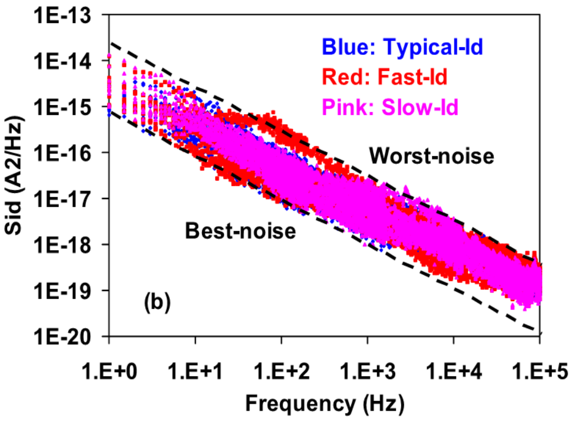
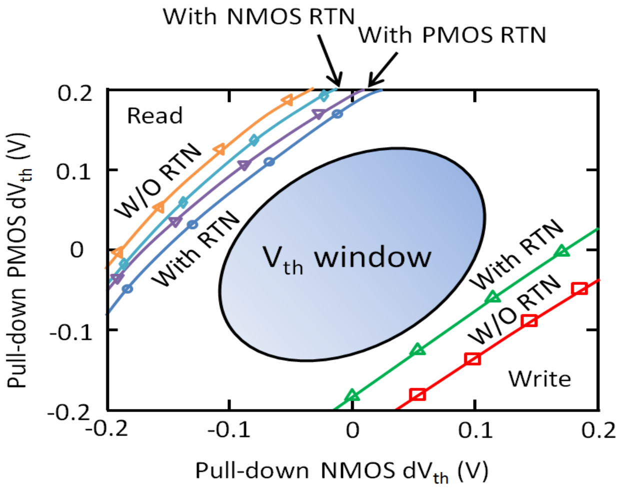
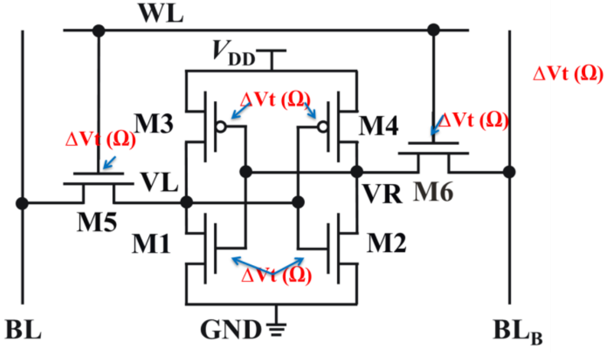
Platform Design Automation - The EDA Platform Company

Noise Characterization, Modeling and Its Impact on Highly Scaled Designs – from 0.1Hz to MMW

http://www.platform-da.com







Agenda

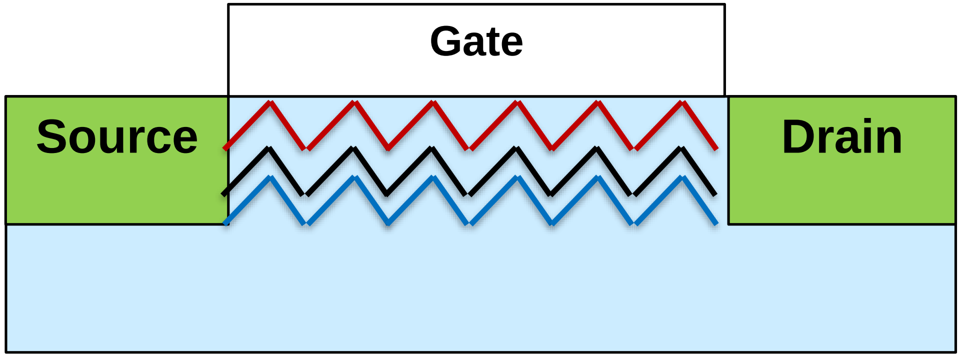
- Noise is a Source of Variability
- Noise Introduction and Its Impact on Designs
  - RTN – SRAM
  - 1/f – VCO
  - Thermal – LNA & ADC
- PDA Noise:NC300A Introduction
  - Reveal Architect Fundamentals
  - Product Advances
- Conclusions

Less Physics

Design Perspectives

Measure/Simulate Noise Accurately

Source of Variabilities

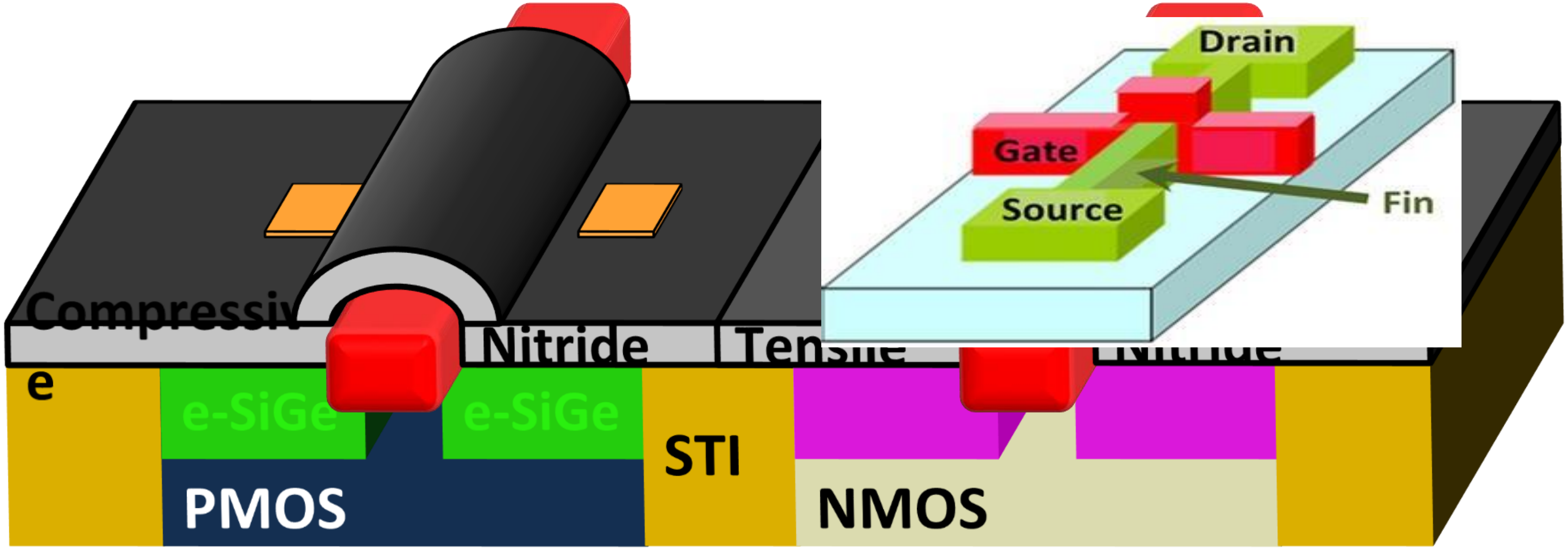


Mobility - LDE

Dopant – RDF: Mismatch

Traps/Defects –NBTI, Noise

- Shallow trench isolation
- Embedded SiGe
- Dual-stress nitride liner
- **Fin**

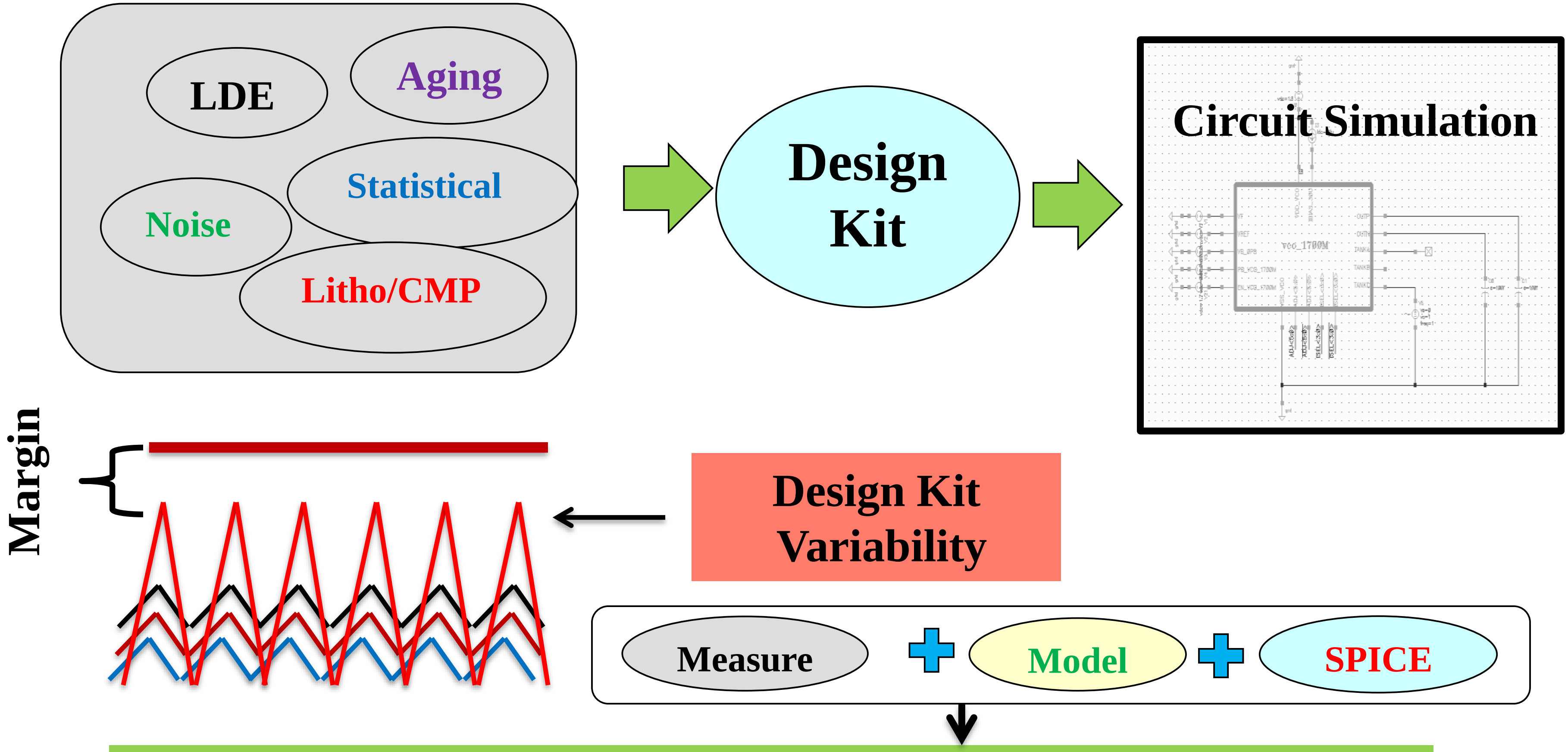


Source: Y.F. Li, et.al "A Complete and Automatic Advanced Model Verification Platform for 32nm Technology and Beyond"

Noise is a source of Variability

Variability in Design Kit vs. Design Margin

- The “Carrier” of Variability is the Design Kit
- “Human” variability may present a bigger challenge that limits design margin



Goal: Enable Accurate Simulation of Variability including Noise!

