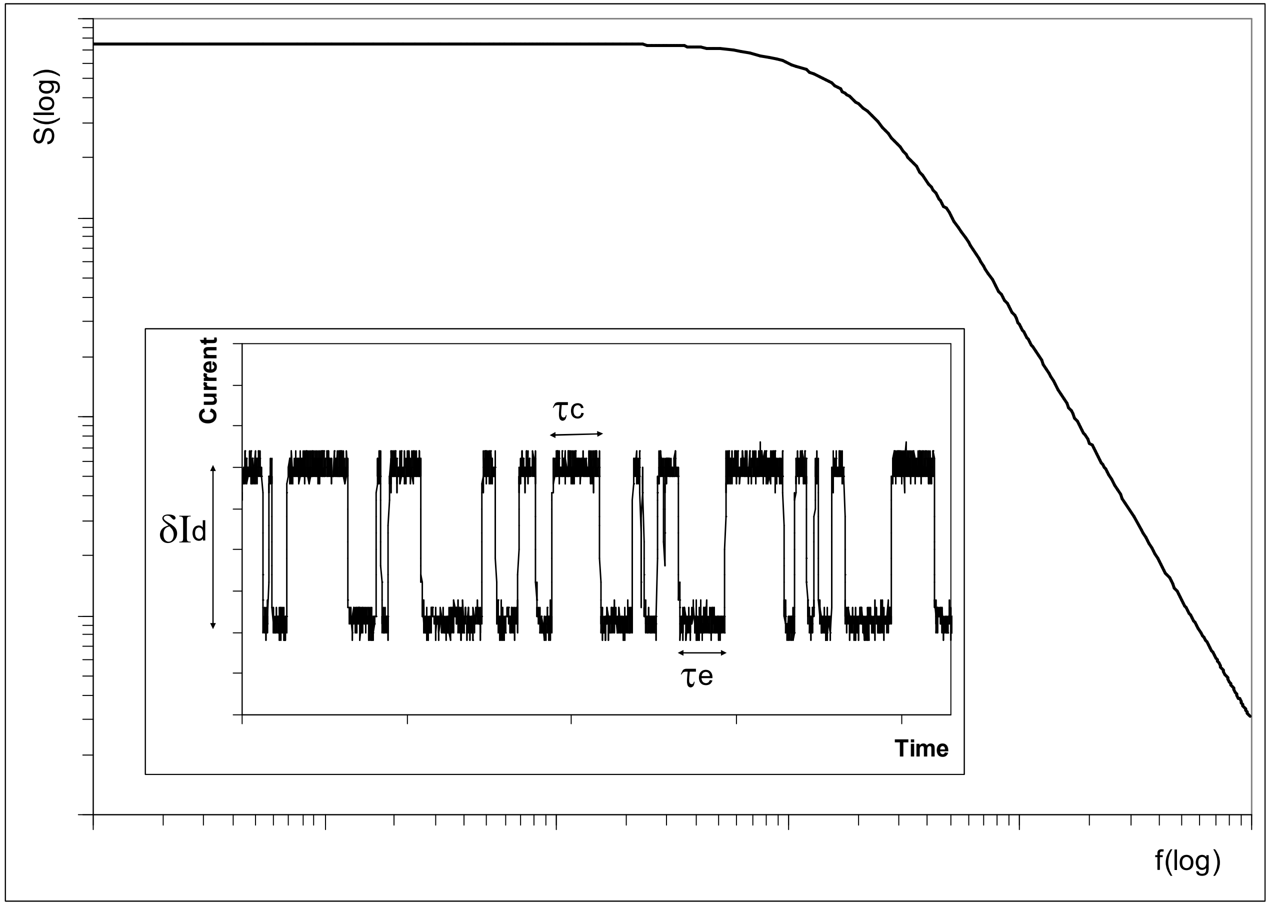
Histogram of $V_{Tjitter}^2$ from MC simulations for two different device sizes. Black diamonds show the average $V_{Tjitter}^2$ for each device size. Please note that the y-axis of the first histogram is in log scale

