

# Direct measurement of white noise in MOSFETs

**Kenji Ohmori\* and Shuhei Amakawa\*,\*\***

\* Device Lab Inc.

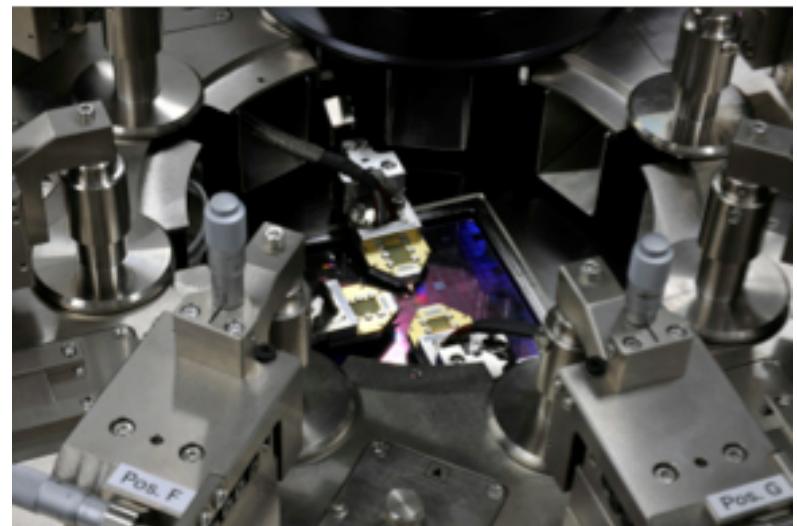
\*\* Hiroshima University

**11th International MOS-AK Workshop  
Silicon Valley, December 5, 2018**

# One-page introduction of Device Lab Inc.

## Spin-off company from University of Tsukuba

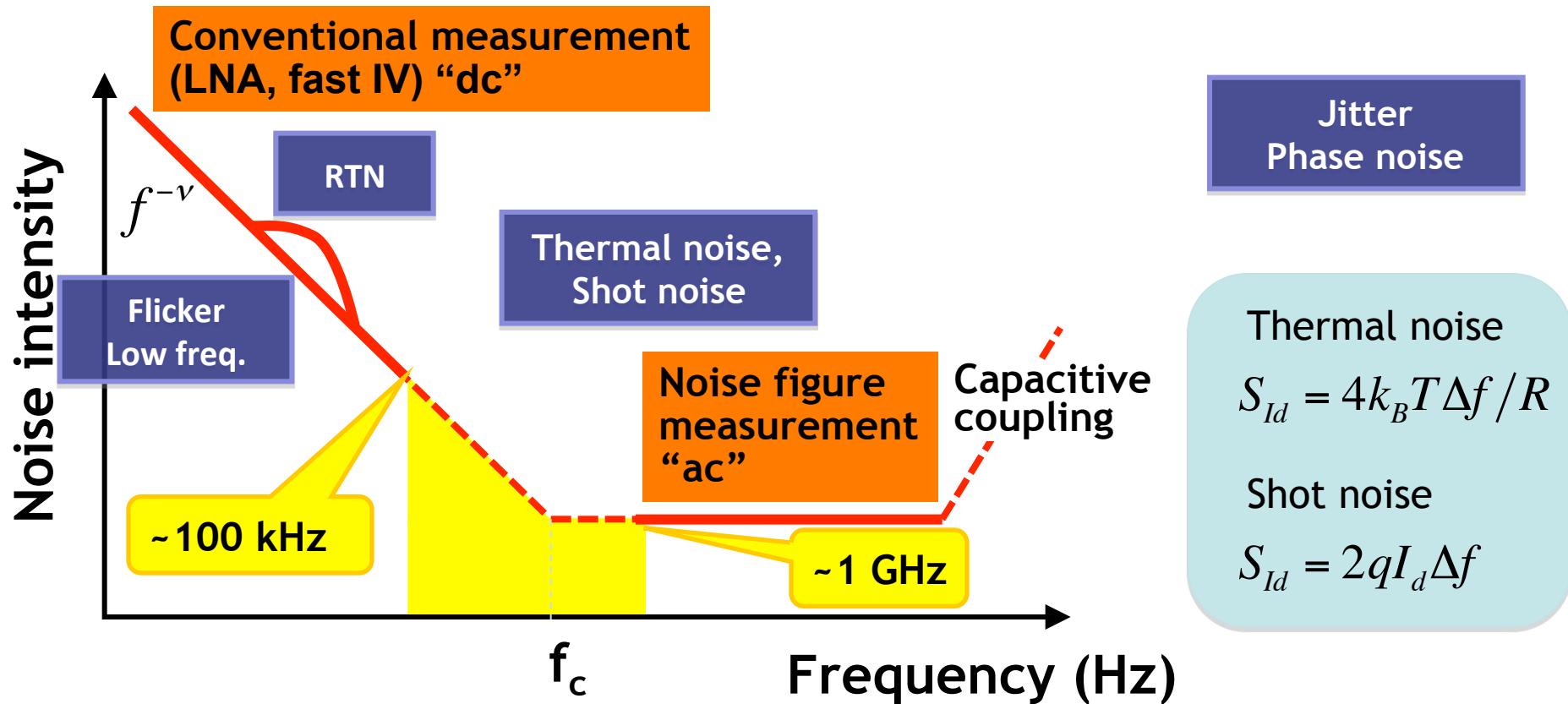
- **Founded in April 2017**
- **Based in Tsukuba, Japan (1 hour from Tokyo)**
- **Focus on electric characterization of devices**
  - ✓ **Entrope™ high-frequency noise probe**
  - ✓ **Measurement solutions for characterizing MOSFETs and neuromorphic devices**



# Outline

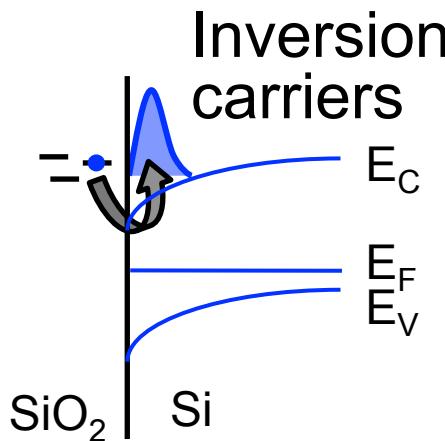
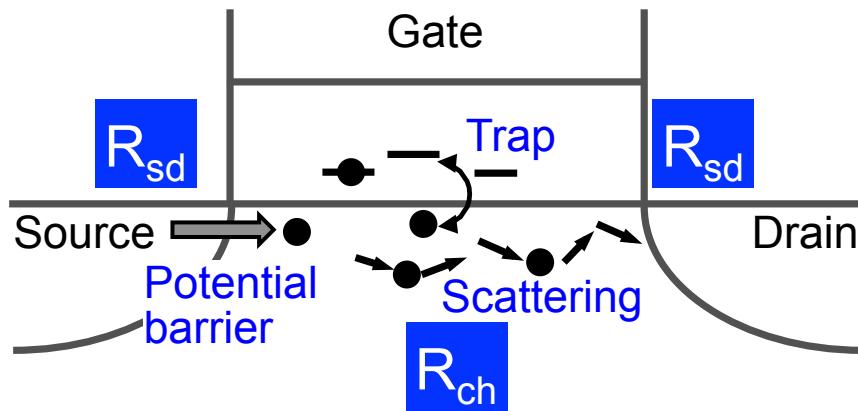
- Noise in MOSFETs
  - ✓ Low frequency ( $1/f$ , RTN)
  - ✓ High-frequency (thermal, shot)
- Measurement systems
  - ✓ Conventional system (low-frequency)
  - ✓ High-frequency noise probe
- Measurement results
- Comparison with models
- Summary

# Schematic diagram of MOSFET noise



- Practical frequency limit in LFN systems: 100 kHz
- Noise figure: complicated, requires noise source
- Direct observation of a corner frequency (under DC bias) is important.