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Design Perspectives

Measure/Simulate Noise Accurately

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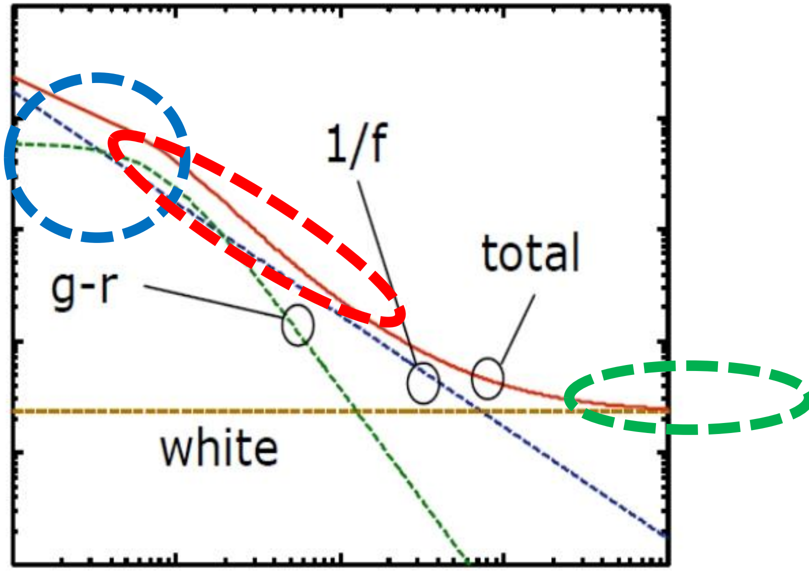
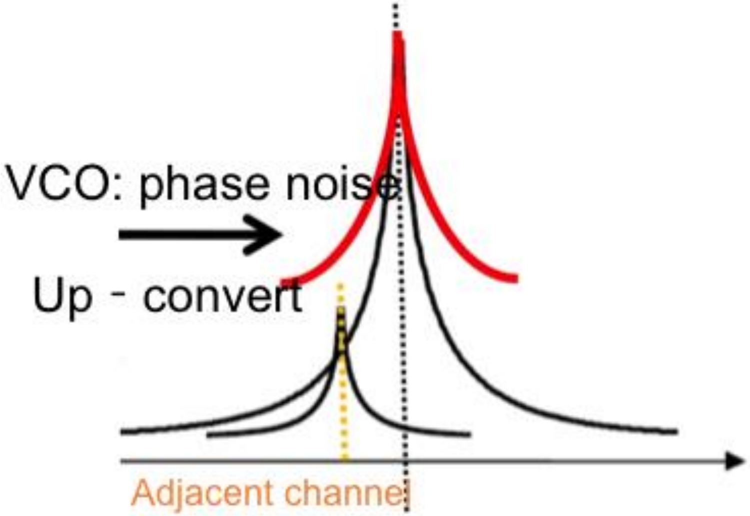
Noise: Introduction

- G-R noise: trap/de-trap (**RTN**)
- Flicker noise: Trap distribution and mobility frustration
- Thermal Noise: **High frequency noise**



Focus

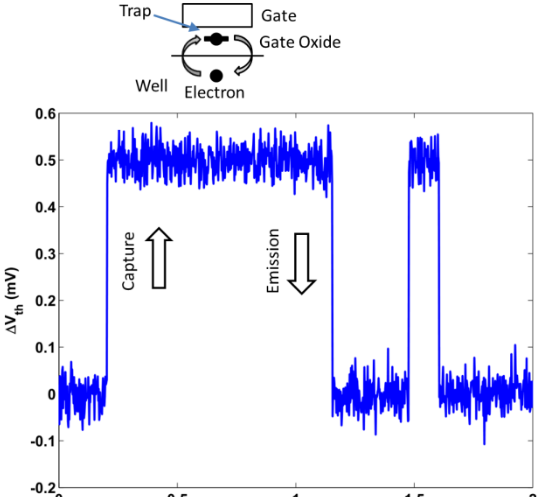
- Why it is required?
- Noise sensitive circuits.
- Modeling and implementation in circuit simulation.
- Characterization techniques

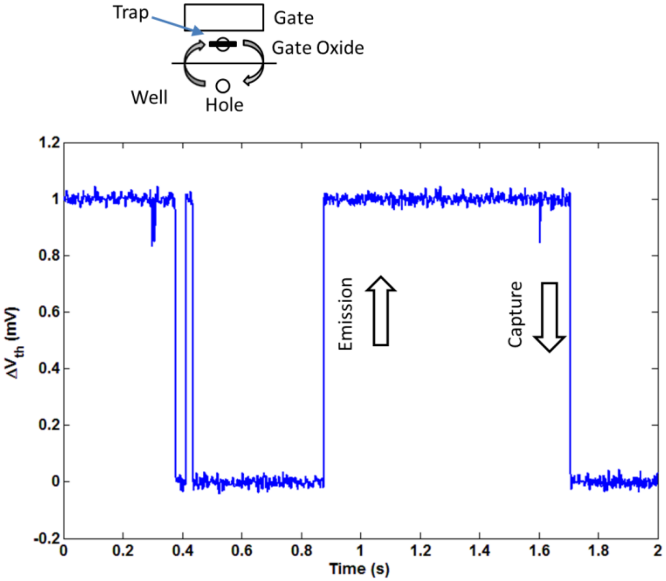


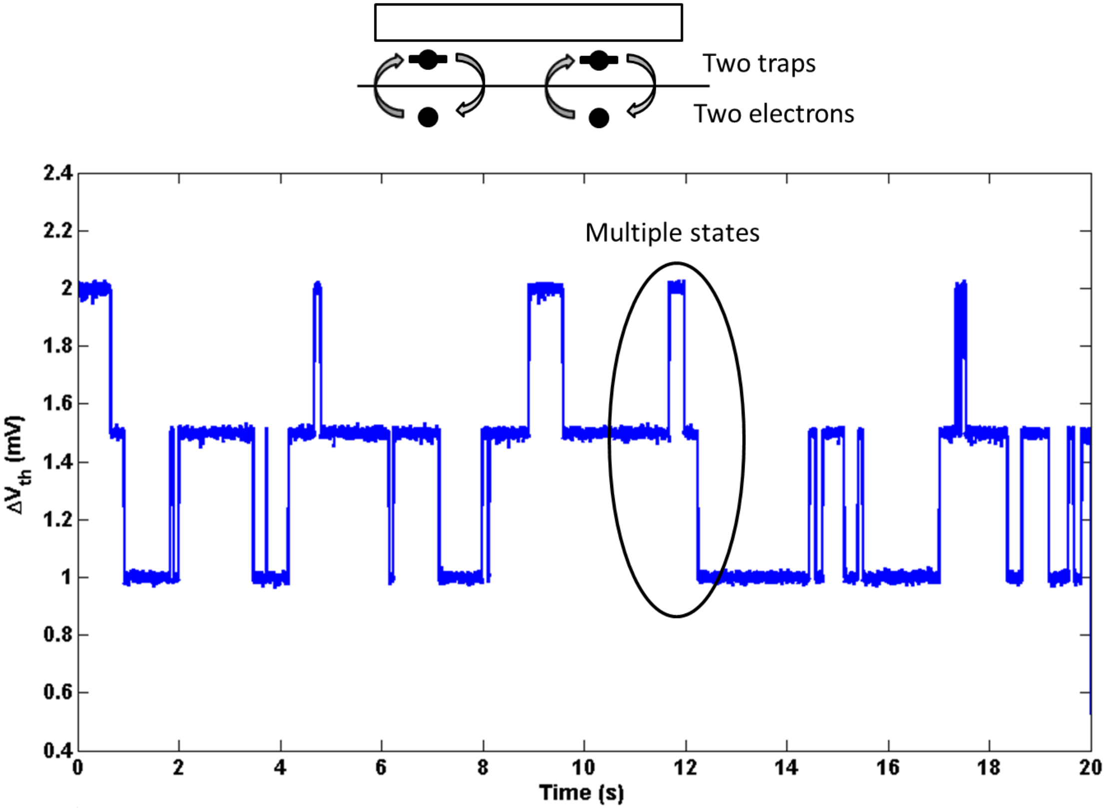
Platform DA

Low Frequency Noise - RTN

- **Random Telegraph Noise: Trap/De-trap**



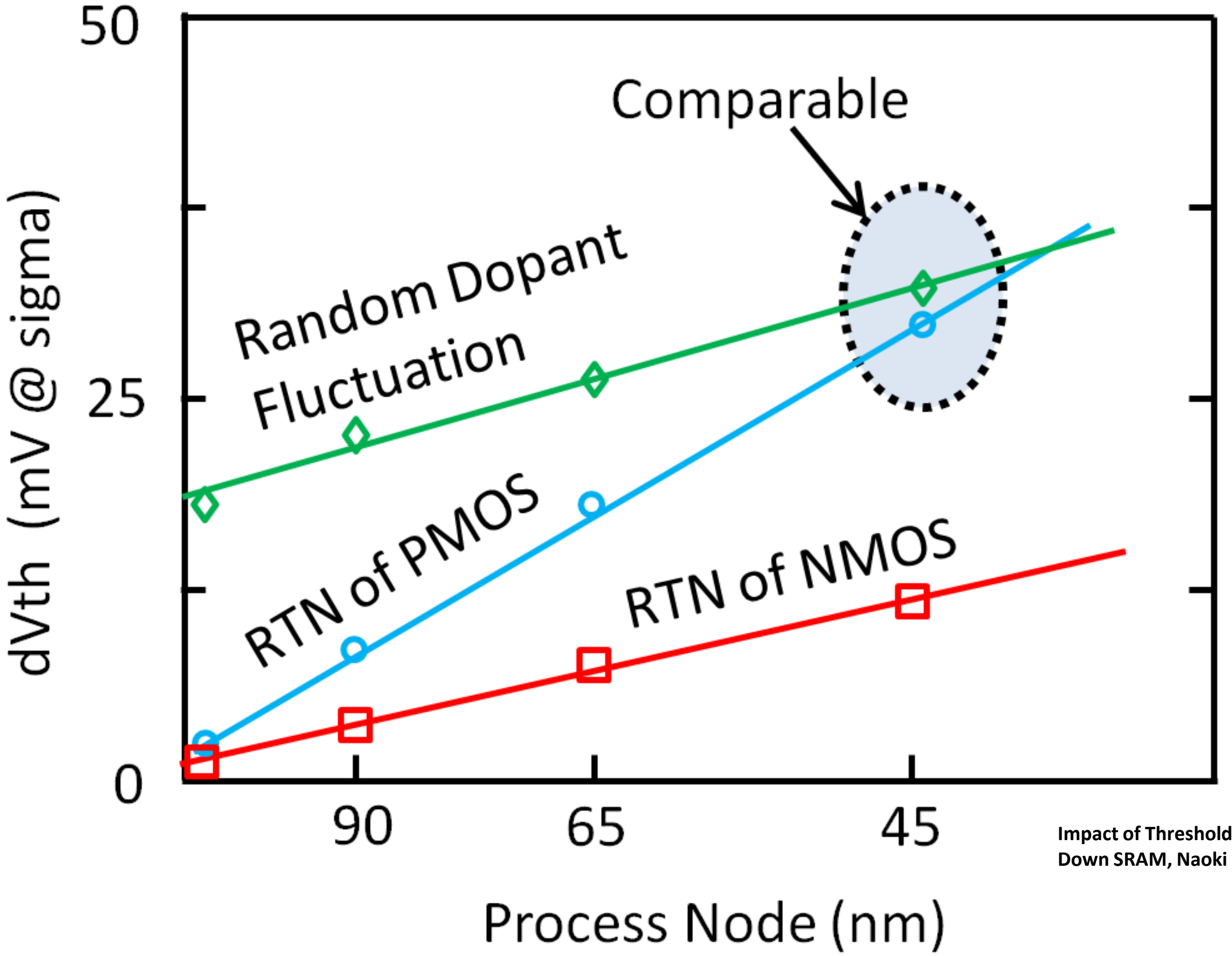




Symptoms: Vibrations in Vth

Why Suddenly RTN is Important?

