Measurements and Characterization of Statistical Variability

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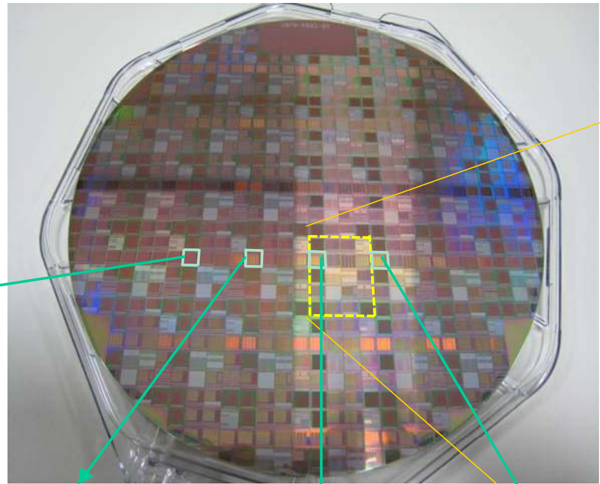
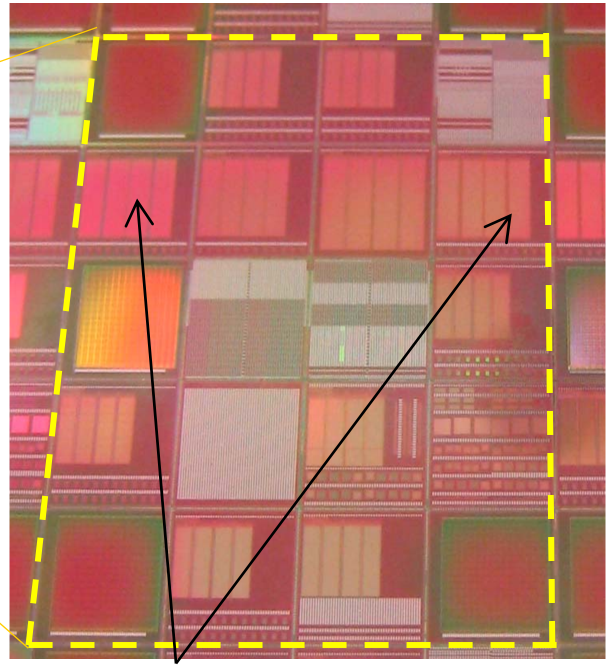
1. Introduction
2. Variability Measurements and Characterization
   (1) Drain Current
   (2) SRAM
3. Summary

This work is performed in the MIRAI-Project supported by NEDO.