# Origins of Noise



- 1/f (flicker) noise, random telegraph noise
  - ✓ trapping/de-trapping between oxide traps and channel electrons (number fluctuation)
  - ✓ mobility fluctuation
- Thermal (Johnson) noise
  - ✓ phonon scattering
  - ✓ resistance
- Shot noise
  - ✓ Discrete nature of conducting electron number

Trap/detrap probability

$$P \propto \text{Exp}\left(\frac{-2d}{\alpha} - \frac{\Delta E}{kT}\right)$$

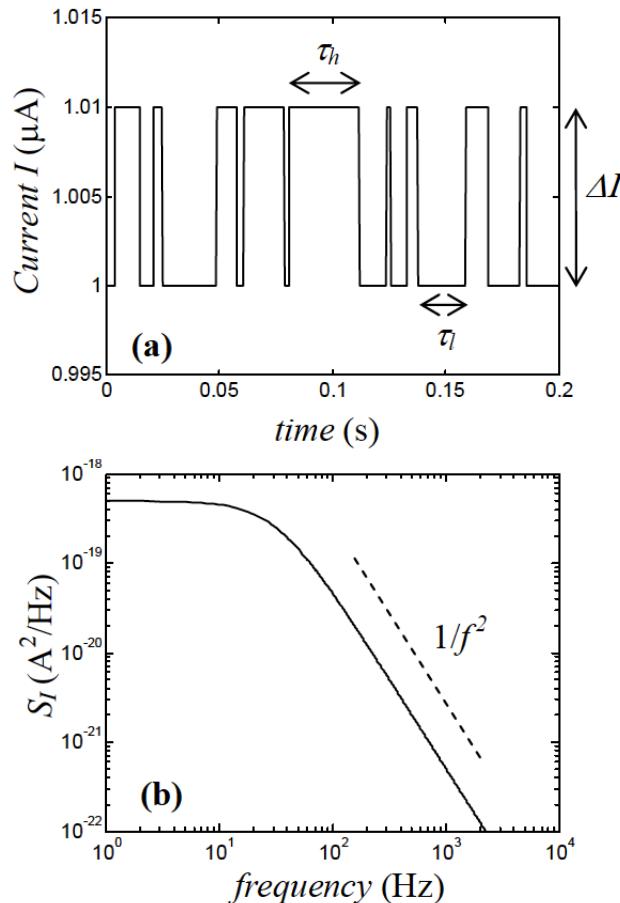
$d$ : distance between a trap and an electron

$\alpha$ : localization length of wave-function

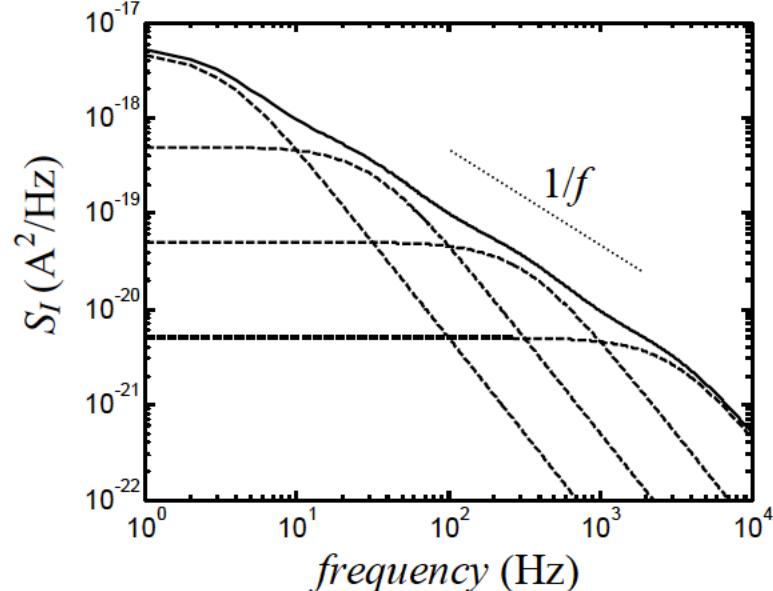
$\Delta E$ : the energy difference between the trap and the electron

# Why 1/f properties?

RTN



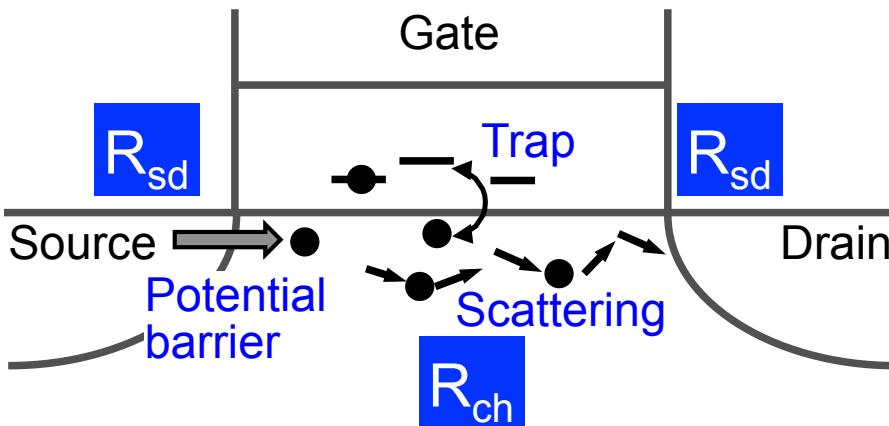
1/f



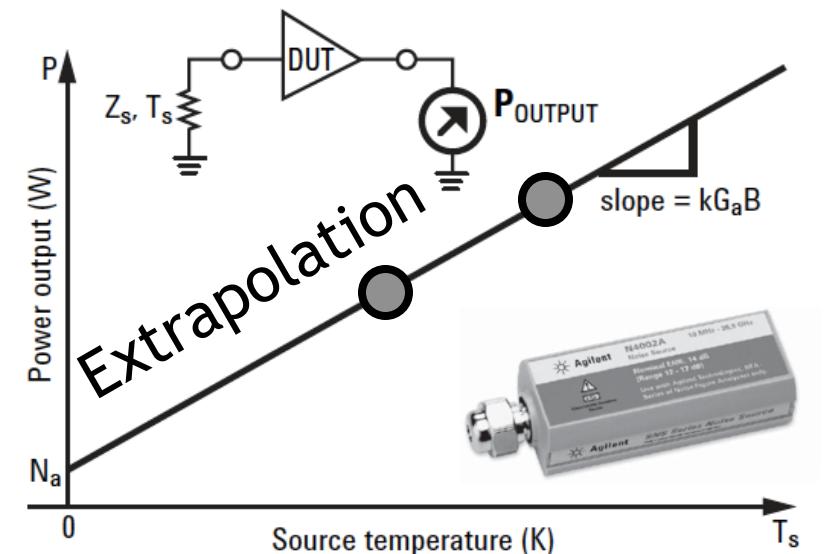
- Random telegraph noise: Lorentzian-shaped power spectral density
- 1/f noise: superposition of Lorentzians with various time constants

From von Haartman, Ph.D thesis (2006).

