Advanced Low-frequency Noise Measurement with High Resolution, Wide Bandwidth and Large Biasing Current Range

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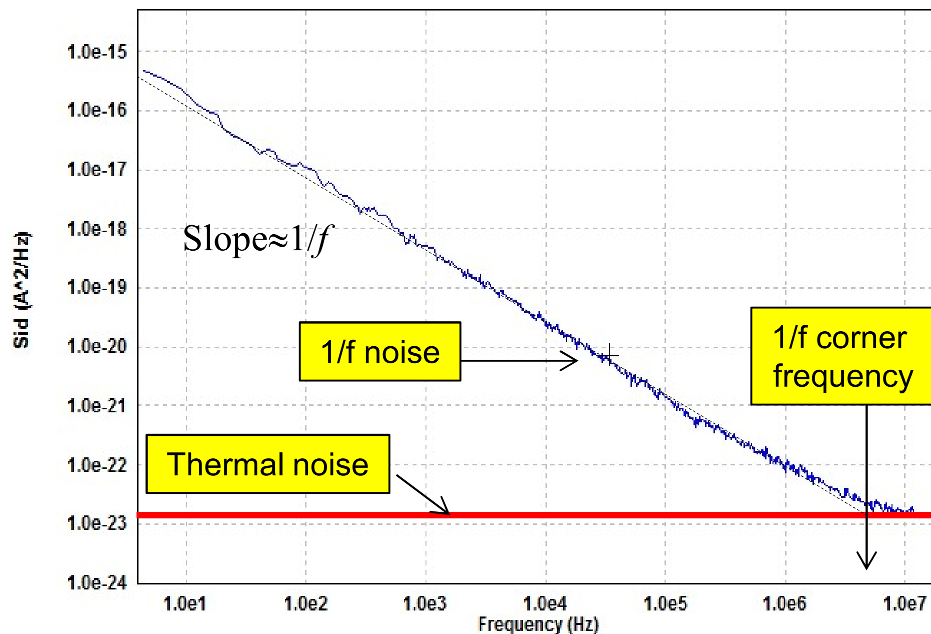
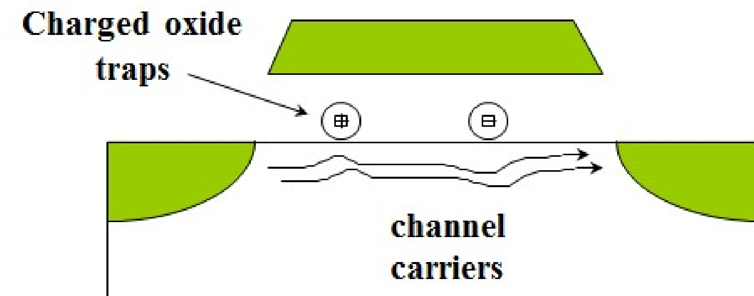
Outline

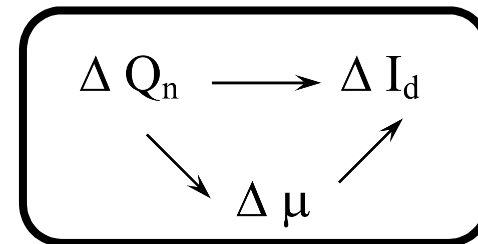
- **Introduction**
- Advanced Noise Measurement System
  - High Resolution and Wide Bandwidth
  - Large Biasing Current Range
  - Others
- Measurement Results and Discussions
- Summary

Low-frequency Transistor Noise

- 1/f noise is a fundamental device characteristic
- Low-frequency noise in scaled devices has increased impacts on process and design

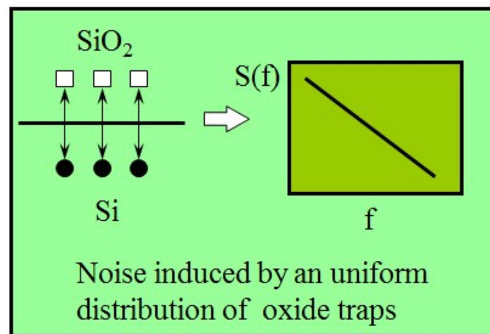


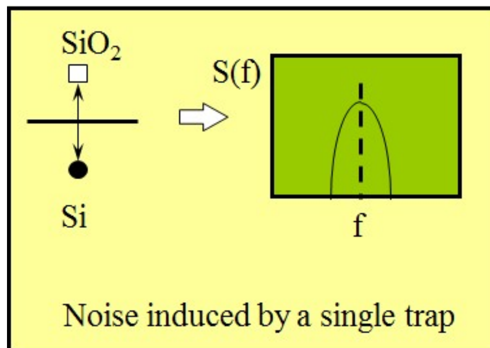


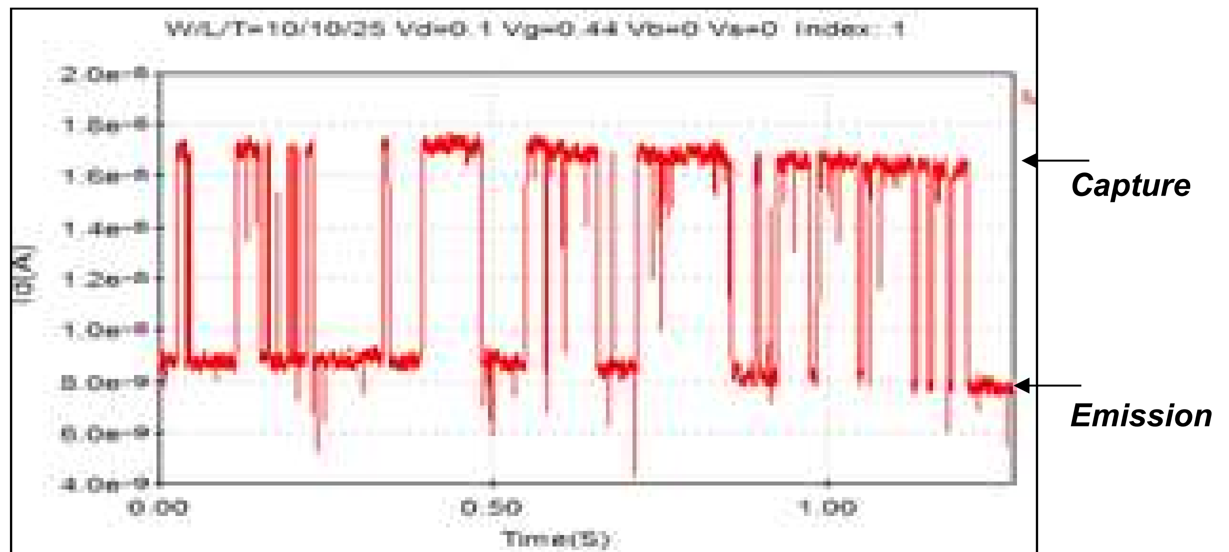


Random Telegraph Signal (RTS) Noise

- In small-geometry transistors, single or multiple traps of oxide may introduce random telegraph signal (RTS) noise.