- ΔVth due to RTN is comparable with ΔVth caused by RDF for advanced process



RTN

$$\Delta V_{\text{th}} = \frac{q}{L_{\text{eff}} W_{\text{eff}} C_{\text{ox}}}$$

RDF

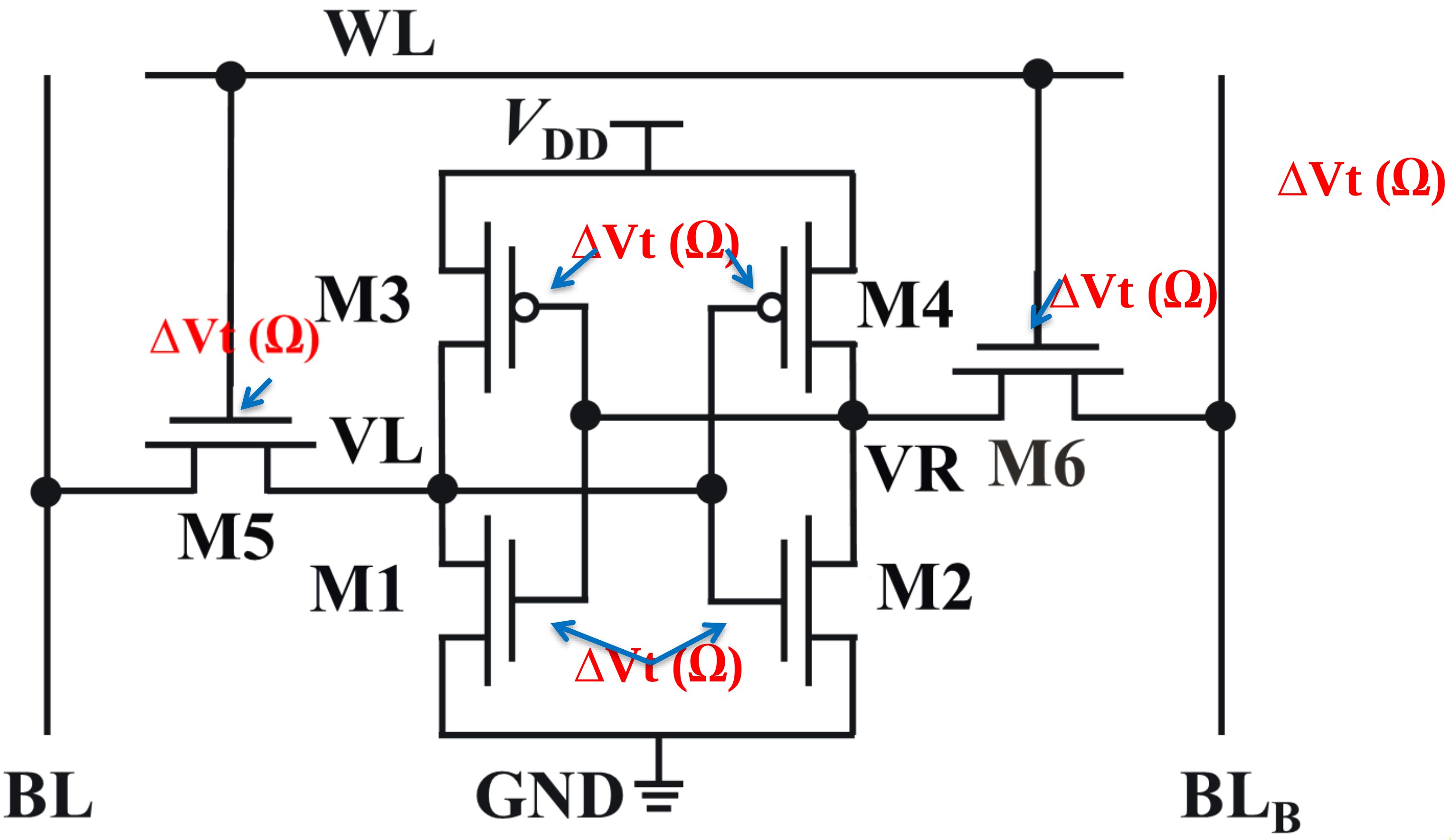
$$\Delta V_{\text{th}} = \frac{AVth0}{\sqrt{LW}}$$

Impact of Threshold Voltage Fluctuation Due to Random Telegraph Noise on Scaled Down SRAM, Naoki Tega, IRPS 2008

RTN Sensitive Circuit - SRAM

- **Circuit sensitive to ΔVth variations are RTN sensitive**
  - SRAM

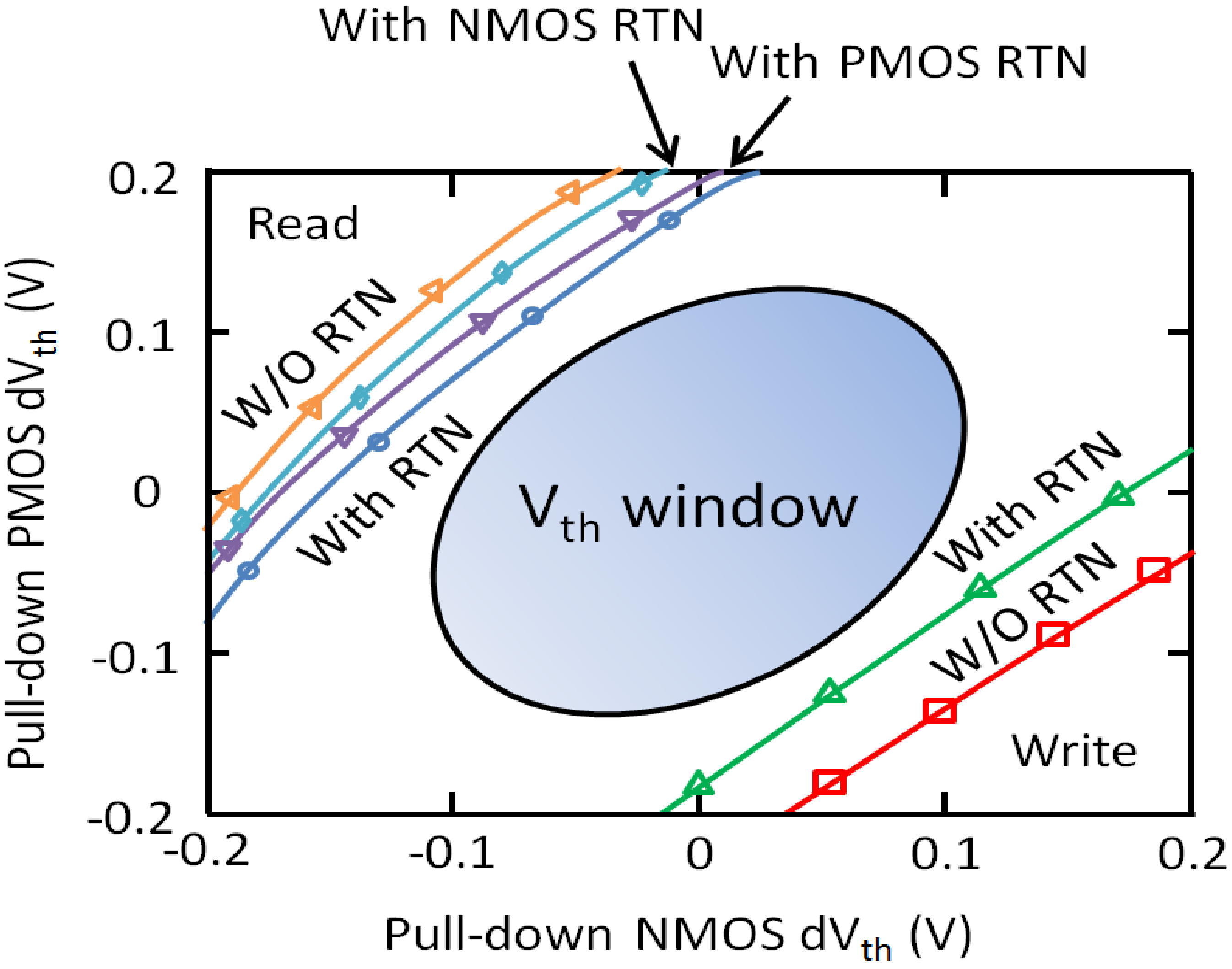
SRAM Analysis supported by MeQLab



Platform DA

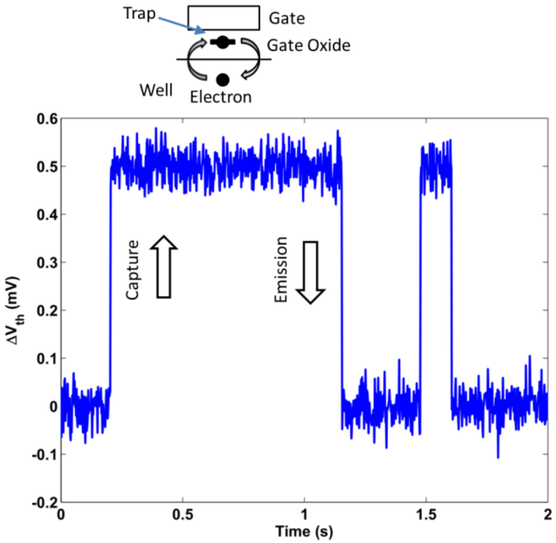
Analyze RTN in SRAM – Method 1: Yield

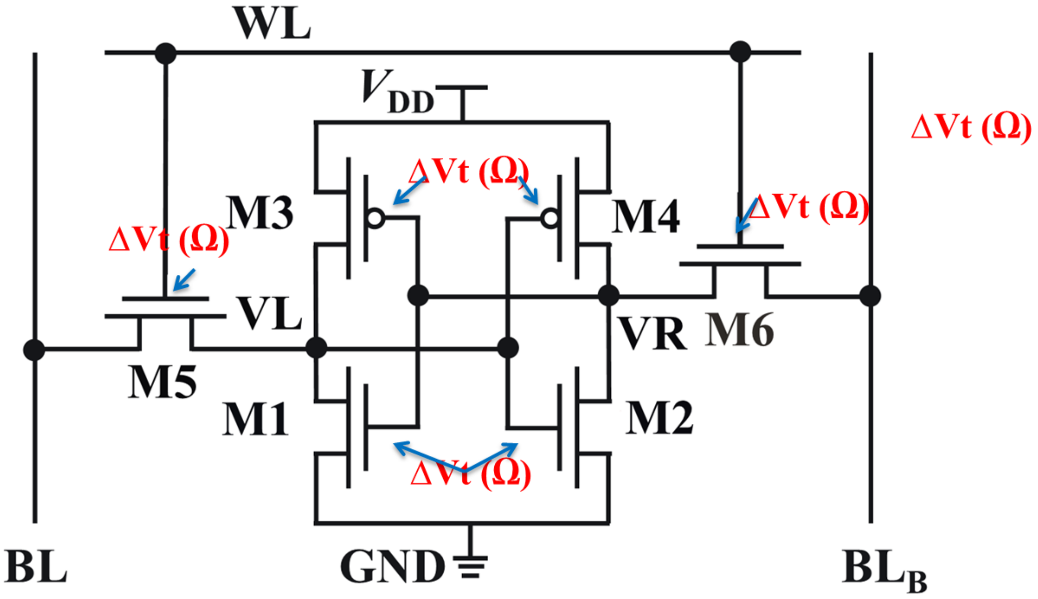
- **Treat RTN caused ΔVth same as ΔVth caused by RDF**



Analyze RTN in SRAM – Method 2: BER

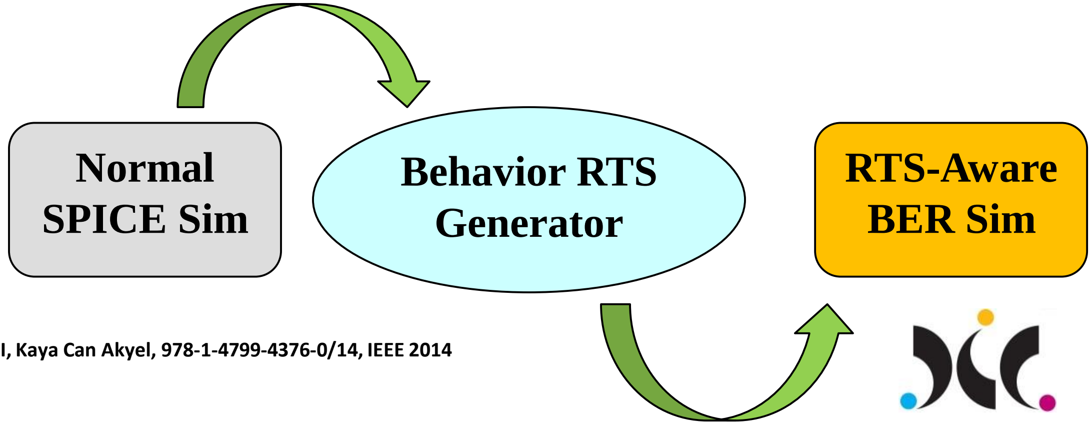
- **Implement RNT caused Vth variation into SPICE as a voltage source and simulate BER**





Behavior description of RTN Vt

$\Delta Vth = f(V, t\dots)$



Normal SPICE Sim

Behavior RTS Generator

RTS-Aware BER Sim

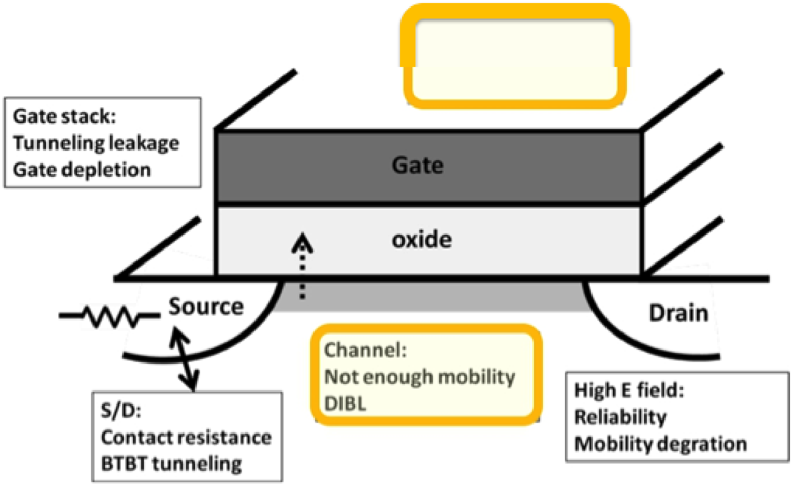
Impact of Random Telegraph Signals on 6T High-Density SRAM in 28nm UTBB FD-SOI, Kaya Can Akyel, 978-1-4799-4376-0/14, IEEE 2014