# Measurement of thermal and shot noise



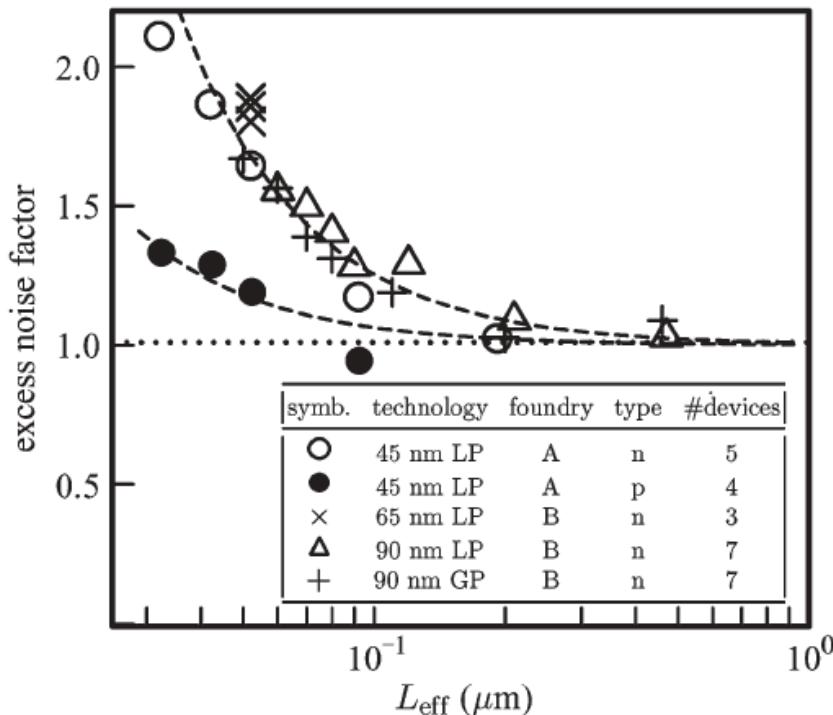
## Noise figure (Y-factor method)



Agilent Application Note 57-1

- Phenomena with ultrafast relaxation time (e.g., phonon scattering)
- Y-factor method on wafer requires
  - ✓ a noise source and high-frequency setups (probes, test structures for de-embedding)

# Excess noise factor @ 10 GHz



- A significant increase in RF noise compared to PSP prediction was observed for sub-100-nm MOSFETs.

PSP: a compact MOSFET model developed by Arizona State University and NXP Semiconductors Research

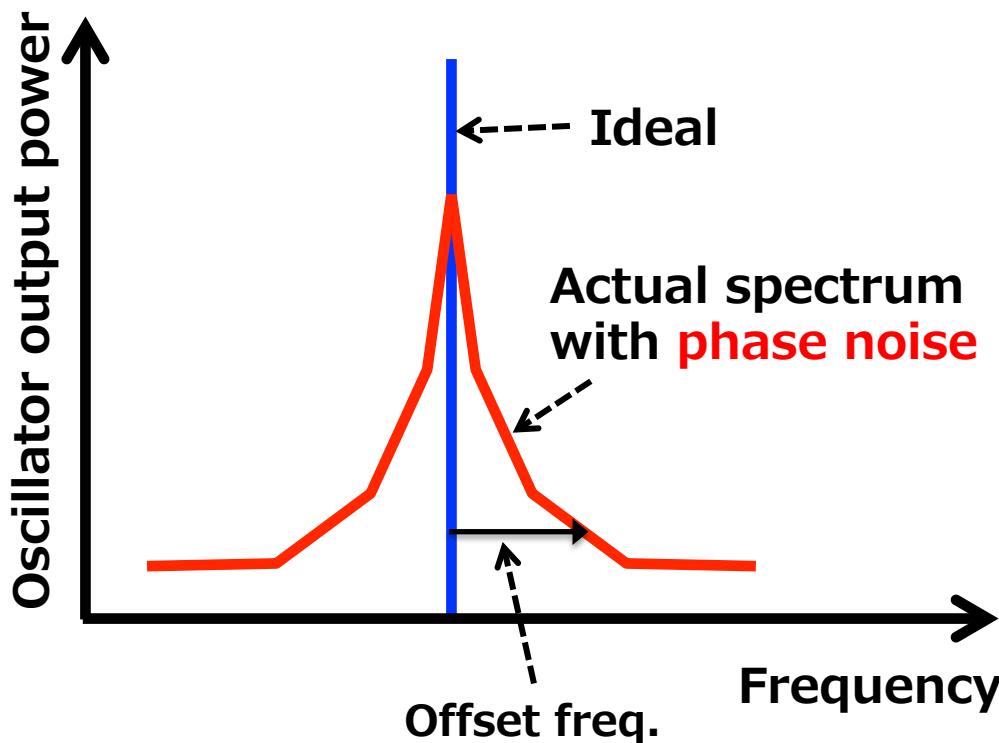
G. D. J. Smit et al., EDL 31 (2010) 884.

# Why measure high-frequency noise?

Shannon's equation

$$C = B \log_2 \left( 1 + \frac{S}{N} \right)$$

C: Channel capacity in bits/s  
B: Channel bandwidth in Hz  
S: Signal power  
N: Noise power



Standard	max B
4G	20 MHz
5G	400 MHz
WiGig (802.11ad)	2.16 GHz
THz (802.15.3d)	69.12GHz

Phase noise originates from devices (thru up-conversion), circuit, and outside

- Phase noise at high offset frequencies ( $\propto B$ ) is assuming greater importance

## Influence of White LO Noise on Wideband Communication

Jingjing Chen<sup>ID</sup>, Member, IEEE, Dan Kuylenstierna, Member, IEEE, Sten E. Gunnarsson, Member, IEEE,  
Zhongxia Simon He<sup>ID</sup>, Member, IEEE, Thomas Eriksson, Member, IEEE,  
Thomas Swahn, Senior Member, IEEE, and Herbert Zirath, Fellow, IEEE

- **Adverse effects of white noise on mm-wave have experimentally been confirmed [1][2]**
- **High-frequency device noise is not merely a theoretical, academic concern!**
- **Measurement-based predictive device noise model is vital to success of 5G and Beyond 5G**

[1] Chen et al., "Influence of white LO noise on wideband communication," IEEE Microwave Theory Tech., vol. 66, no. 7, pp. 3349–3359, July 2018.

[2] Chen et al., "Does LO noise floor limit performance in multi-gigabit millimeter-wave communication?," IEEE Microwave Compon. Lett., vol. 27, no. 8, pp. 769–771, Aug. 2017.

# Low-frequency noise (empirical)

## McWhorther model

- Number fluctuation

## Hooge model

- Mobility fluctuation model

$$\frac{S_{id}}{I_d^2} = \frac{\alpha_H}{f \cdot N}$$

$$qN = WLC_{ox} |V_g - V_t|$$

# Noise models

## 1/f noise (SPICE2)

$$S_{Id} = \frac{KF g_m^2}{C_{ox} WL_{eff}} \frac{1}{f^{AF}}$$

## 1/f noise (BSIM3)

$$S_{Id,1/f} = \frac{q^2 k T I_d \mu_{eff}}{L_{eff}^2 C_{ox} f^{ef} 10^8} \left[ NOIAln\left(\frac{N_0 + N^*}{N_L + N^*}\right) + NOIB(N_0 - N_L) + \frac{NOIC}{2} (N_0^2 - N_L^2) \right] + \dots$$

## Thermal noise (SPICE2)

$$S_{Id,therm} = \frac{8}{3} kT (g_{ds} + g_m + g_{mb}) \quad \text{for } V_{ds} > V_{dsat}$$

# Low-frequency noise measurement systems

## ➤ ProPlus Design Solutions

- ✓ 9812D Advanced 1-f Noise Analyzer
- ✓ Maximum frequency: 10 MHz
- ✓ Current LNA noise floor:  $3.6 \times 10^{-23} \text{ A}^2/\text{Hz}$  @ 5 kHz (Wideband)