Two-Levels RTS Noise

Measuring Low-frequency Noise Is Critical

- Technology Development
  - Process development
    - Monitor quality of oxide and Si/SiO2 interface
  - SPICE model extraction
    - Capture typical noise level and its statistical variation range
- Circuit Design
  - Process evaluation or benchmarking
    - Correlate to process quality and technology performance
  - Spice model
    - Perform circuit noise analysis for circuit performance and yield
    - Optimize circuit device sizing for PPA or others

Noise Measurement Challenges

- Noise System Capabilities and Spec
  - High Resolution with Wide Bandwidth (system level, on-wafer)
  - Large Biasing Current Range (from low current to high current)
  - High Biasing Voltage Range
  - Wide Impedance Matching Range
  - Fast Measurement Speed and High Throughput
- Noise System Applications and Adoptions
  - Noise System Versatility – One System for All Applications
  - Proven Cases, Widespread Adoption and Track Records

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Advanced Noise Measurement System

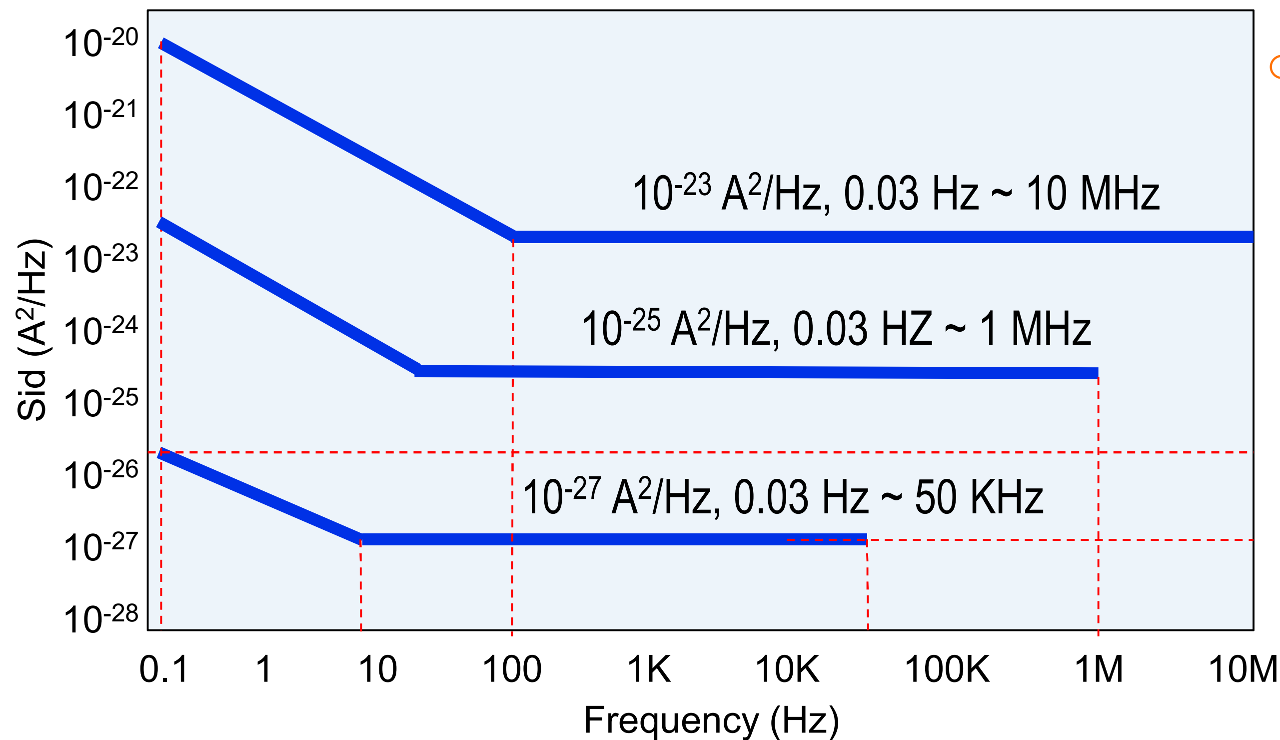
- High Resolution with Wide Bandwidth (system level, on-wafer)
  - 10^{-23} A^2/Hz @ 10 MHz
  - 10^{-25} A^2/Hz @ 1 MHz
  - 10^{-27} A^2/Hz @ 50 KHz
- Low Biasing Current (0.1 nA ~ 1 nA)
  - Low power applications require low biasing current and/or at subthreshold region
- High Biasing Current (20 mA ~ 200 mA)
  - RF or I/O applications (multi-gate, multi-finger, 3D, GaAs and GaN, etc.) operating at high biasing current

Advanced Noise Measurement System (cont.)

- High Biasing Voltage (20 ~ 200 V)
  - High voltage devices (HVMOS, LDMOS, etc.)
- Wide Impedance Matching (< 10 ohms)
  - High impedance (weak inversion FETs, photo diode), low impedance (saturated RF FETs), wide range of resistors (10 to 10M ohms), voltage controlled resistors (4-terminals), etc.
- Fast Measurement Speed and High Throughput (10 ~ 30 sec/bias)
  - Essential for statistical noise measurement and RTS measurement
- System Versatility
  - MOSFET (Bulk, SOI, FinFET), LDMOS, BJT, JFET (GaAs, GaN), Diode (photo or laser or Zener), Resistor (metal film resistor), IC, etc.