Variability of V_T Jitter

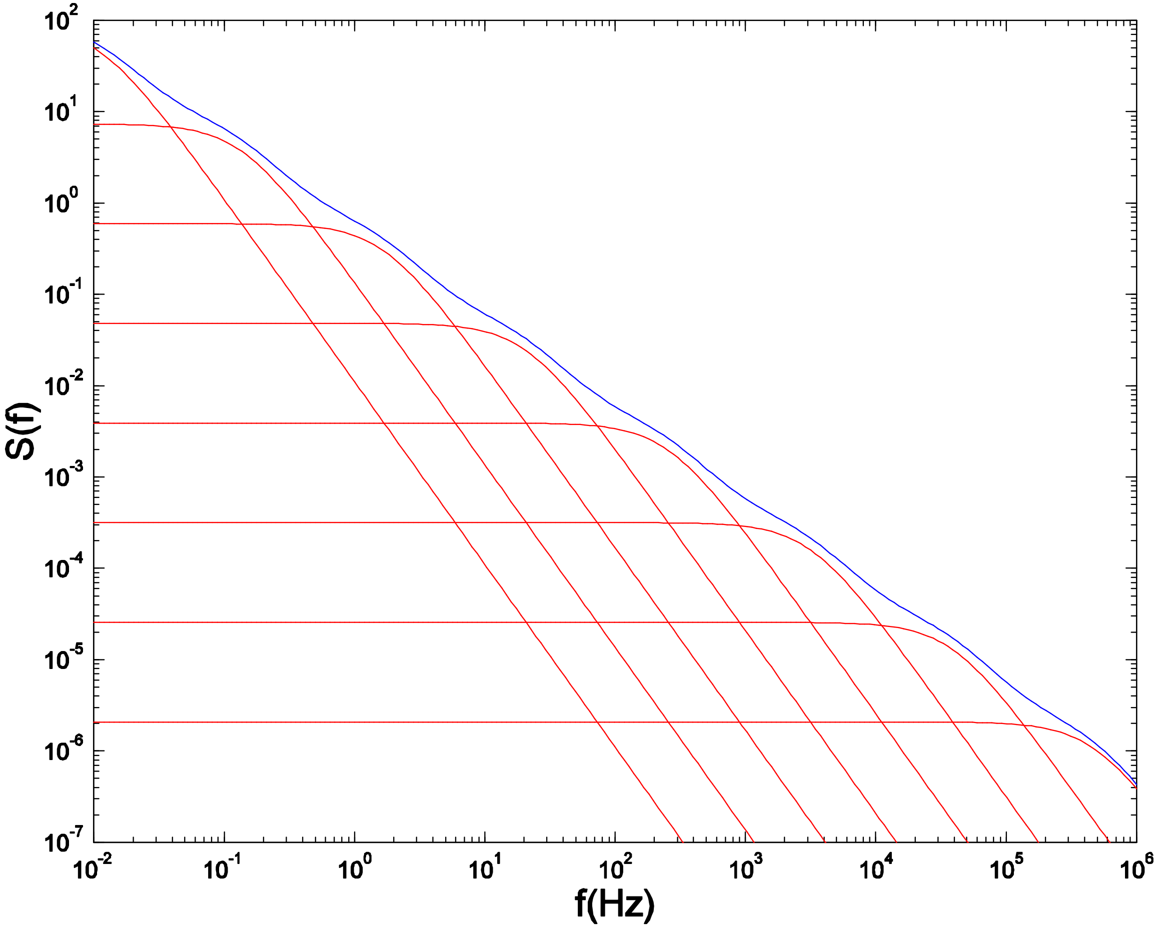


Each point in the graph is the V_T jitter of a single device.
Black diamonds show the average jitter for each area

RTN: Random Telegraph Noise



Evaluating the Noise Power due to Many Traps



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

1/f Noise Statistical Model

- Average Value (µ)

$$E[S(f)] = \frac{E[{A_i}^2]N_{dec}WL}{f}\frac{\pi}{2}$$

$$E[N_{tr}] = N_{dec}WL\ln(10)\log\left(\frac{f_{max}}{f_{min}}\right)$$

- Variance (σ²)

$$Var[S(f)] = \frac{E[{A_i}^4]N_{dec}WL}{2}\frac{1}{f^2}$$

$$E[{A_i}^2] = E[\delta {V_{Ti}}^2 . \frac{\beta_i}{(1+\beta_i)^2}]$$

RTN Statistical Model

- Average Value (μ)

$$E[{V_{Tjitter}}^2] = E[N_{tr}]E[{A_i}^2]$$

$$E[N_{tr}] = N_{dec}WL\ln(10)\log\left(\frac{t_{max}}{t_{min}}\right)$$

- Variance (σ²)

$$Var[{V_{Tjitter}}^2] = E[N_{tr}]E[{A_i}^4]$$

Parameter Extraction *f* domain

$$\frac{Var[S(f)]}{E[S(f)]} = \frac{E[{A_i}^4]}{E[{A_i}^2]\pi f}$$

If it is assumed that A_i is exponentially distributed, $E[X^n] = n!/\lambda^n$

$$E[A_i] = \sqrt{\frac{\pi\, f\, Var[S(f)]}{12\, E[S(f)]}}$$

$$N_{dec} WL = \frac{E[S(f)]\, f}{E[A_i]^2} \frac{1}{\pi}$$

Parameter Extraction *t* domain

$$\frac{Var[V_{Tjitter}{}^2]}{E[V_{Tjitter}{}^2]} = \frac{E[A_i{}^4]}{E[A_i{}^2]}$$