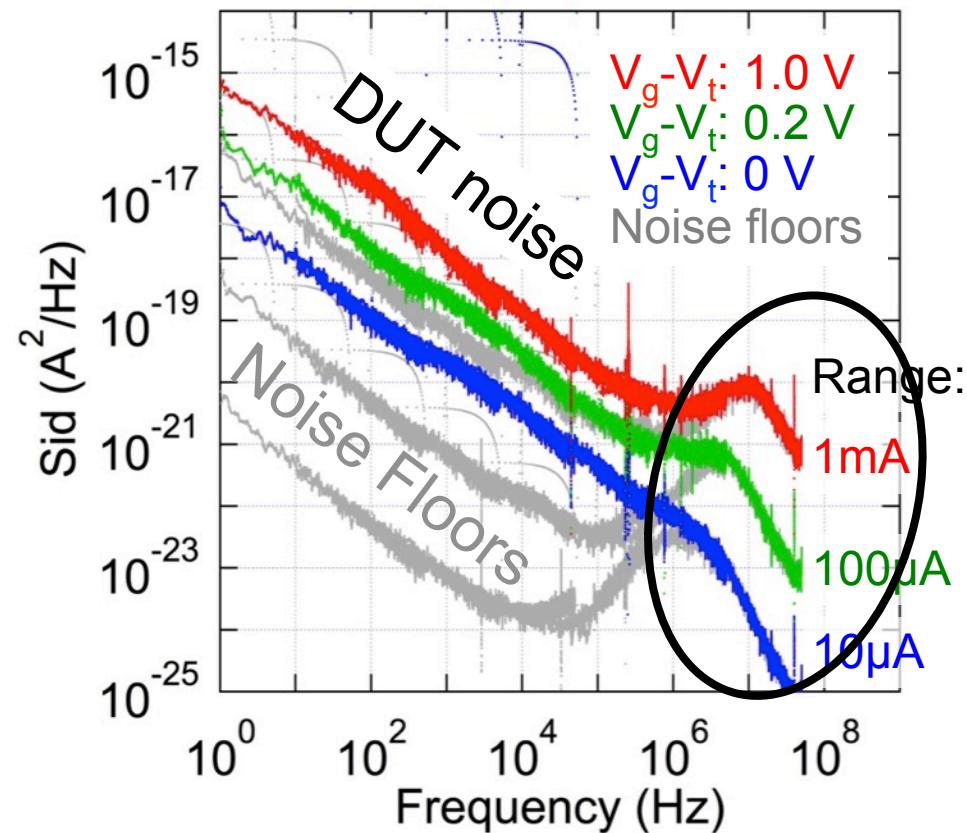
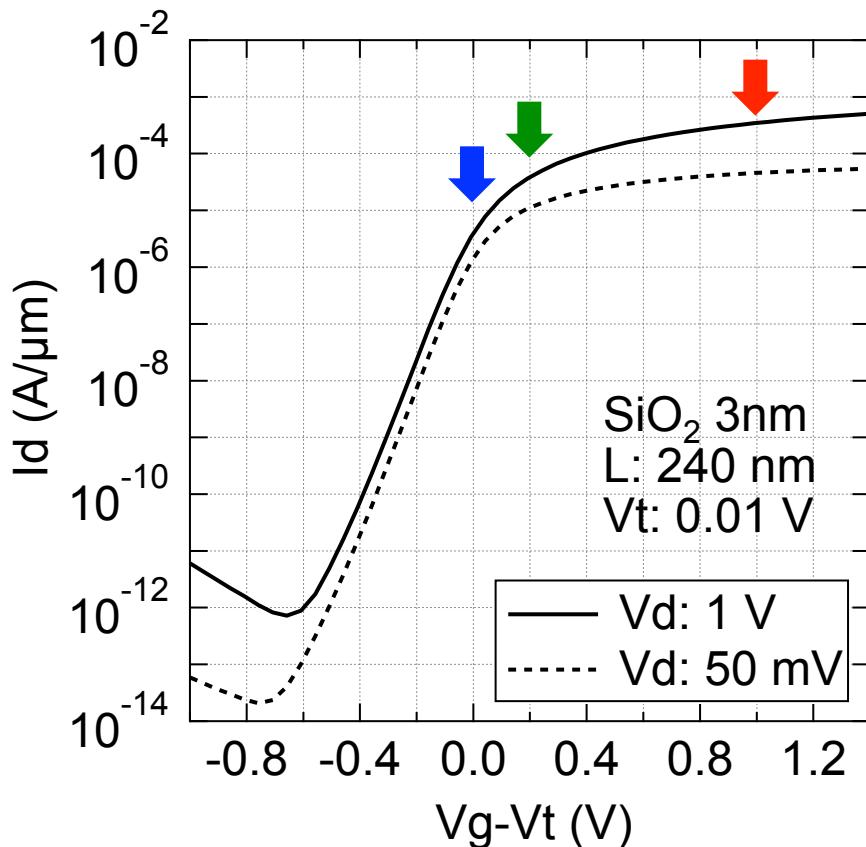
## ➤ Keysight Technologies

- ✓ E4727A Advanced Low-Frequency Noise Analyzer
- ✓ Maximum frequency: 40 MHz
- ✓ Current LNA noise floor:  $1 \times 10^{-24} \text{ A}^2/\text{Hz}$  @ 10 kHz



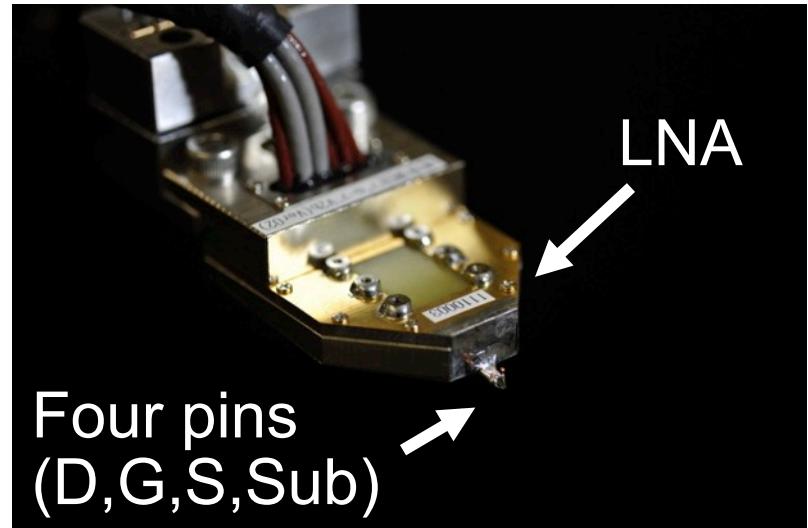
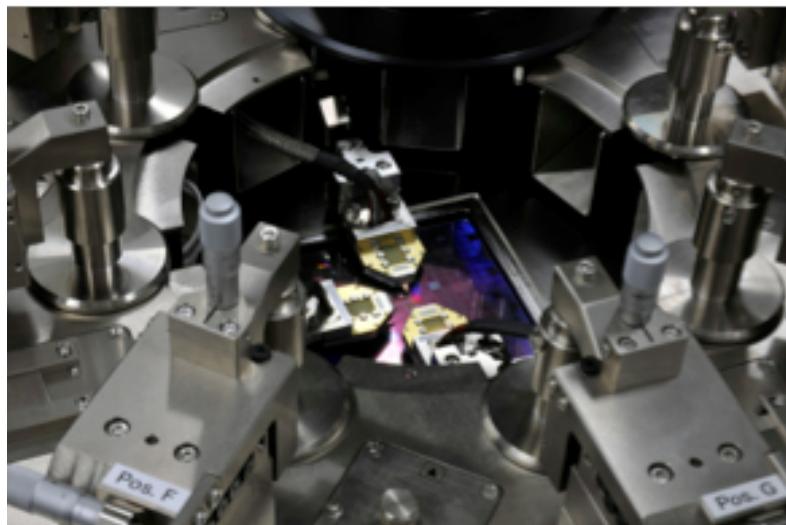
# Noise floor and frequency limit

Demonstration by Keysight B1530A WGFMU (Fast IV)



- Limitation
  - ✓ Amplifier design
  - ✓ Configuration (wiring)