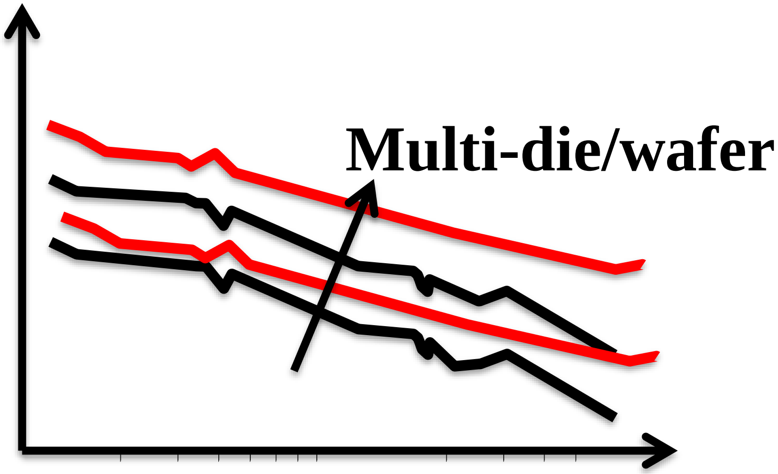
RTN Summary

- Comparable to RDF at advanced process node
- Strong impact on small geometry devices
  - SRAM
- Measuring RTN is only half-way through, modeling implementation and circuit simulation are required to complete the task
  - Yield based simulation similar to that of RDF
  - SPICE BER simulation with behavior RTN model

Low Frequency Noise – 1/f

- Circuits are more sensitive to 1/f noise at advanced process nodes
  - Becomes a must-have SPEC by designers
- Variability of Noise scales with process variability
  - Needs to measure "Corner"
- Design requires accurate noise simulation
  - Requires accurate noise and its statistical modeling

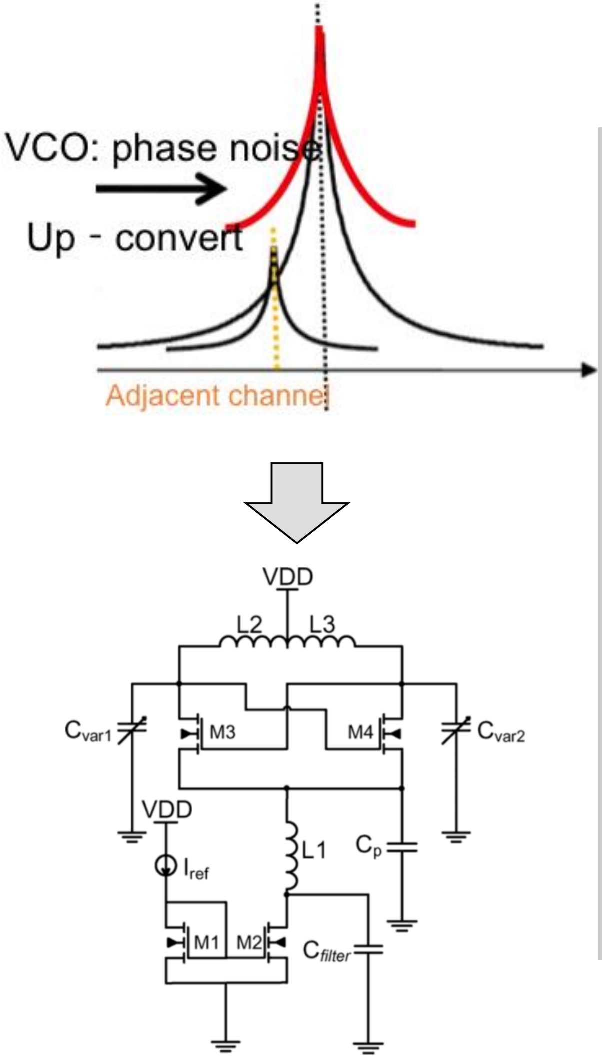




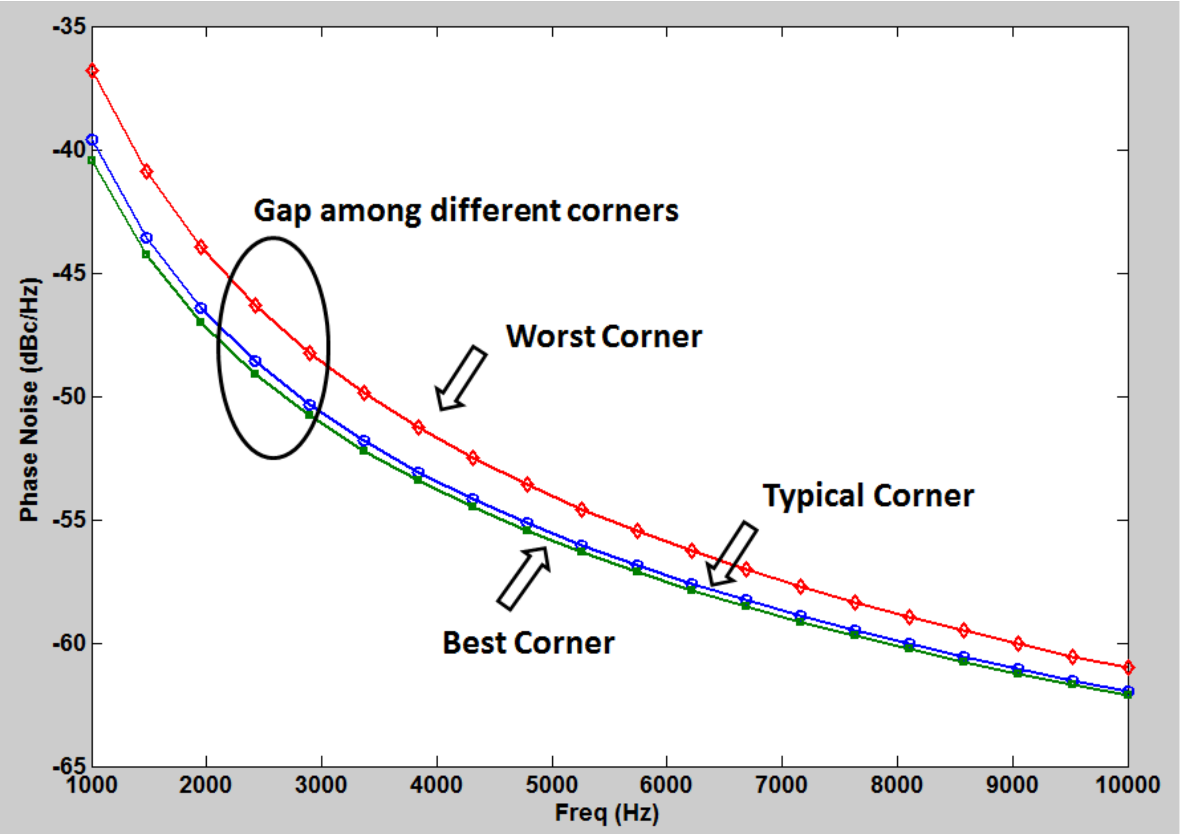
Current Solutions are expensive and slow!

Why Designers Want Noise “Corner”

- Variation big enough to bring significant impact on design.

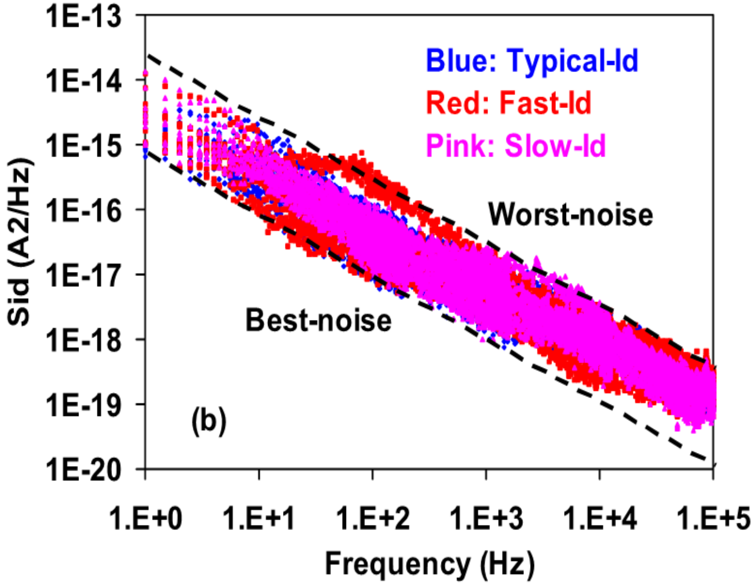


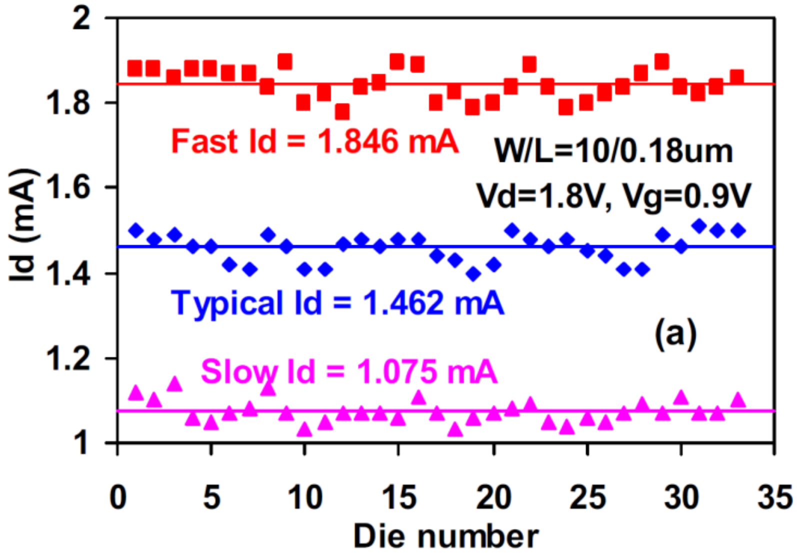
VCO Phase noise analysis with MeQLab



Noise “Corner” Key Aspects

- Sid should be normalized by Id
- Variation of Sid should be Area dependent
  - Similar to that of mismatch
- Variation of Sid should be Bias dependent
  - Bigger Vg should have Less Variation