System-level Noise Spec

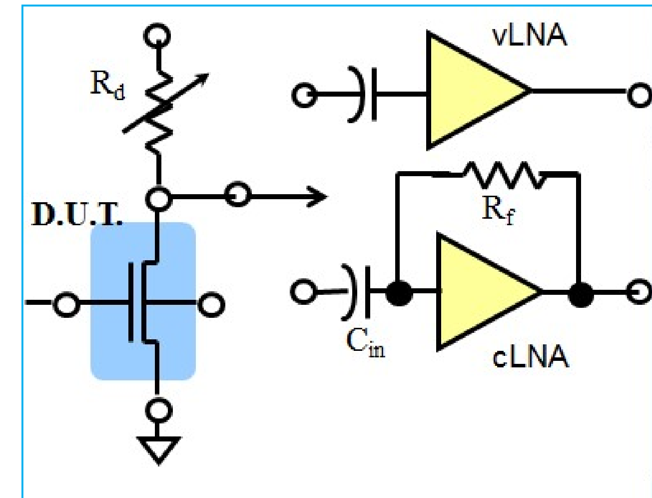
- The high resolution and wide bandwidth on wafer level
  - Use multiple amplifiers, i.e. current and voltage amplifiers, with different circuit schemes, to achieve various levels of high resolution and wide bandwidth spec



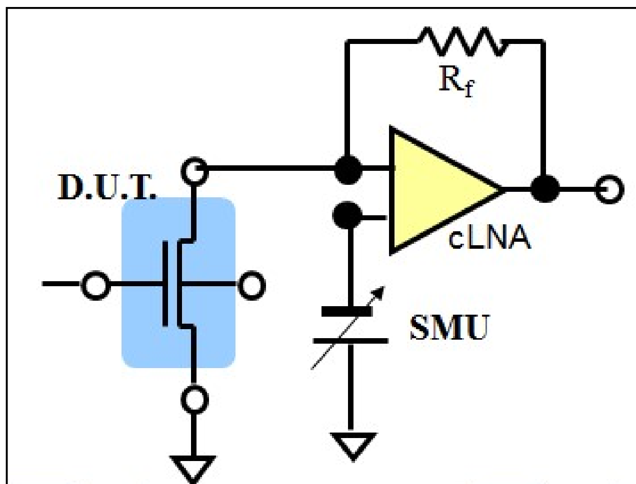
- Resolution & bandwidth
  - **10^{-23} A^2/Hz @ 10 MHz**
  - **10^{-25} A^2/Hz @ 1 MHz**
  - **10^{-27} A^2/Hz @ 50 KHz**

AC Coupling vs. DC Coupling

- AC Coupling
  - Need to charge and discharge during measurement
  - Suitable for small current, high current, and high voltage devices
  - Good for both high and low impedance devices
  - Dynamic range is large



- DC Coupling:

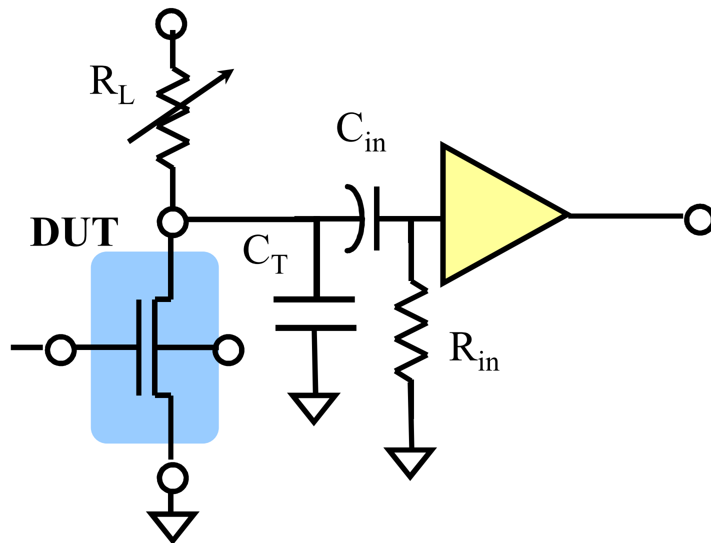


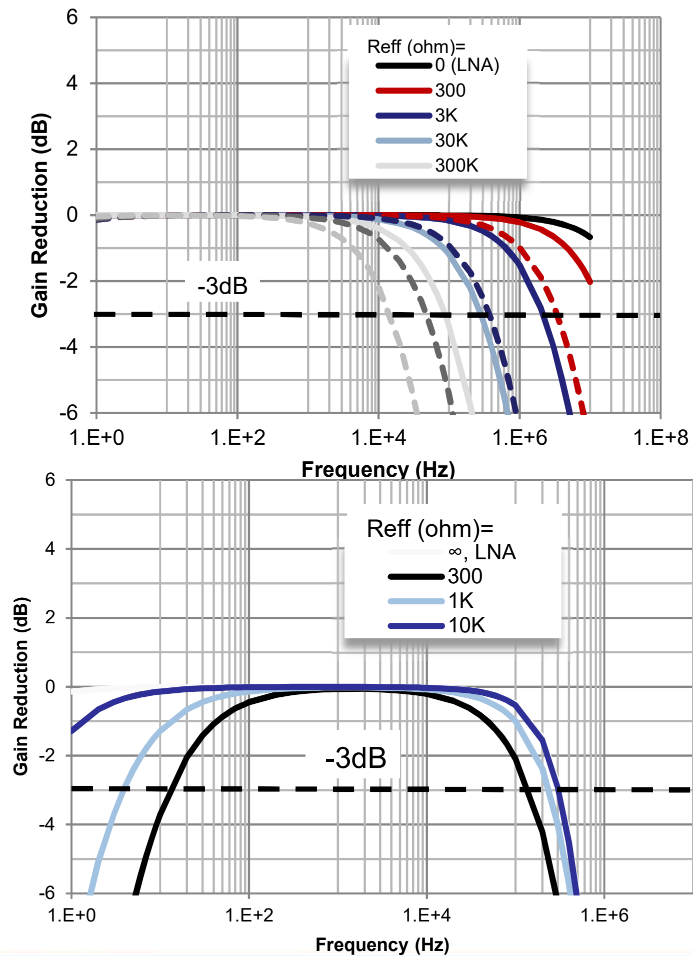
  - No charge and discharge for the coupling capacitor
  - Suitable for small current devices
  - Dynamic range is small
  - Cannot measure high current or high voltage devices
  - Cannot measure low impedance devices (Vout < Vin of LNA)

System Resolution, Bandwidth and Roll-off

- Optimize system-level high resolution and wide bandwidth for voltage amplifier in real applications