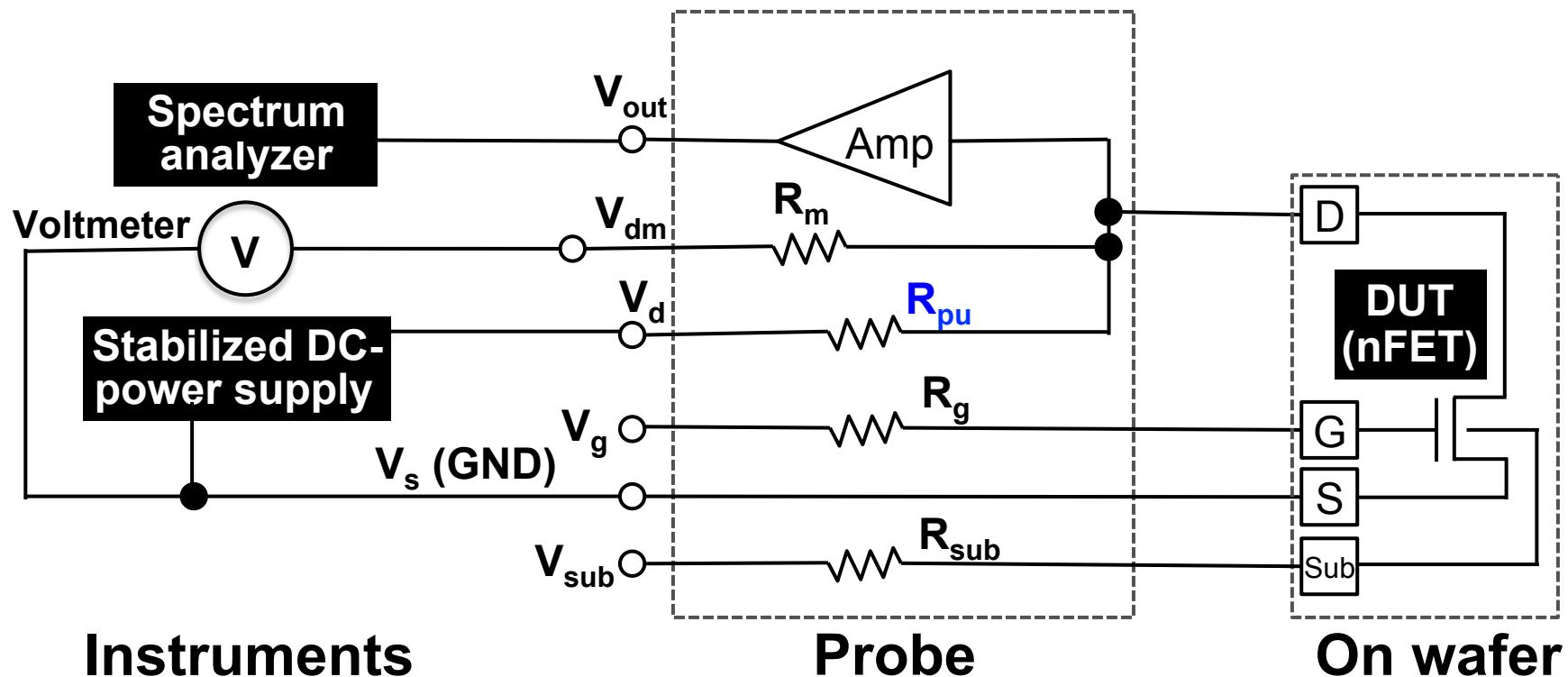
# Concept of high-frequency noise probe



- **Concept of high-frequency noise probe**
  - ✓ Locate the LNA as close to DUTs as possible
  - ✓ Very wideband LNA

K. Ohmori et al., 2012 VLSI Technology.  
K. Ohmori et al., 2013 VLSI Circuits.

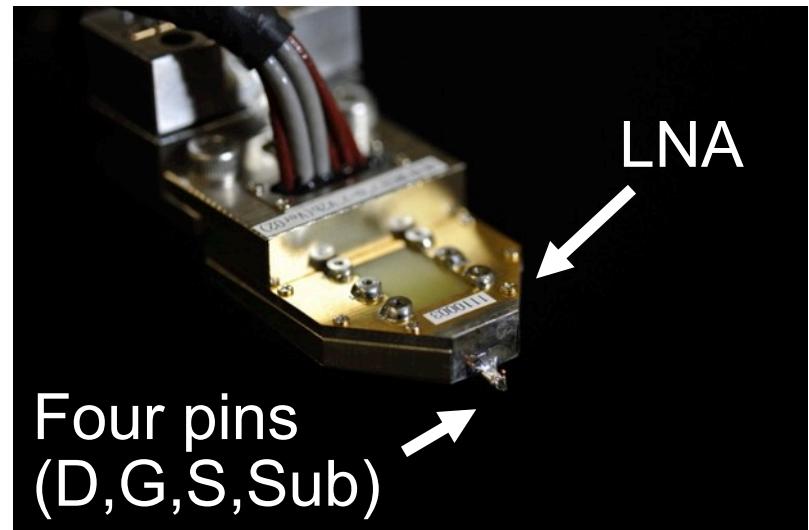
# Simplified diagram of the Noise Probe System



- Probe's built-in amplifier enables high-frequency measurements.
- The pull-up resistor,  $R_{pu}$ , often (but not always) dictates floor noise and the permissible  $I_d$  current.

# Amplifier calibration for noise measurement

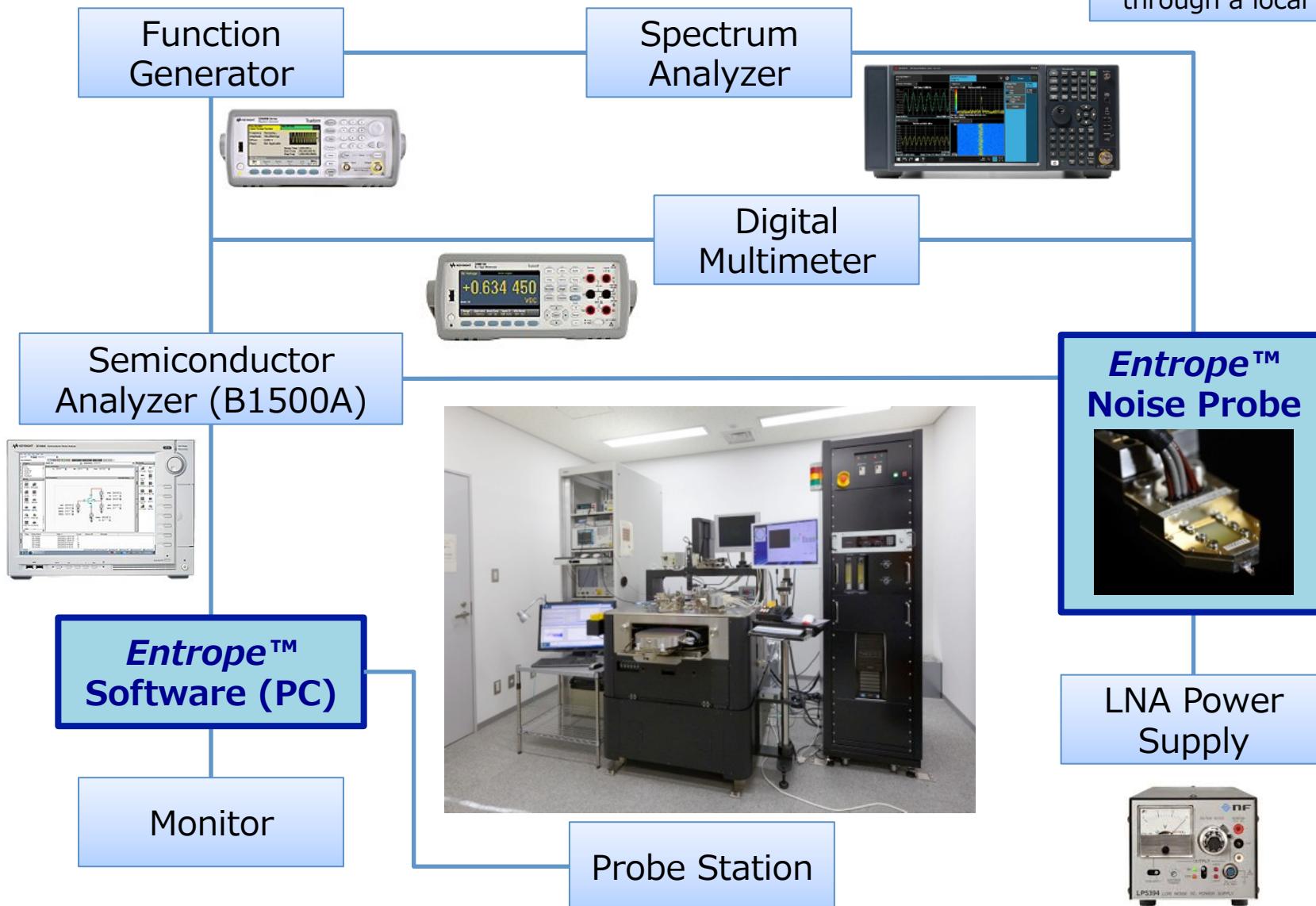
- Detailed measurement-based calibration
  - ✓ Solid theoretical foundations
  - ✓ No fudge factors
  - ✓ Amplifier noise accounted for