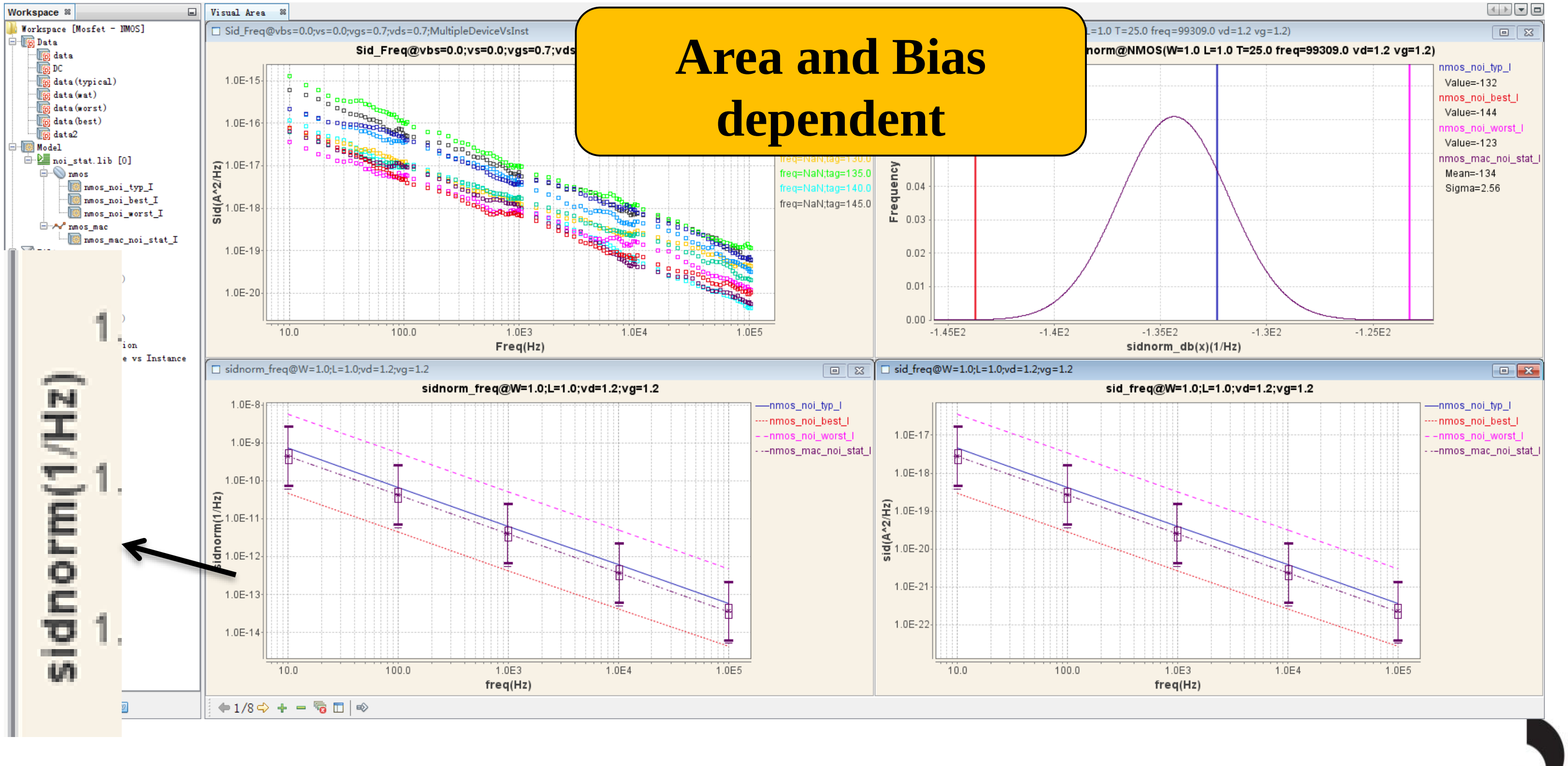


CR018 Wideband Noise Model for AMS/RF CMOS Simulation. M. T. Yang, *et al.* 2007 IEEE Radio Frequency Integrated Circuits Symposium

Statistical 1/f Noise Modeling with MeQLab

- Statistical noise model can be automatically generated after noise data is collected.

Statistical noise model example with MeQLab



Area and Bias dependent

Platform DA

1/f Noise Summary

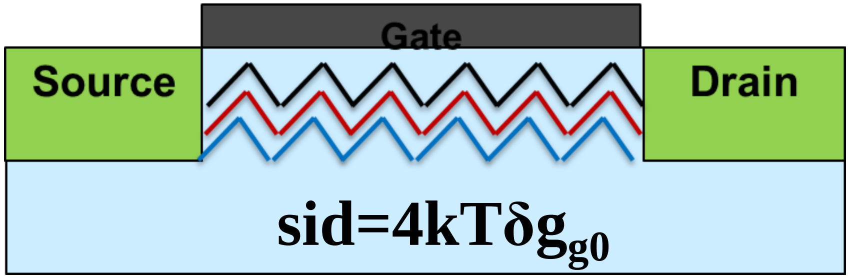
- Need to address noise variability for advanced nodes
  - Require large sample measurement
  - Require statistical noise modeling
  - Analog circuit require noise of small current (around Vt)
- Modeling Noise Corner is different from IV corner
  - Sid Normalization, area and bias dependent
- Measuring 1/f is only half-way through, modeling implementation and circuit simulation are required to complete the task

Hi Frequency Noise – Thermal Noise

- AKA white noise, independent of frequency.
- Unlike LF noise, gate noise contribute greatly at radio frequency
  - Also there is “Drain induced Gate noise”
- Currently measuring thermal noise is taking an indirect approach
  - Nfmin, Gamma(M), Gamma(P), Rn

4KTR

$\mathrm{sig}=4kT\gamma g_{d0}$

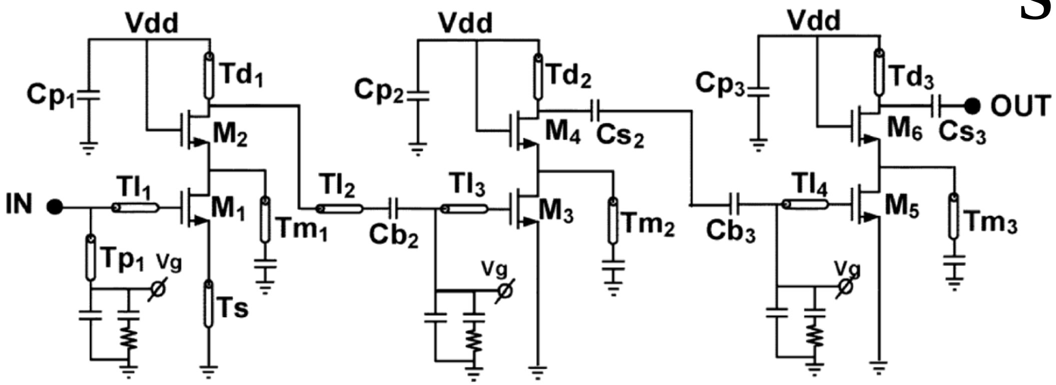


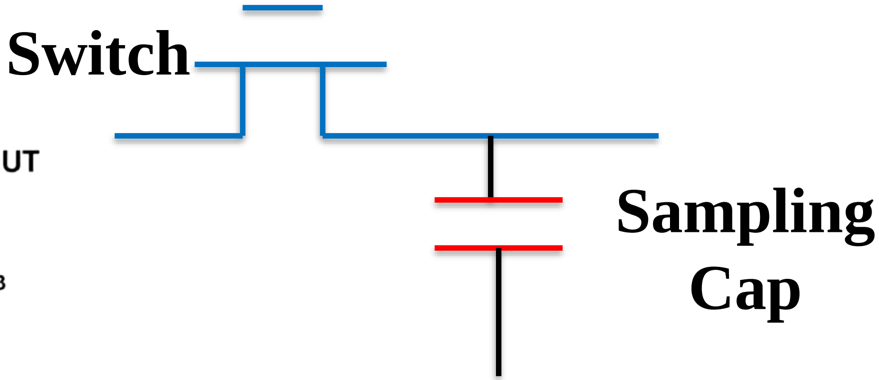
$\mathrm{sid}=4kT\delta g_{g0}$

Expensive and Unstable!

Why Designers Care about Thermal Noise

- LNA’s noise figure is decided by thermal noise
- High speed, high bit ADC
  - Thermal noise decides LSB
  - User can increase switch capacitance to minimize thermal variation, however it limits the speed.

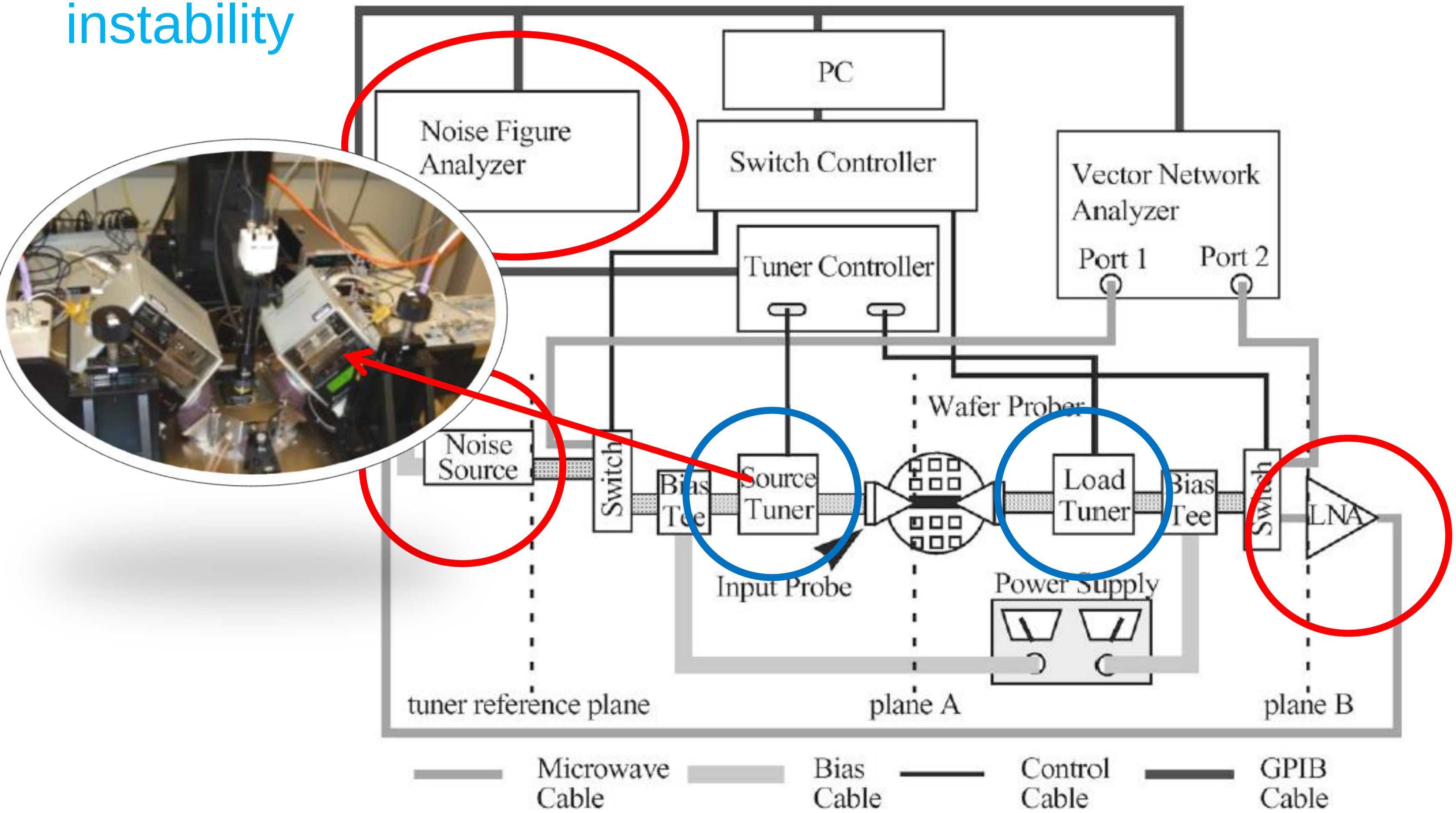




$$V^2(\text{noise\_rms}) = \frac{s * KT}{C}$$

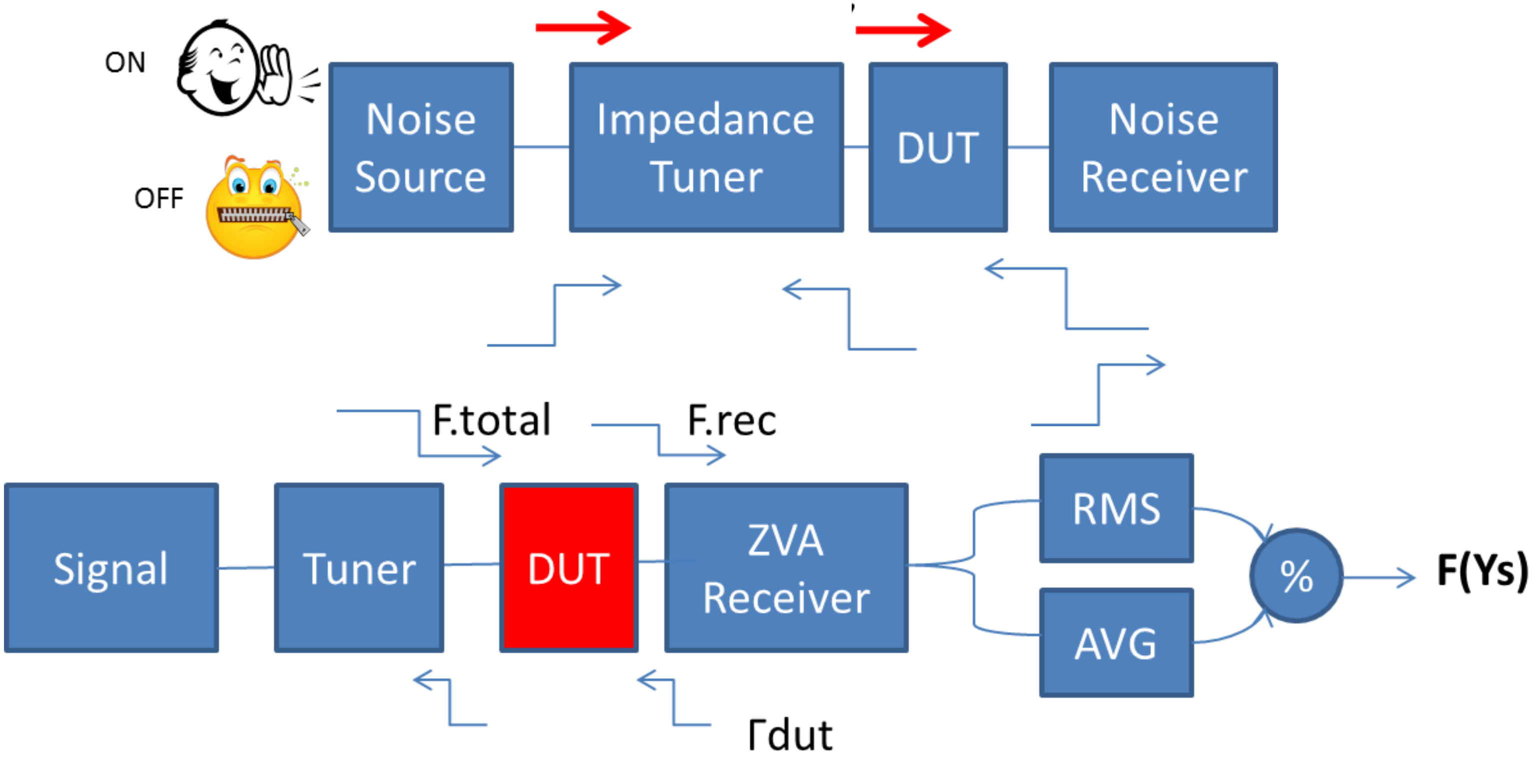
Thermal Noise Challenges

- Expensive: $$ and time: expensive parts and complex calibration
- Questionable results: mixed system noise and temperature instability