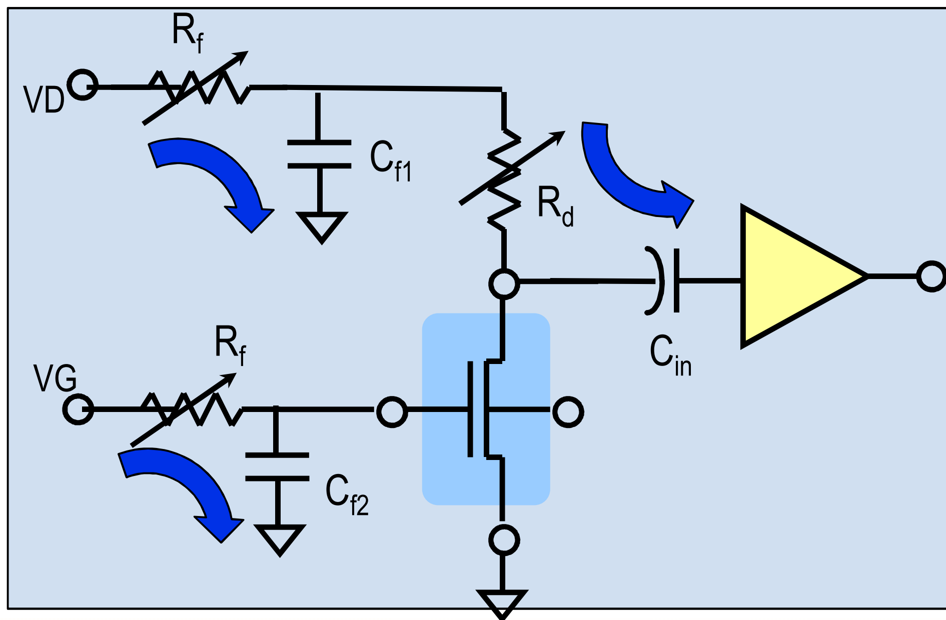
$$f_T = \frac{1}{2\pi C_T R_{in} // R_L // R_{out}}$$





Achieving Fast Noise Measurement

- Advancements in software algorithm and hardware architectures
- Major time spent during noise measurement
  - Bias setup – charging and discharging C_{f1}, C_{f2} and C_{in}
  - DC measurement – Ids, Vth, Rout, etc.
  - FFT Sampling – FFT length and frequency resolution, average, etc.



A typical measurement: **10 ~ 30 sec**
(1 Hz ~ 100 KHz, 10+ average times)

- Bias setup: 5 ~ 20 sec
- DC measurement: 2 ~ 5 sec
- FFT Sampling: 2 ~ 3 sec

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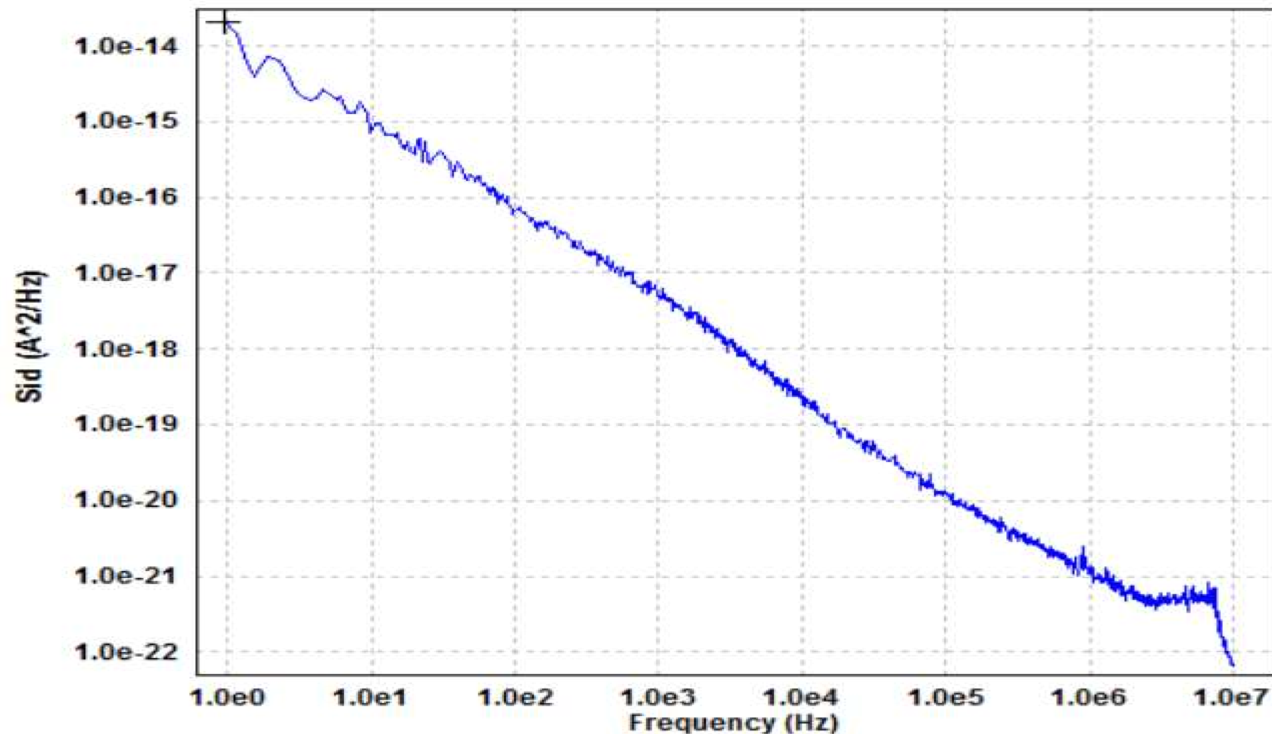
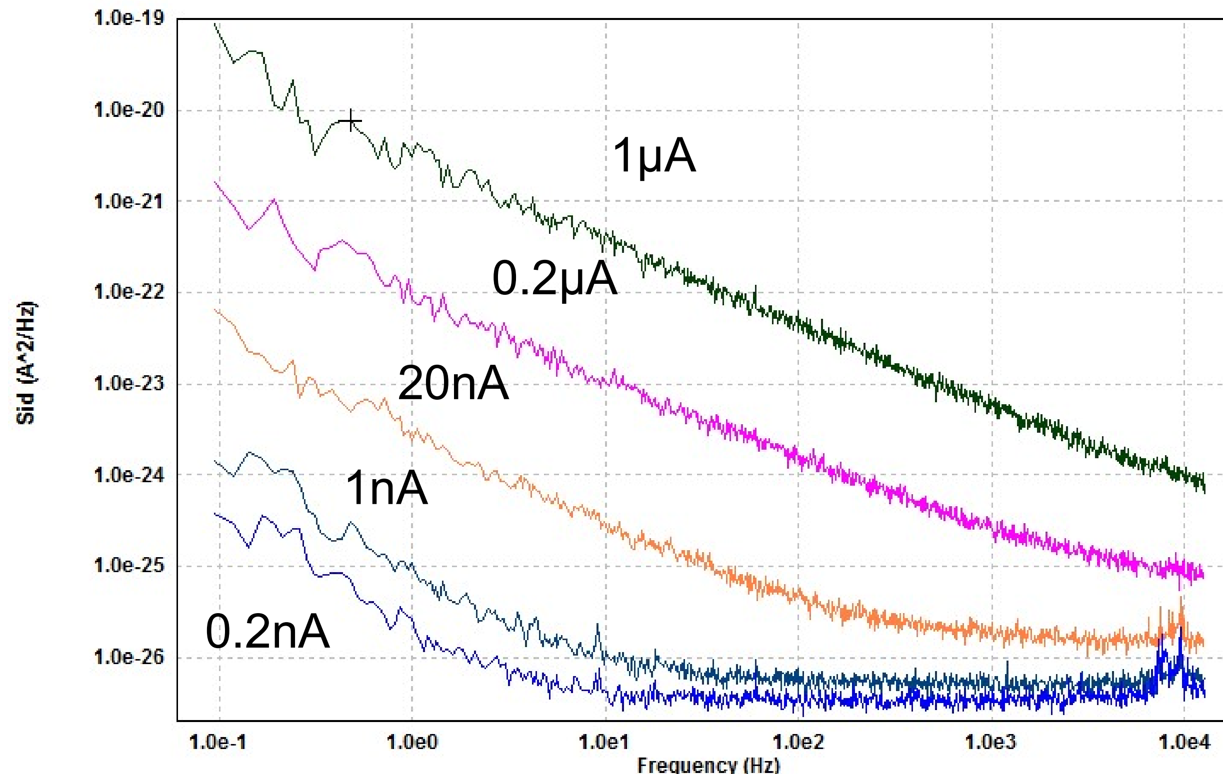
Full Sid Spectrum up to 10 MHz