# Hardware components

*Entrope™ system*

Should be purchased through a local distributor



# Specification of *Entrope*™ Noise Probe

Probe type	Frequency	Floor noise (minimum)
<i>Entrope</i> ™ 101A	100k - 100MHz	$\sim 3 \times 10^{-23}$ (A <sup>2</sup> /Hz) @ 10 MHz
<i>Entrope</i> ™ 102A	100k - 100MHz	$\sim 5 \times 10^{-23}$ (A <sup>2</sup> /Hz) @ 10 MHz

## System specification

Max DUT bias voltage	40 V
Max drain current	5 mA
No. of biasing terminals	3 (Source: GND)
R <sub>DUT</sub>	> 50 Ω

# Sample and measurement conditions

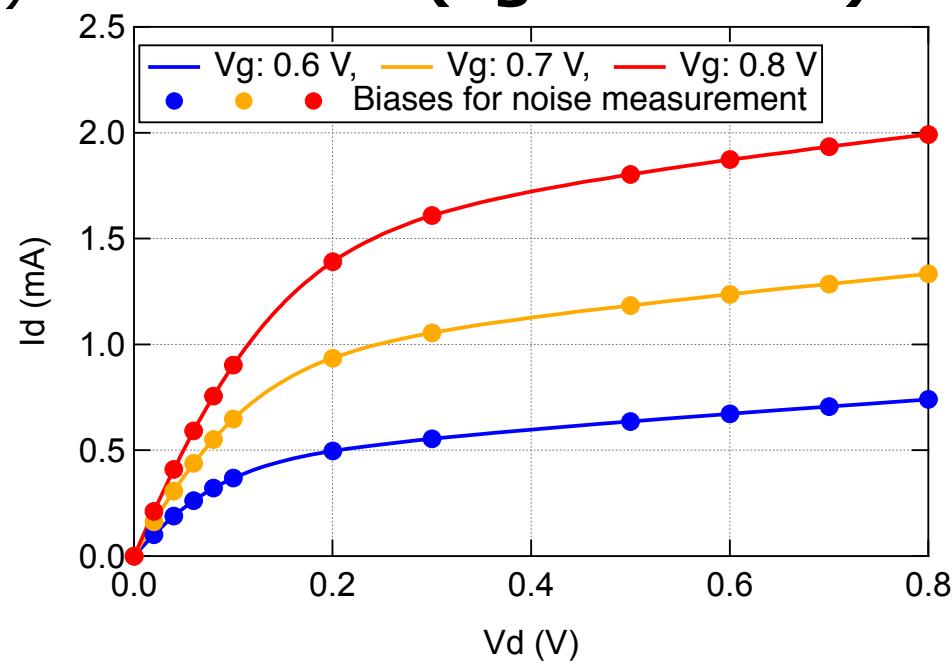
## ➤ Sample

- ✓ n-MOSFET
- ✓ Technology node: 0.13  $\mu\text{m}$
- ✓  $L_g$ : 120/180/240/300 nm

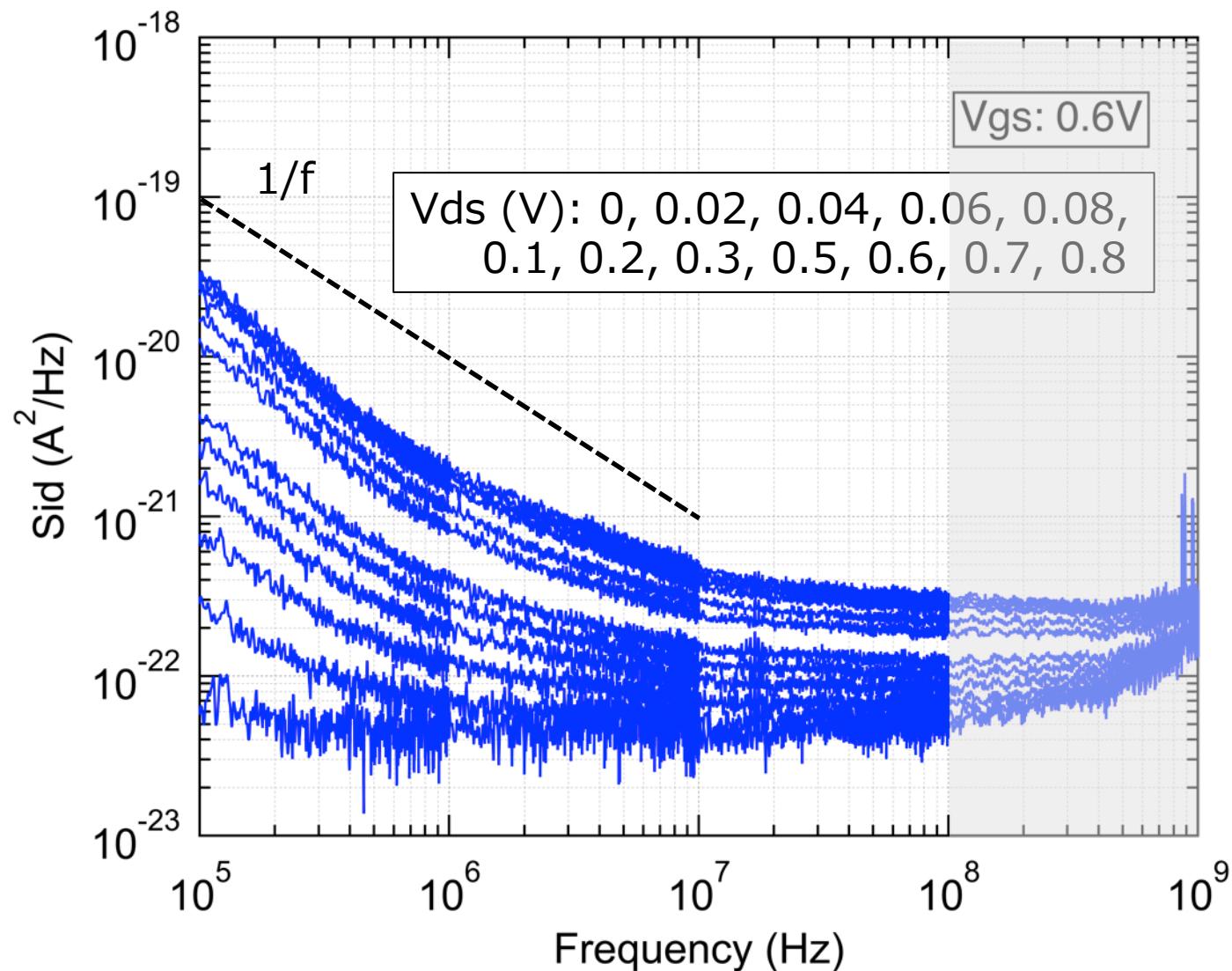
## ➤ Measurement

- ✓ dc ( $I_d$ - $V_d$ ,  $I_d$ - $V_g$ ,  $I_d$ - $V_b$ )
- ✓ noise
- ✓ at room temperature