Current Thermal Noise Approaches

- 1:Compare noise output with 2 levels of source noise power
- 2: Calibrate noise receiver with noise source, rely on s-parameter to derive noise.
- 3: Signal/Noise ratio, no noise source is required



ON

OFF

Noise Source

Impedance Tuner

DUT

Noise Receiver

Method 1 & 2

F.total

F.rec

Signal

Tuner

DUT

ZVA Receiver

RMS

AVG

%

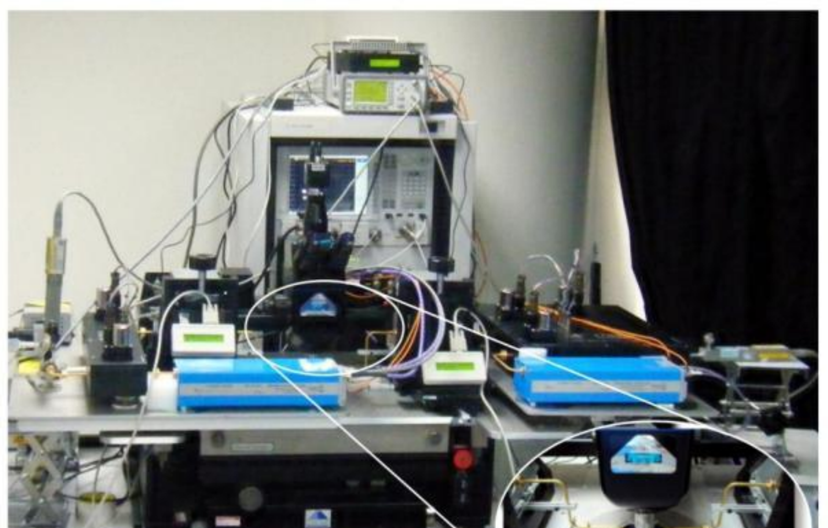
F(Ys)

Γdut

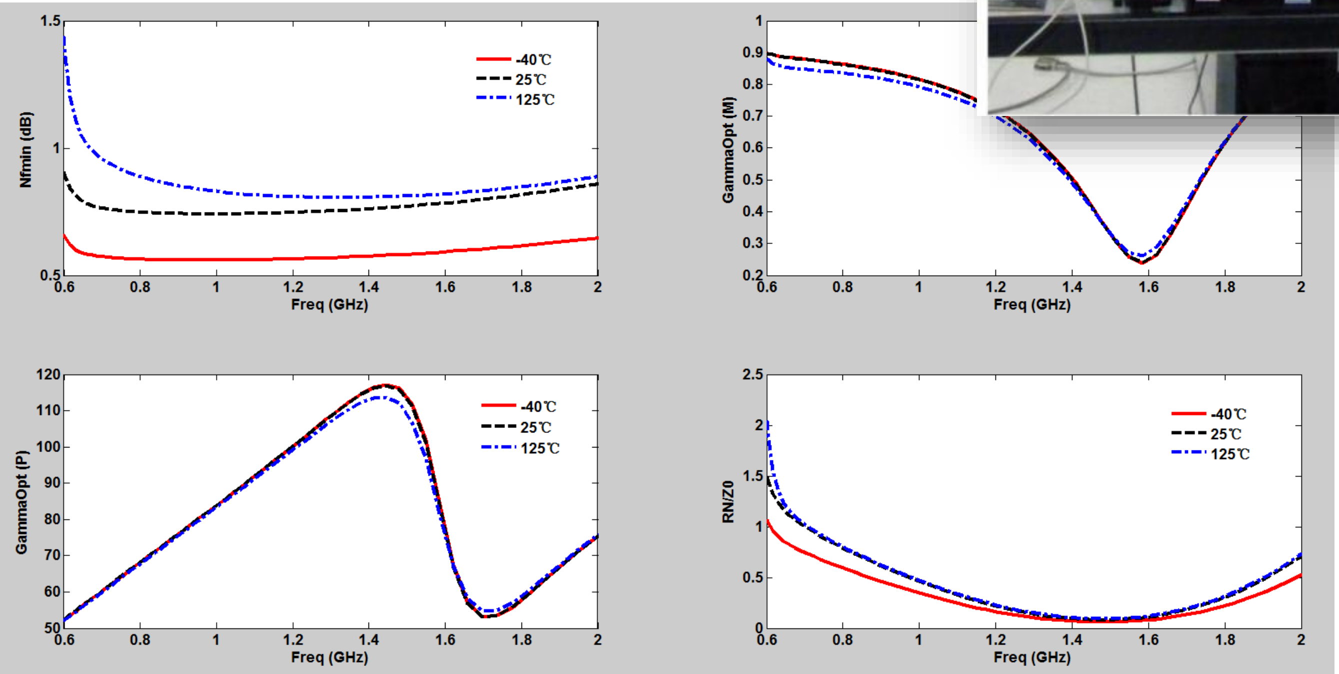
Method 3

Thermal Noise: Think Outside of the Box

- Most sensitive to Temperature by nature
- SPICE is still the carrier – Text book equations
- Expensive but yet not stable
  - Remove more expensive parts such as tuner?



VCO Analysis with MeQLab



Thermal Noise Equations

$$R_n = \frac{\boxed{S_{i_d}}}{4\,kT|Y_{21}|^2}$$

$$B_{\text{opt}} = -B_{\text{cor}} = \frac{\boxed{S_{i_g i_d^*}}\text{Re}(Y_{21})}{4\,kTR_n|Y_{21}|^2} - \text{Im}(Y_{11})$$

$$G_{\text{opt}} = \left(\frac{\boxed{S_{i_g}}}{4\,kTR_n} - |Y_{11}|^2 + 2\left[\text{Re}(Y_{11})G_{\text{cor}} + \text{Im}(Y_{11})B_{\text{cor}}\right] - B_{\text{opt}}^2\right)^{\frac{1}{2}}$$

$$F_{\min} = 1 + 2R_n(G_{\text{cor}} + G_{\text{opt}})$$

$$F_{50} = F_{\min} + \frac{(\frac{1}{50} - G_{\text{opt}})^2 + (-B_{\text{opt}})^2}{\frac{1}{50}}R_n.$$

For BSIM 3/4 Models

$$\boxed{S_{i_d} = S_{i_d\_\text{ch}} + S_{i_d\_\text{sub}} + 4\,kTg_m^2R_g}$$

$$S_{i_d\_\text{ch}} = 4\,kT\left(\frac{W}{L_{\text{eff}}}\mu_{\text{eff}}C'_{\text{ox}}\right) \times \left(\frac{V_{GT}^2 - \alpha V_{GT}V_{\text{DSeff}} + \frac{\alpha^2}{3}V_{\text{DSeff}}^2}{V_{GT} - \frac{\alpha}{2}V_{\text{DSeff}}}\right)$$

$$\boxed{S_{i_g i_d^*} = S_{i_g i_d^*\_\text{ch}} + S_{i_g i_d^*\_R_g}}$$

$$S_{i_g i_d^*\_R_g} = j4\,kT\omega C_{gg}g_mR_g$$

$$S_{i_g i_d^*\_\text{ch}} = \frac{j4\,kT\omega W^3C'^3_{\text{ox}}\mu_{\text{eff}}^2}{L_{\text{eff}}I_{\text{DS}}^2}\left(\frac{1}{1+\frac{V_{\text{DSeff}}}{E_cL_{\text{eff}}}}\right) \times \left[-\frac{1}{4}\alpha^2V_{\text{DSeff}}^4 + \frac{\alpha}{3}\left(\alpha V_{as}+2V_{GT}\right)V_{\text{DSeff}}^3 - \frac{V_{GT}}{2}\left(2\alpha V_{as}+V_{GT}\right)V_{\text{DSeff}}^2+V_{GT}^2V_{as}V_{\text{DSeff}}\right]$$

$$\boxed{S_{i_g} = S_{i_g\_\text{ch}} + S_{i_g\_R_g}}$$

$$S_{i_g\_R_g} = 4\,kT\omega^2C_{gg}^2R_g$$

$$S_{i_g\_\text{ch}} = \frac{4\,kT\omega^2W^4C'^4_{\text{ox}}\mu_{\text{eff}}^2}{I_{\text{DS}}^3}\left(\frac{1}{1+\frac{V_{\text{DSeff}}}{E_cL_{\text{eff}}}}\right) \times \left[\frac{\alpha^2}{5}V_{\text{DSeff}}^5 - \frac{\alpha}{2}(\alpha V_{as}+V_{GT})V_{\text{DSeff}}^4 + \frac{1}{3}\left(\alpha^2V_{as}^2+4\alpha V_{GT}V_{as}+V_{GT}^2\right)V_{\text{DSeff}}^3 - V_{GT}V_{as}\left(\alpha V_{as}+V_{GT}\right)V_{\text{DSeff}}^2+V_{GT}^2V_{as}^2V_{\text{DSeff}}\right]$$

Platform DA

Thermal Noise Summary

- Thermal noise greatly limits the design performance of RF and high-speed ICs
- Current thermal noise characterization systems are expensive and return questionable results.
- Stay tuned for a new thermal noise solutions.