- The measured Sid versus frequency up to 10 MHz (on-wafer level).



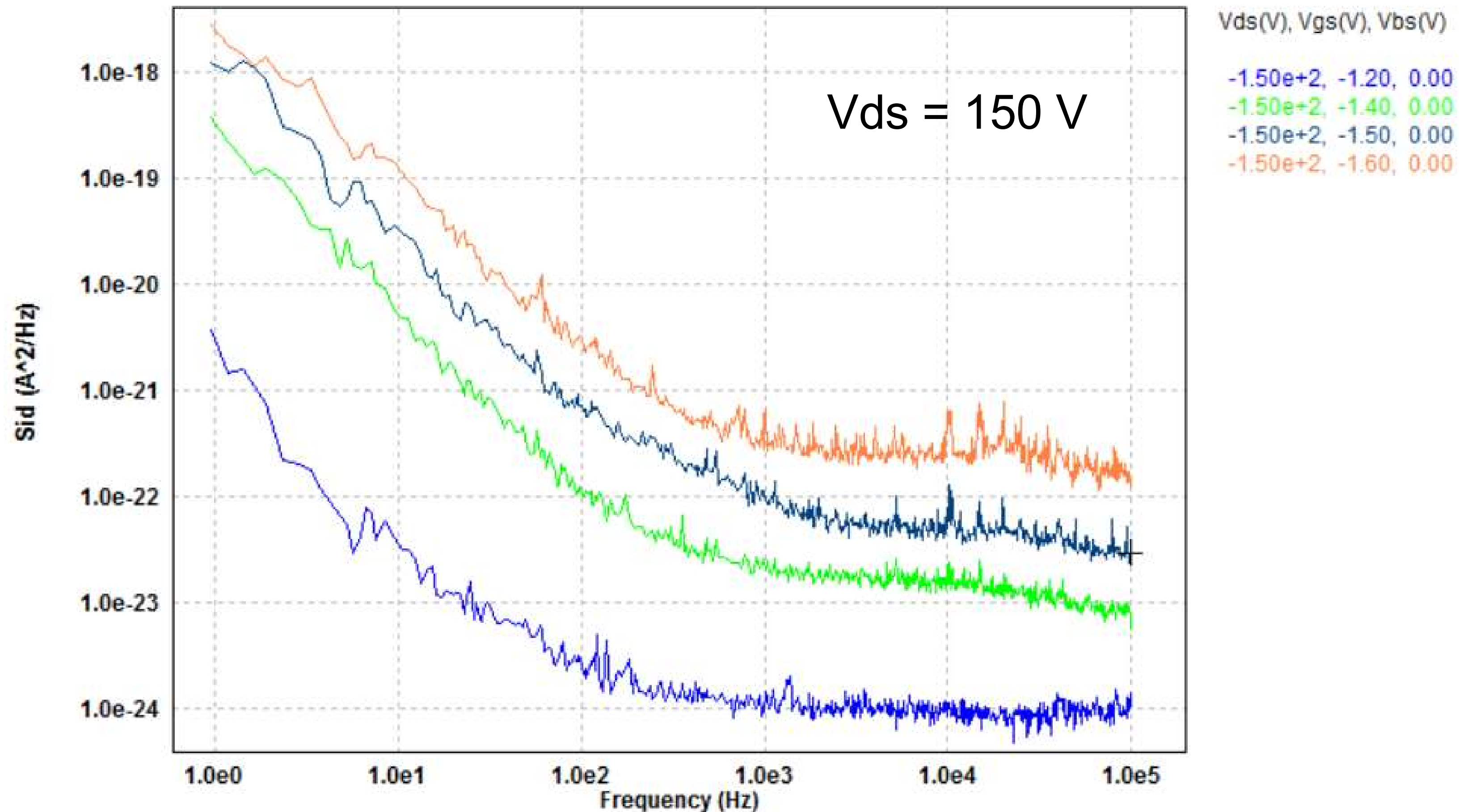
Measuring Noise at Low Biasing Current

- Reliable and accurate noise measurements with a MOSFET biased in sub-threshold region, e.g. 0.1nA. The wide and valid bandwidth up to 20kHz was demonstrated for wafer-level measurement.