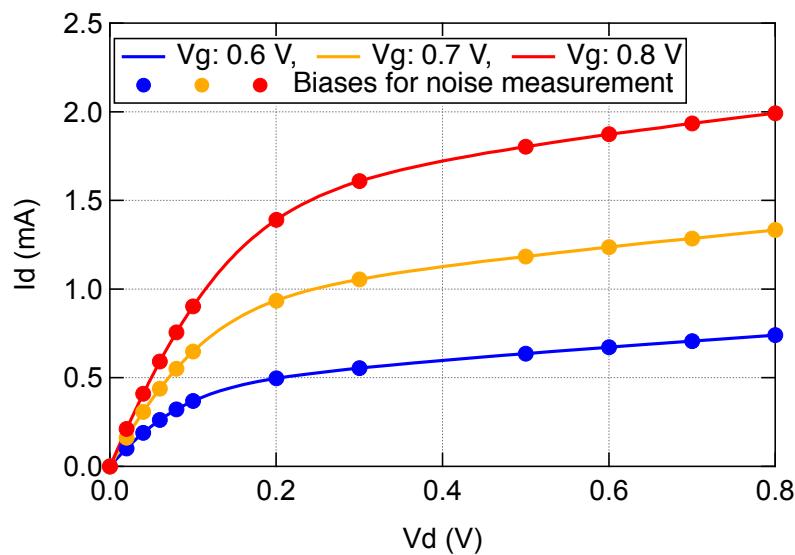
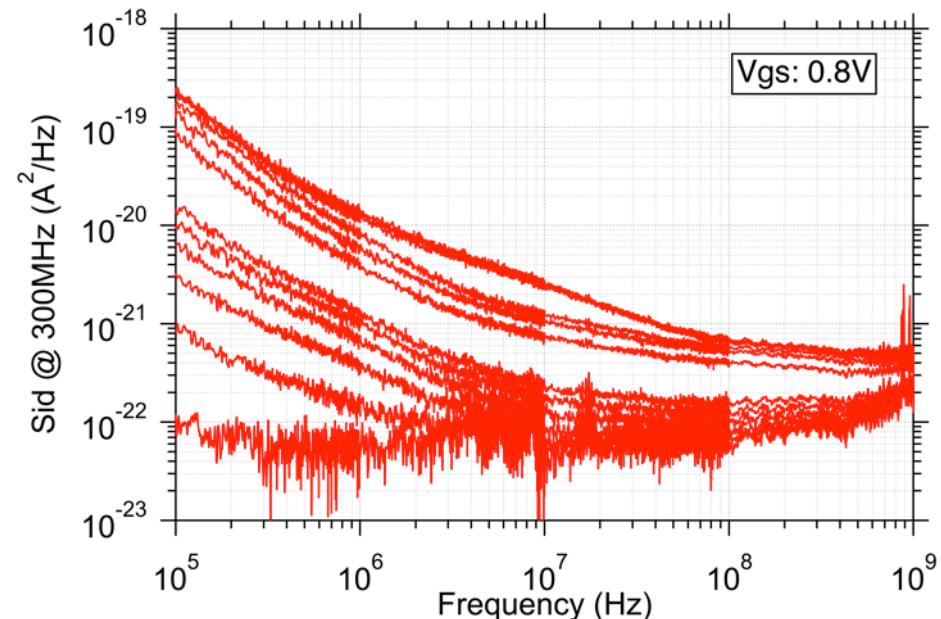
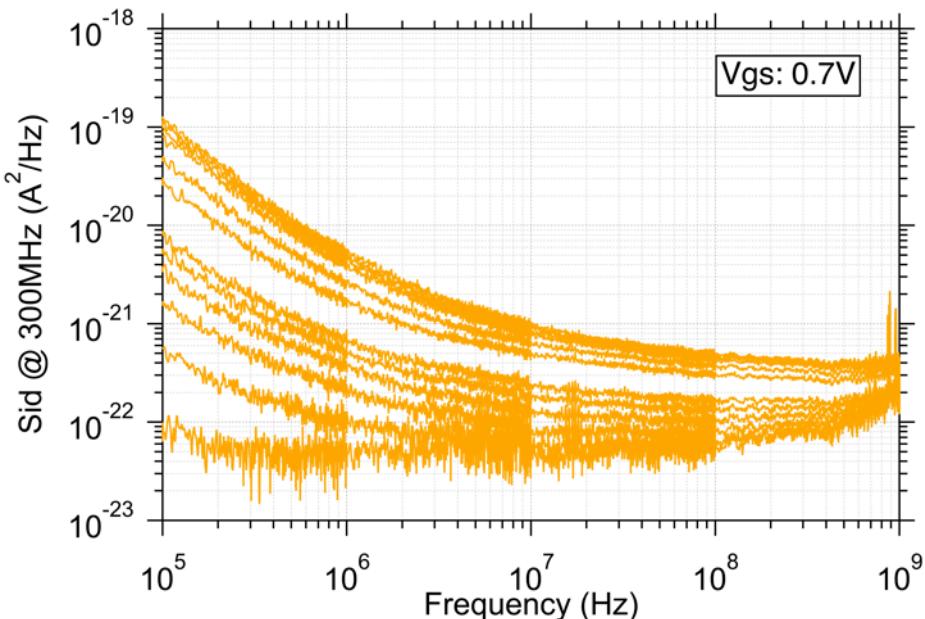
**$I_d$ - $V_d$  ( $L_g$ : 120 nm)**