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Less Physics

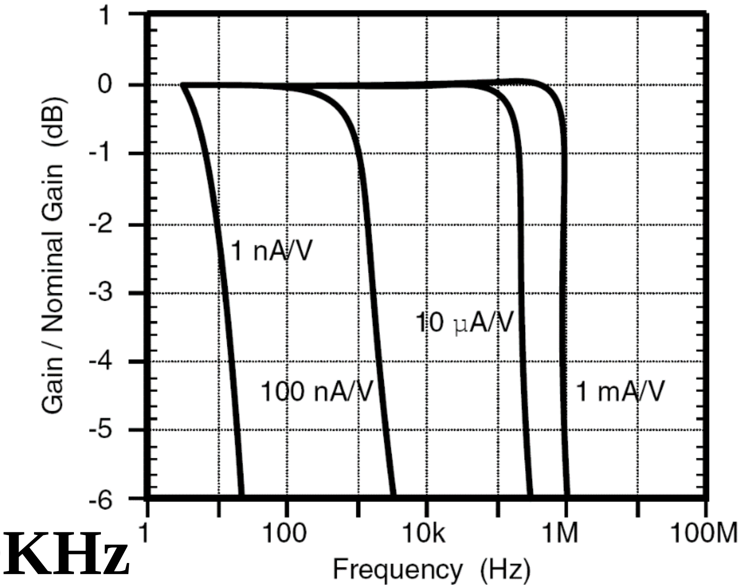
Design Perspectives

Measure/Simulate Noise Accurately

Platform DA

Noise Characterization System Design Guidance

- Amplifier Design – Smart LNA
  - Bandwidth vs. Sensitivity
  - Roll-off $F_{rolloff} = \frac{1}{2\pi RC}$
- "Self-adjust" Algorithm – Plug & Play
  - All-in-one
- Remove the time-consuming piece – Fast



100pf, 10K, 150KHz

LPF

DSA

Calibration

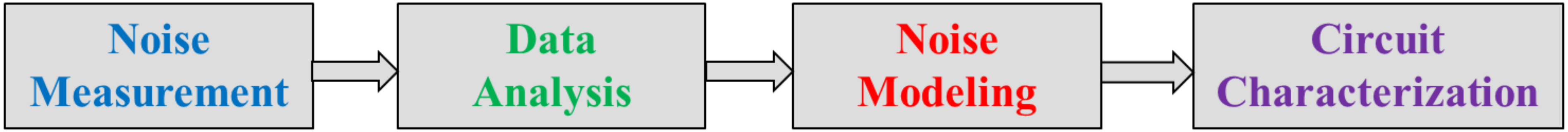
Decide R-load

Other Iterations…

True Innovation is enabled by Hardware + Software

Advanced Noise Requirement Summary

- High throughput – Fast
- Able to measure noise of small current
- Flexible and compact Configuration
  - On-Wafer (WAT and Modeling) and packaged part ready
  - Plug & Play (Never complain customer’s environment)
- Complete



NC300A - SPEC

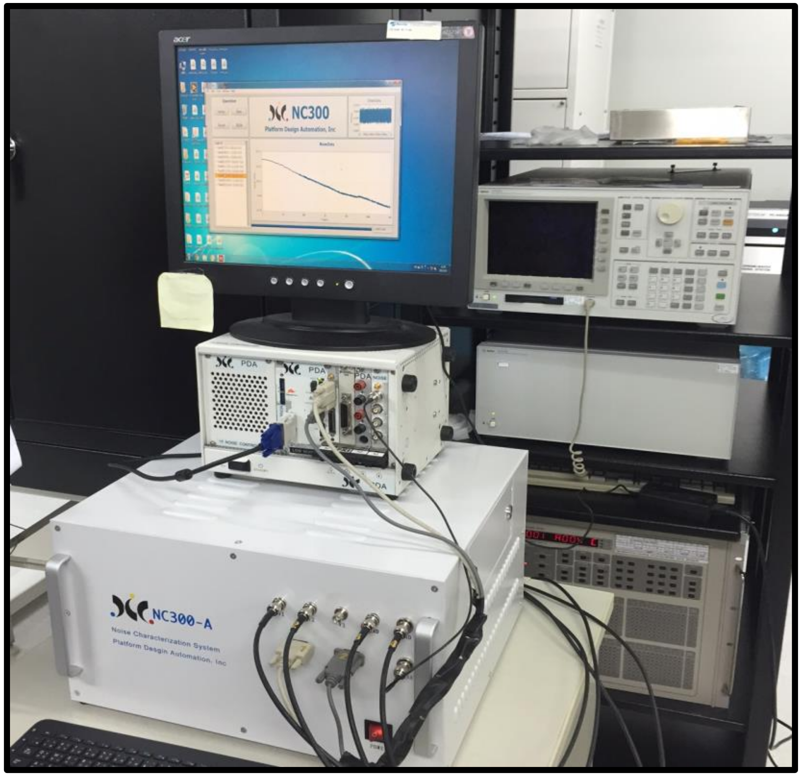
1. Fast speed: 10X speed up with the same accuracy
2. Compact: Integrate proprietary SMU , DSA, Smart LNA, all-in-one design
3. Low current noise measurement: 1pA
4. Multi-die or multi-wafer support
5. RTN support
6. Lowest System Noise Floor (Sid): $<10^{-29}(A^2/Hz)$
7. Noise modeling built-in: typical, corner and statistical
8. Built-in circuit analysis of noise impact

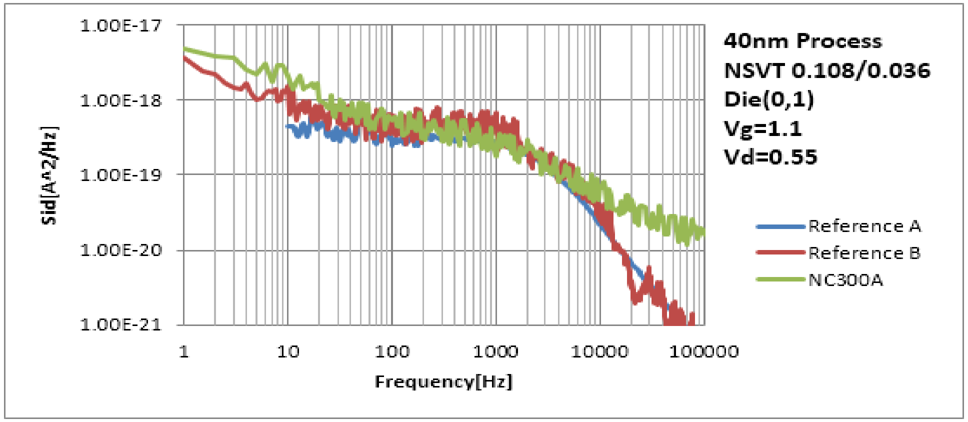
Close Alliance with National Instruments

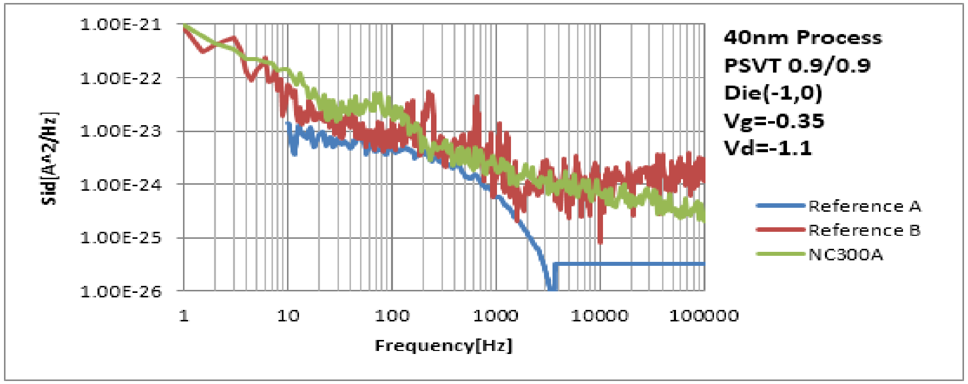
Platform DA

NC300A – Performance

- Average measurement time for each bias: ~15 seconds
- Roll-off frequency is much higher