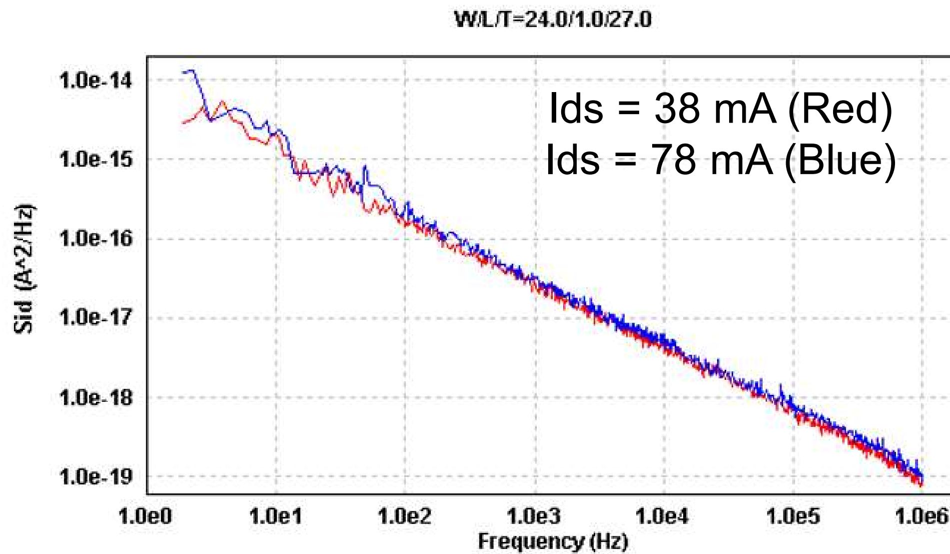
Noise Measured at High Voltage

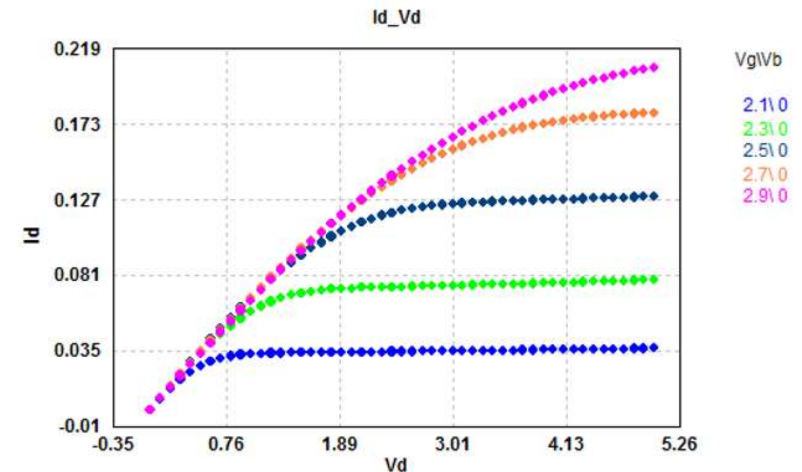
- Drain current noise measured at high voltage levels up to 200 V



Noise Measured at High Current

- Drain current noise measured at high current levels up to 200 mA
  - DC measurement without oscillation