If it is assumed that A_i is exponentially distributed, $E[X^n] = n!/\lambda^n$

$$E[A_i] = \sqrt{\frac{Var[V_{Tjitter}{}^2]}{12\,E[V_{Tjitter}{}^2]}}$$

$$E[N_{tr}] = \frac{E[V_{Tjitter}{}^2]}{2E[A_i]^2}$$

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Parameter Extraction *BTI*

- Average Value (μ)

$$E\left[\boldsymbol{V_{T,BTI}(t)}\right] \sim E[\delta V_{Ti}]\ E[N_{tr}(t)]$$

- Variance (σ²)

$$Var\left[\boldsymbol{V_{T,BTI}(t)}\right] \sim E[\delta V_{Ti}{}^2]\ E[N_{tr}(t)]$$

$$E[\delta V_{Ti}] = \frac{Var\left[\boldsymbol{V_{T,BTI}(t)}\right]}{2\ E\left[\boldsymbol{V_{T,BTI}(t)}\right]}$$

Area Scaling

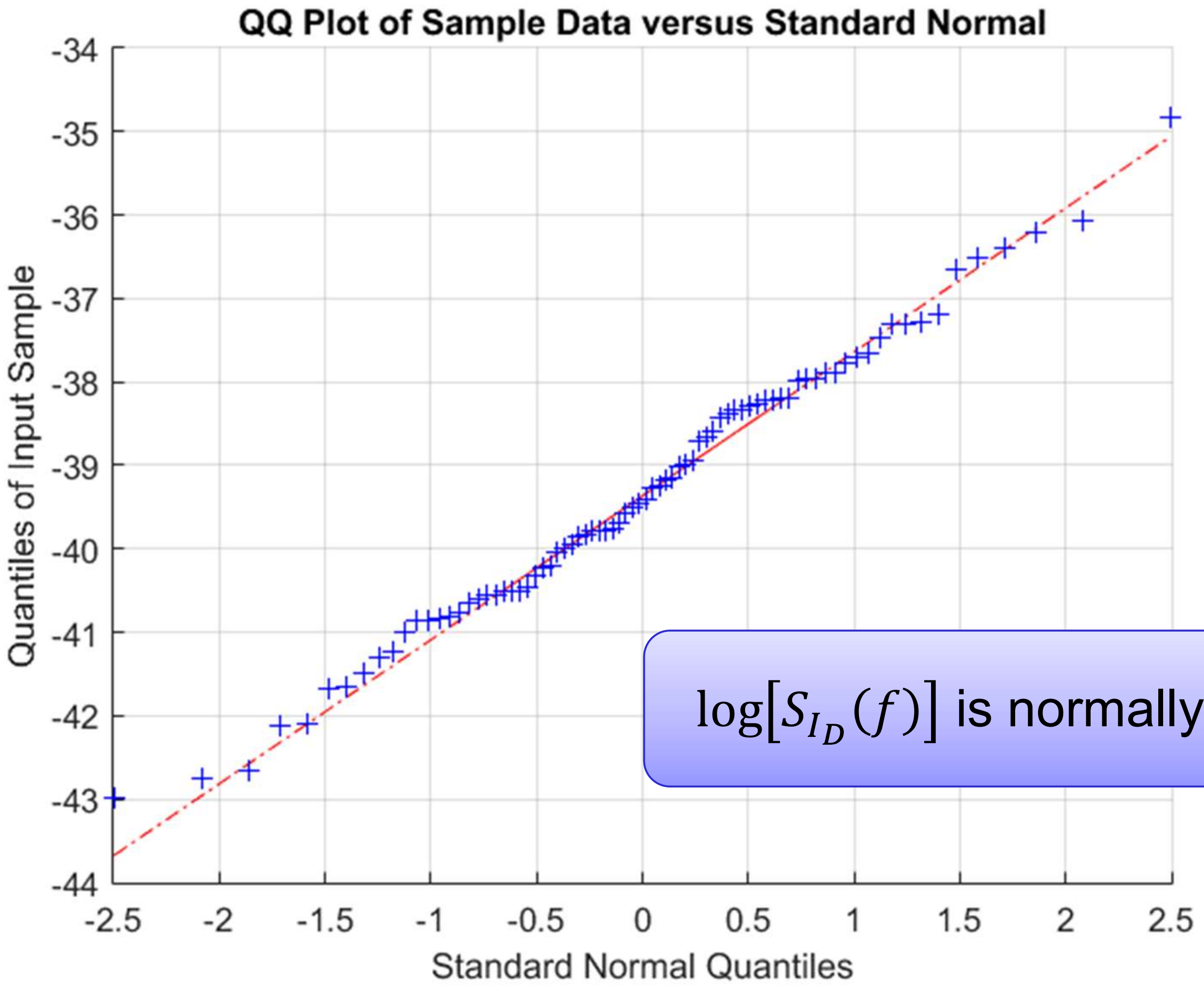
$E[\mathrm{S(f)}] \sim {}^{1}/_{WL}$

$E[{V_{Tjitter}}^{2}] \sim {}^{1}/_{WL}$

$Var[\mathrm{S(f)}] \sim {}^{1}/_{(WL)^3}$

$Var[{V_{Tjitter}}^{2}] \sim {}^{1}/_{(WL)^3}$

How to statistically describe the noise?



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

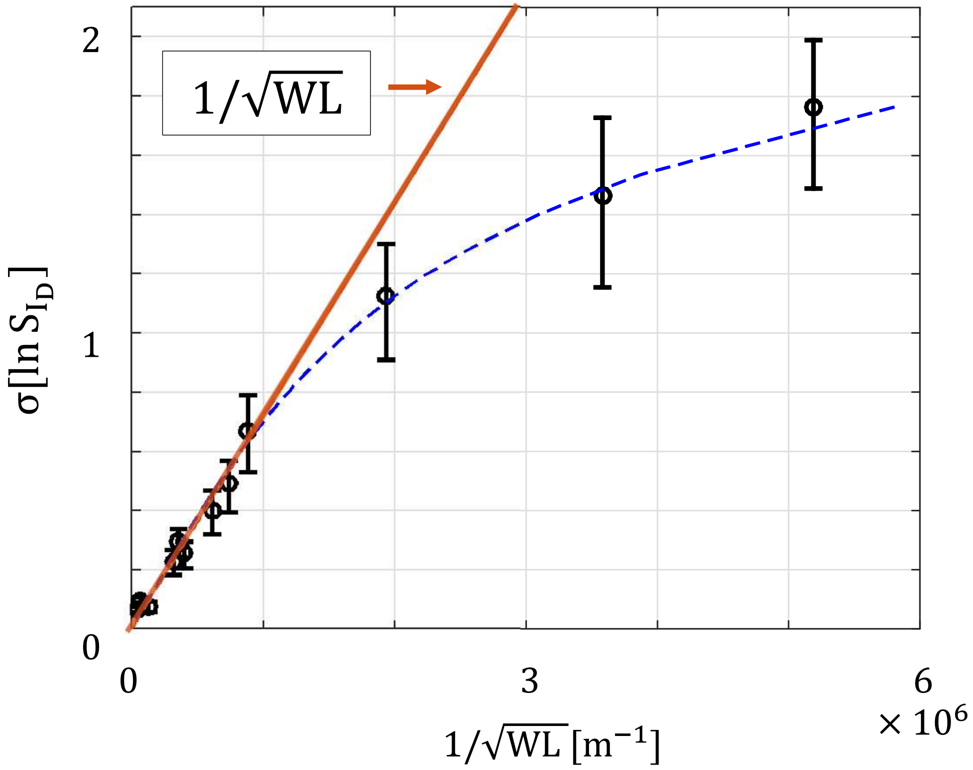
How to statistically describe the noise?

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

$$Var[\ln S(f)] = \ln\left(1 + \frac{K}{WL}\right)$$

$$K = \frac{2}{\pi^2 N_{dec}} \frac{E[A_i{}^4]}{E[A_i{}^2]^2}$$

$V_{GS} = 0.1$ V, $V_{DS} = 1.4$



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Conclusion

A microscopic, statistical modeling approach for charge trapping is presented.
It unifies the modeling of BTI, RTN and 1/noise, allowing parameter extraction and the investigation of the involved physical mechanisms.
It is a statistical model, accounting for the variability among devices and its area scaling.
Parameter extraction is discussed.

Work here presented is due to

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- People at NXP: Andries Scholten, Hans Tuinhout, Lucas Brusamarello.
- and many others …

Comments / Questions

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A few Refs

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