# Noise measurement (Vgs: 0.6V, Lg: 120 nm)

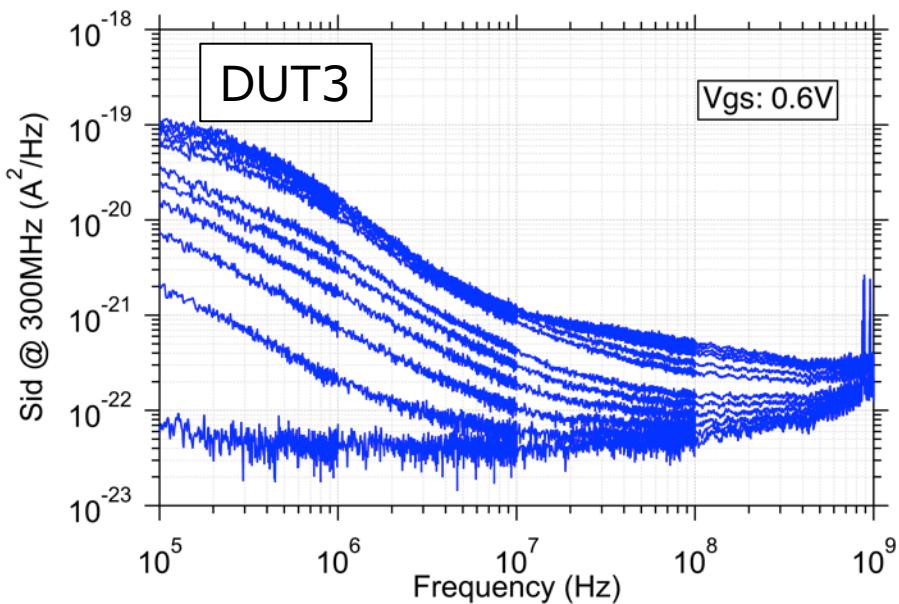
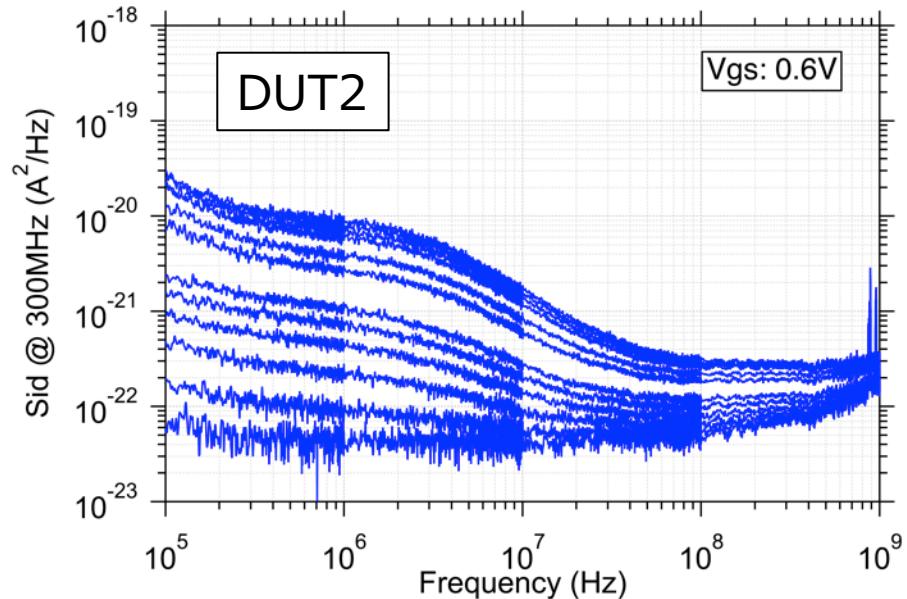
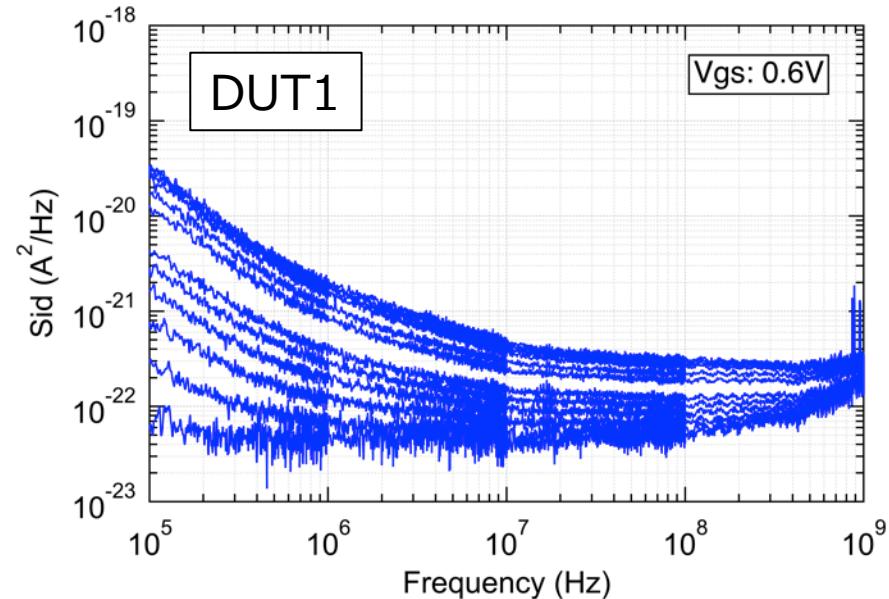


# Noise measurement (Vgs: 0.7/0.8V, Lg: 120 nm)



**V<sub>gs</sub>: 0.6, 0.7, 0.8 V**  
**V<sub>ds</sub>: 0, 0.02, 0.04, 0.06,  
0.08, 0.1, 0.2, 0.3,  
0.5, 0.6, 0.7, 0.8 V**

# Variability (Lg: 120 nm)



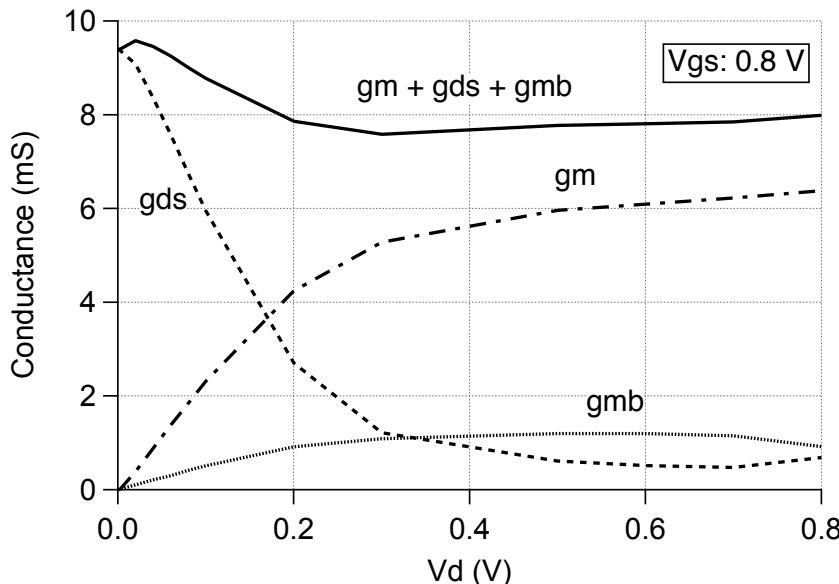
- Device-to-device variability seems to be large in the lower frequency region.
- RTN appears even in the higher frequency region.

# $S_{Id}$ extraction in saturation (Lg: 120 nm)

- **Sid values at 300 MHz**
- **Saturation region ( $V_{ds} > 0.2$  V)**

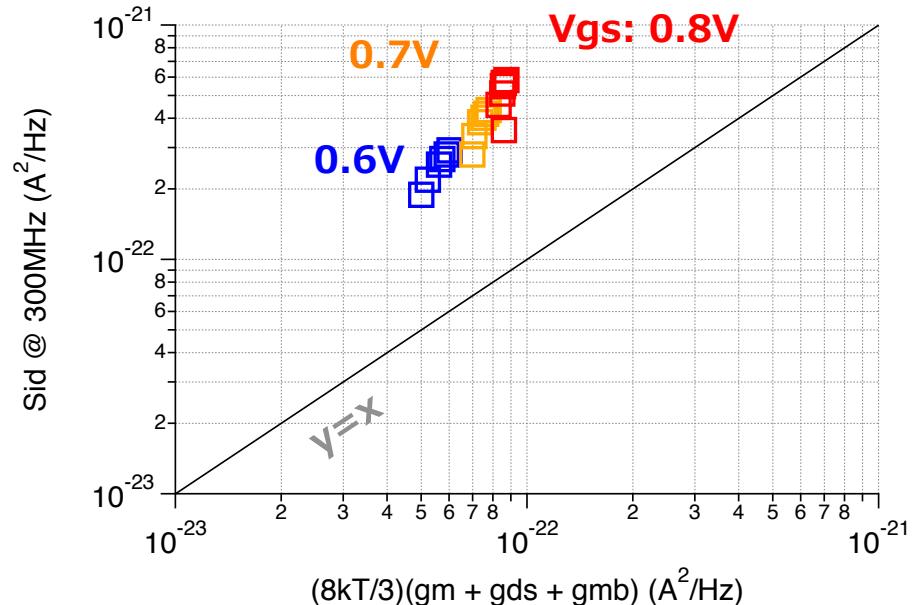
$$S_{Id,therm} = \frac{8}{3}kT(g_{ds} + g_m + g_{mb}) \quad \text{for } V_{ds} > V_{dsat} \quad \text{SPICE2}$$

**Conductance (gds, gm, gmb)**



**Excess noise confirmed!**

**Model: only thermal noise**



$V_{gs}$ : 0.6, 0.7, 0.8 V  
 $V_{ds}$ : 0.2, 0.3, 0.5, 0.6, 0.7, 0.8 V

# Summary of our message

- Measurement-based predictive white noise model is vital to success of 5G and Beyond 5G
- By using Entrope™ Noise Probe, we demonstrated higher frequency noise measurement
  - ✓ Clear direct observation of white noise
  - ✓ Simple reliable approach for predictive noise models