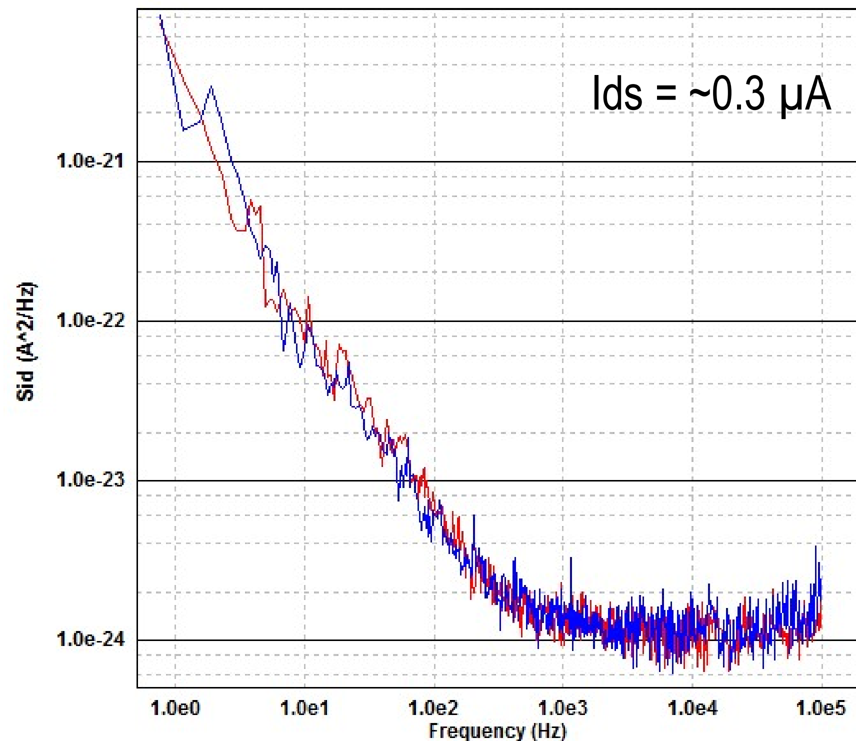


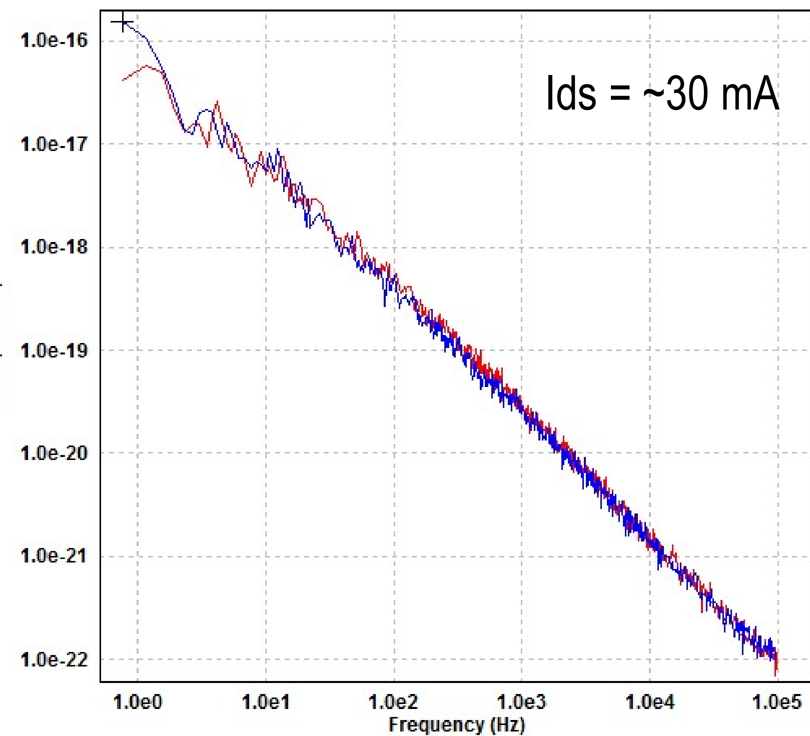


Fast Noise Measurement for MOSFET

- A reliable and fast noise measurement at a speed of ~10 sec / bias

Red Color: 10 sec / bias **Blue Color: ~ 90 sec / bias**

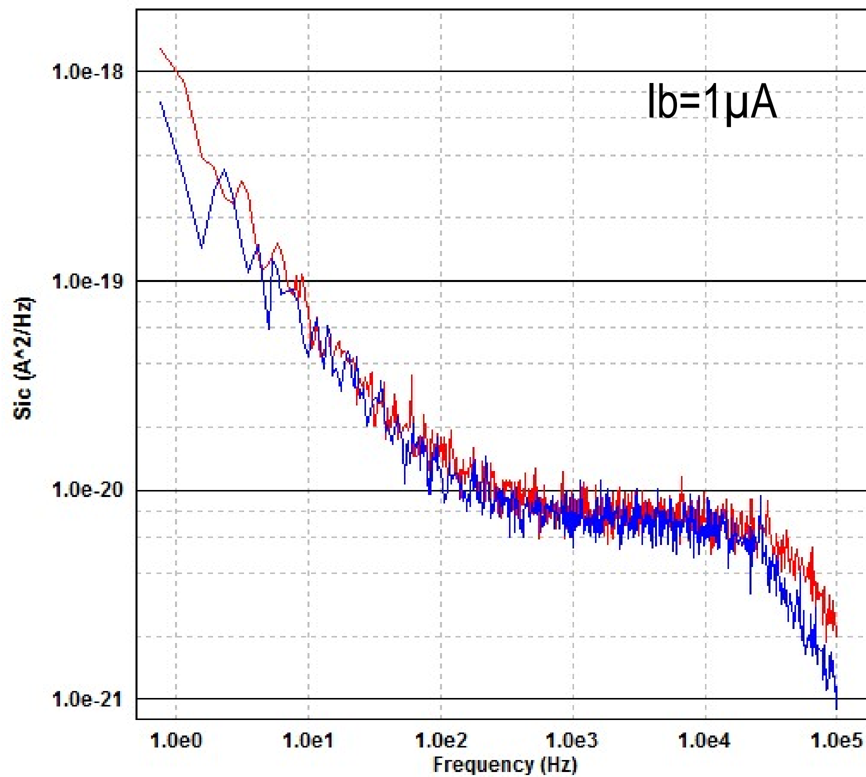


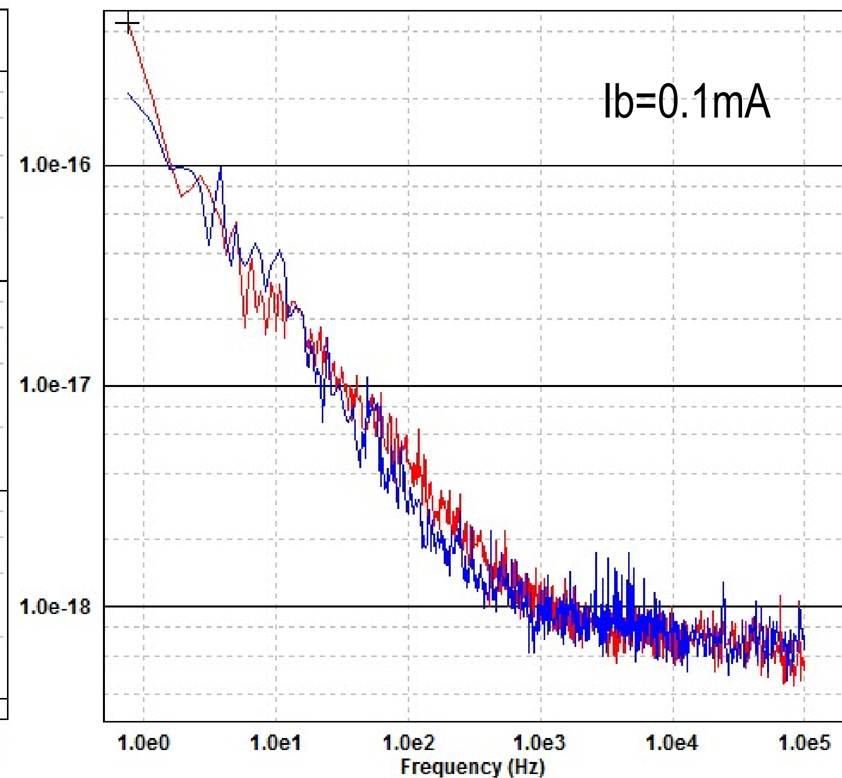


Fast Noise Measurement for BJT

- A reliable and fast noise measurement at a speed of ~20 sec / bias

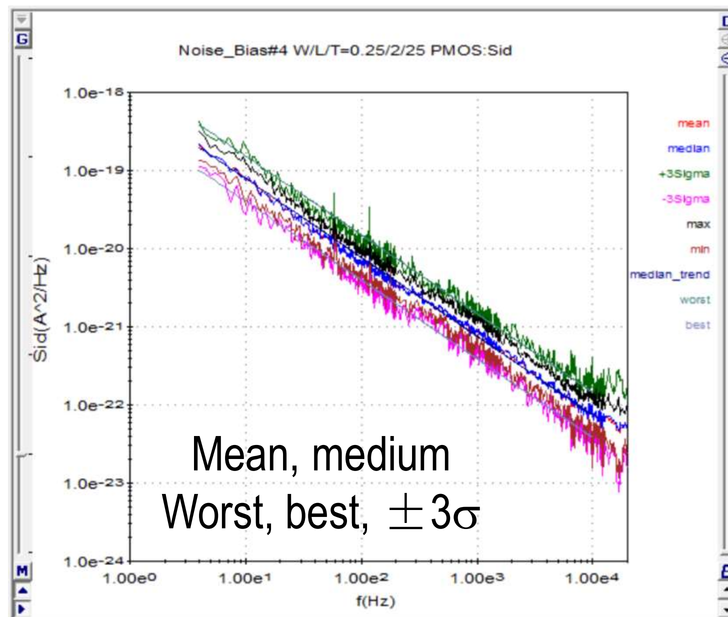
Red Color: ~ 20 sec / bias **Blue Color: ~ 90 sec / bias**