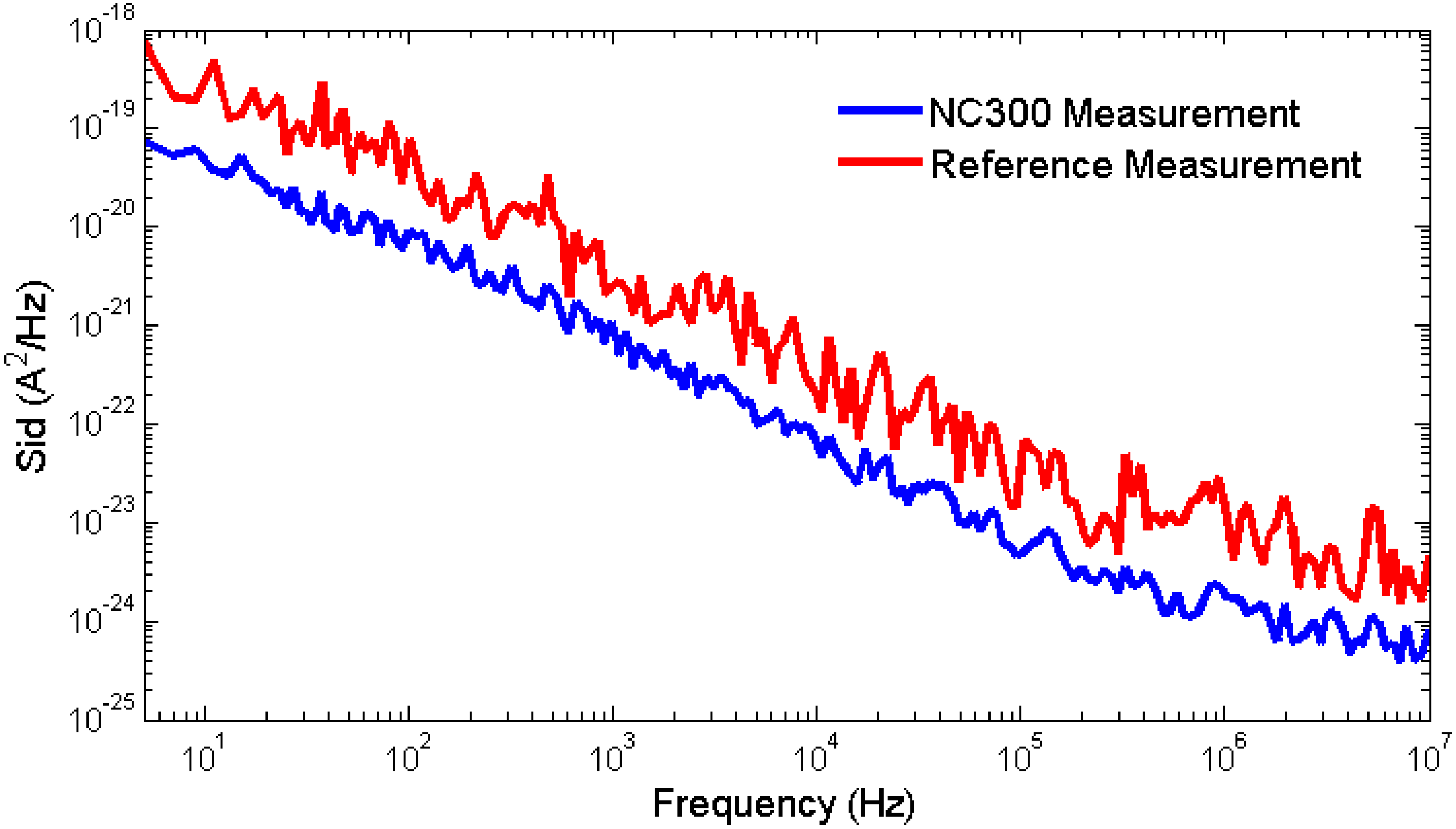




Competition tends to roll-off fast for small current

NC300A - Performance

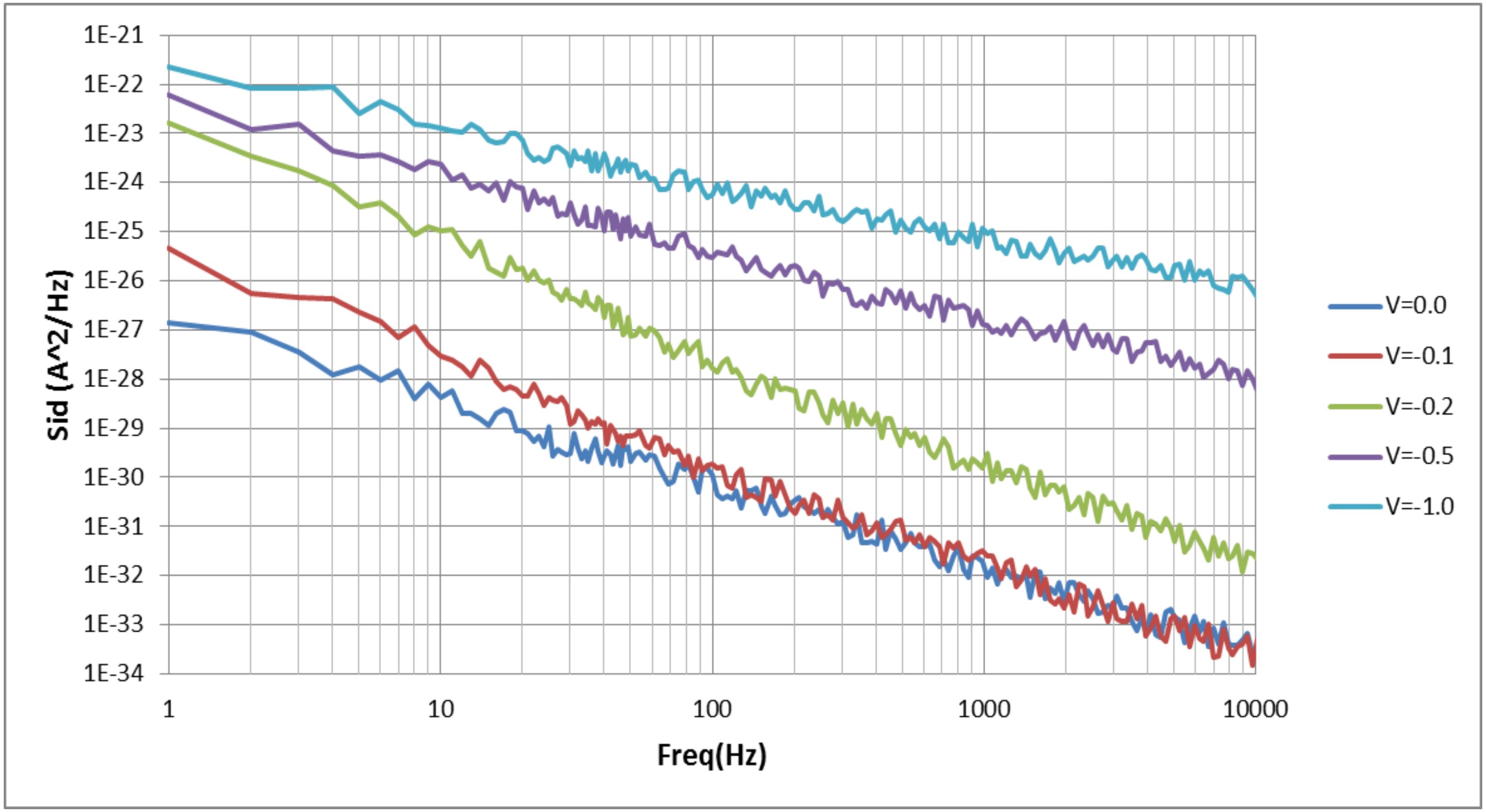
- Return true DUT current



Some system measures higher DUT current due to incorrect drain bias iterations

NC300A - Performance

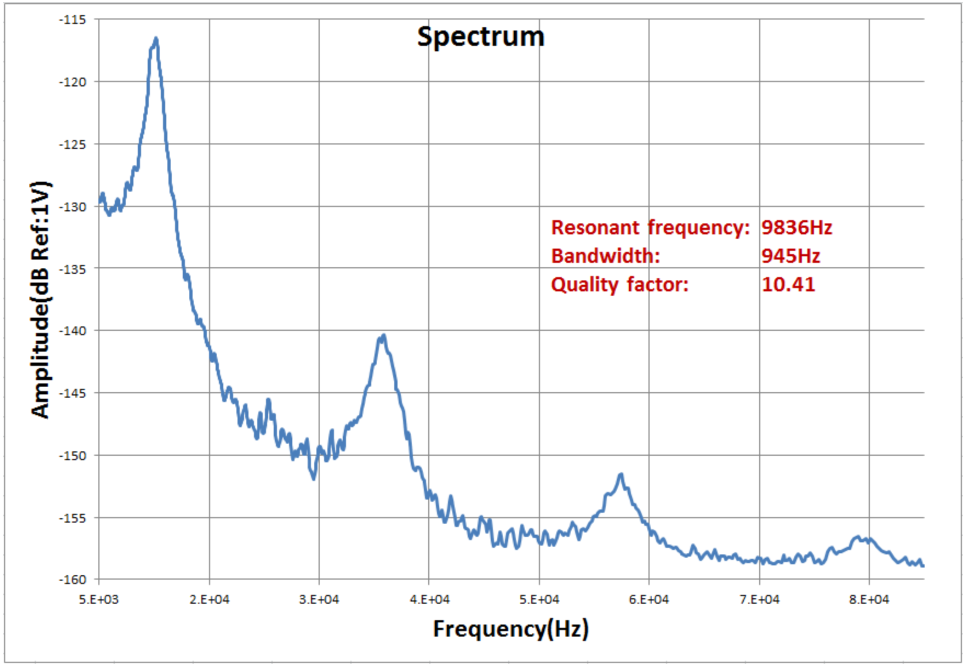
- The only system that can measure down to pA current
  - Sample shown is the noise measurement of “dark current” of a photo diode.



Platform DA

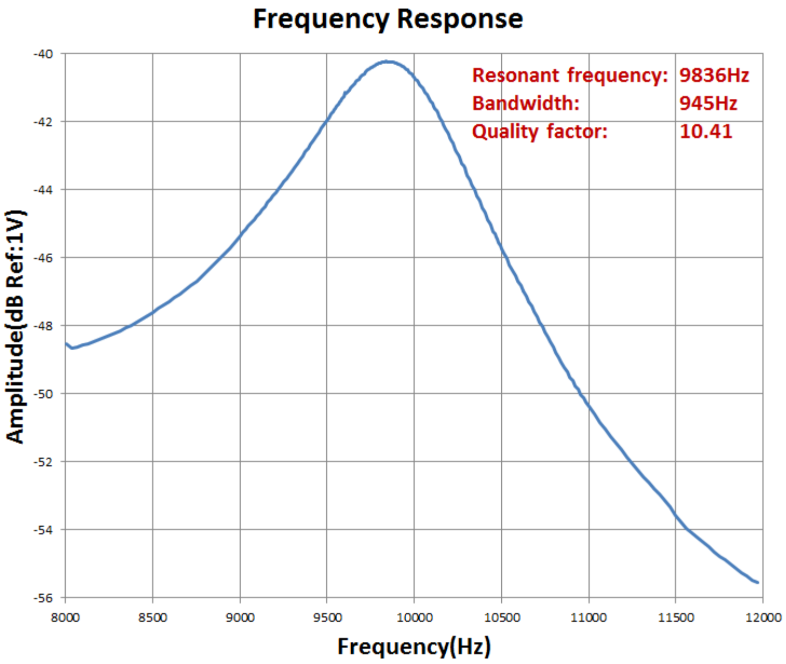
NC300A – New Applications

- MEMs Sensor Production Tests
  - Greatly save testing time – suitable for mass production test
  - Output Resonant Frequency and Quality Factor directly



Resonant frequency: 9836Hz
Bandwidth: 945Hz
Quality factor: 10.41

Pressure Sensor Low Frequency Spectrum

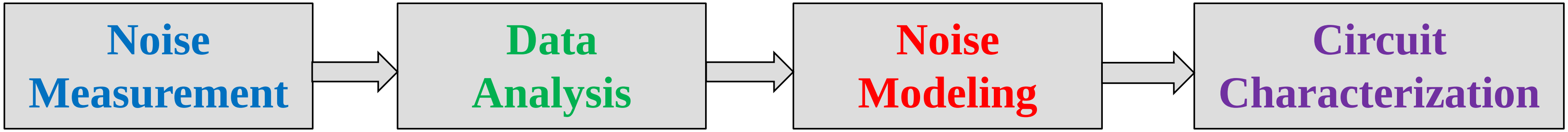


Resonant frequency: 9836Hz
Bandwidth: 945Hz
Quality factor: 10.41

Derived Quality Factor

Solution Summary

- Fast
  - Average 15s a bias
- Accurate
  - Lowest system noise
  - High Roll-off frequency
- Complete


Noise Measurement → **Data Analysis** → **Noise Modeling** → **Circuit Characterization**

Conclusion

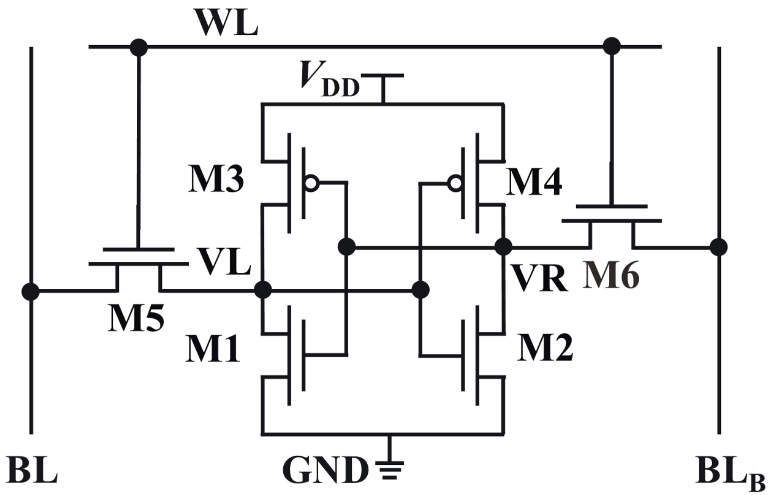
- Noise is an important variability for highly scaled designs.
- Reviewed different Noise implementation and analysis in circuit simulations.
- Low frequency noise and thermal noise characterization insights and challenges
- NC300A is a complete and competitive low frequency noise solution.

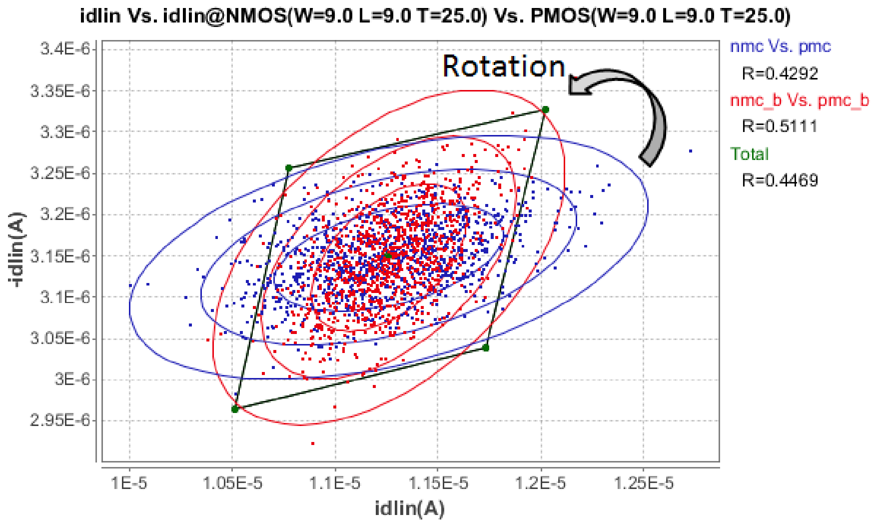
Thank you & Questions?

Platform DA

A Machine-Learning Driven Algorithm to Achieve True Automatic Statistical and Mismatch Model Generation

http://www.platform-da.com





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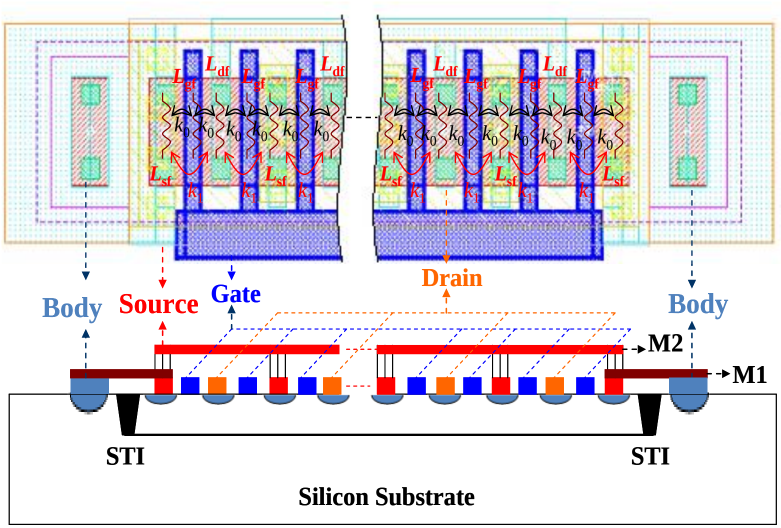

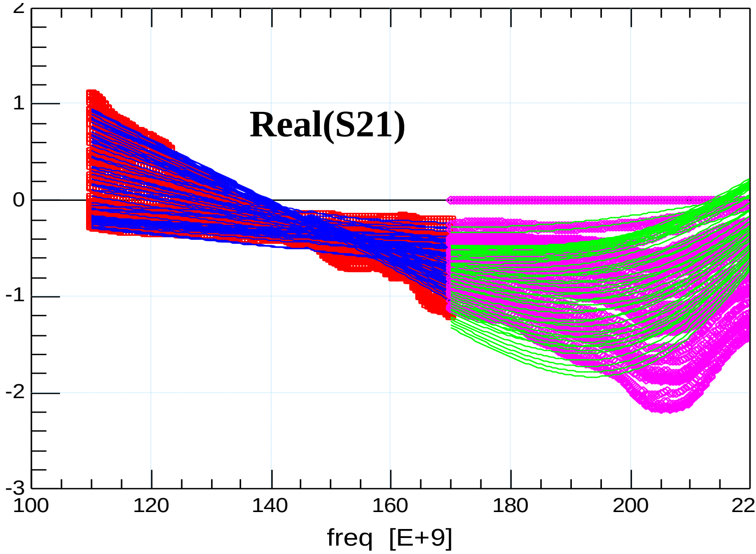

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