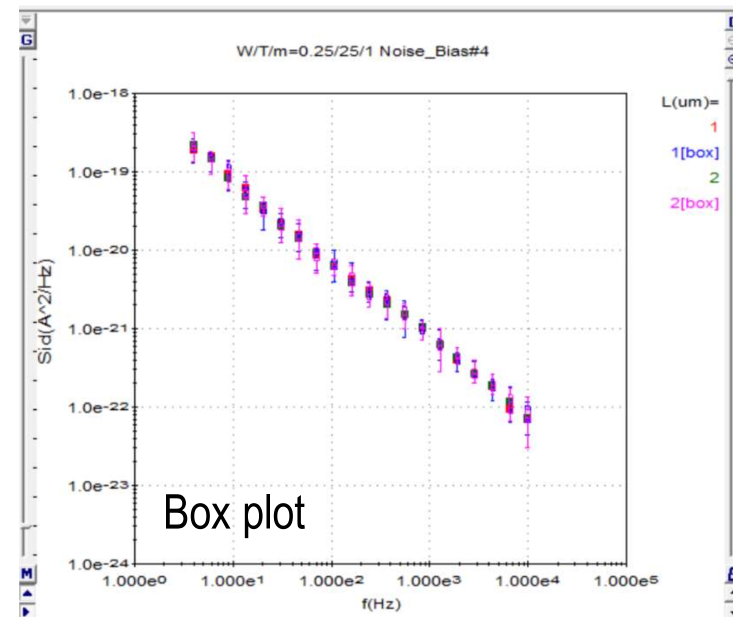




High-speed Statistical Noise Measurement

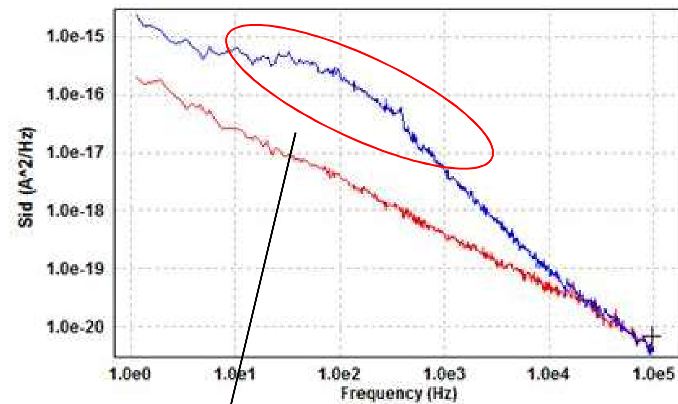
- A complete solution for statistical noise measurement, analysis & modeling
  - On-wafer multi-die, multi-device and multi-bias auto-mapping noise measurement
  - DC measurements and noise measurements to be performed all together
  - Statistical noise data analysis, statistical and corner model extraction & strategies

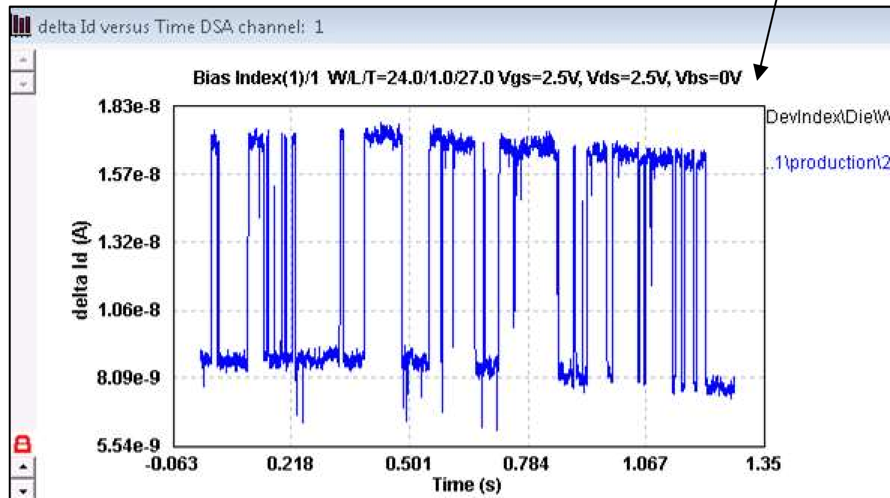


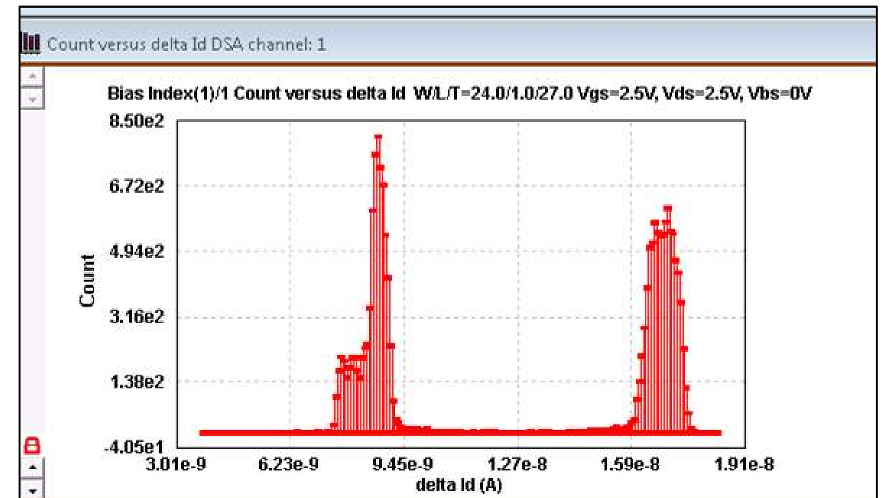


Measurement of Flicker and RTS Noise

- The correlation of flicker and RTS noise under the same measurement conditions







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Summary

- A versatile low-frequency noise system was developed for highly accurate, reliable and fast on-wafer noise measurement.
- The full system capabilities and superior performance were demonstrated through its high system resolution of 1e-27 A^2/Hz at wide bandwidth, large biasing current range (0.1nA ~ 200mA), wide impedance matching and fast measurement speeds, etc..
- This sophisticated noise system, capable of measuring most types of semiconductor devices and IC chips at wide output impedance, has been successfully proven and widely adopted by the IC industry.