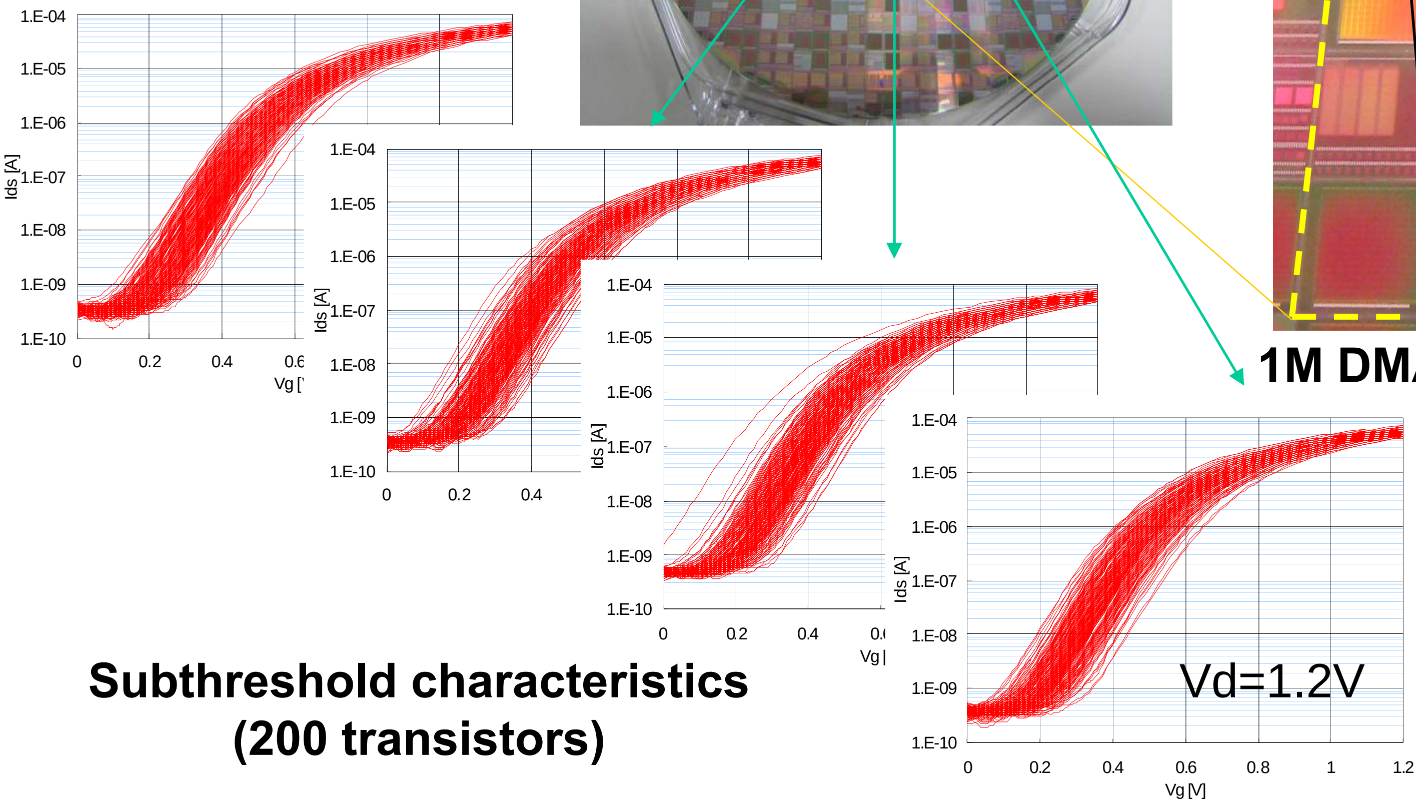
Large-Scale DMA-TEG

1 million transistors in each chip





1M DMA-TEG

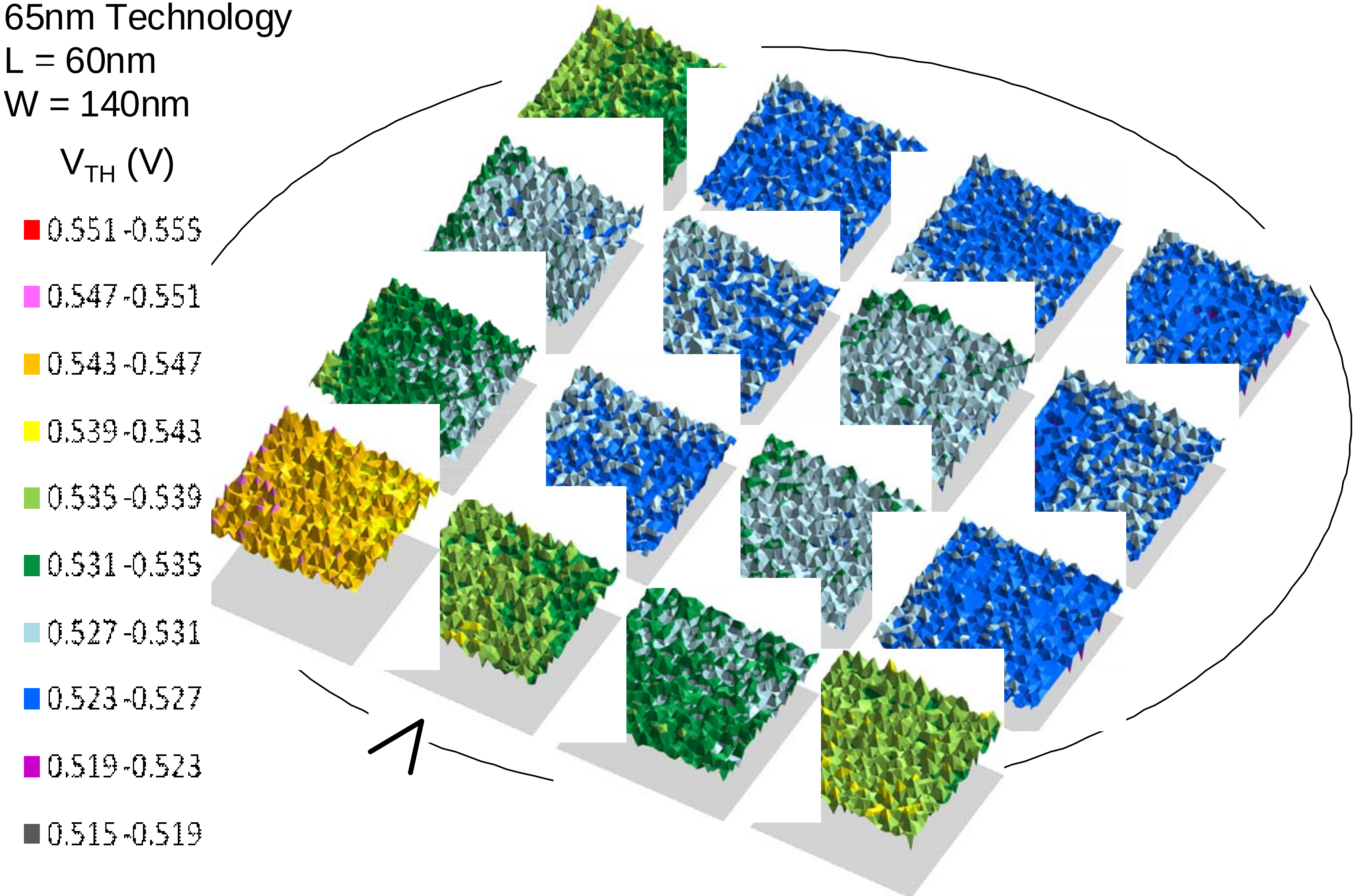


Subthreshold characteristics (200 transistors)

T. Hiramoto et al., MIRAI Project Meeting, 2007.

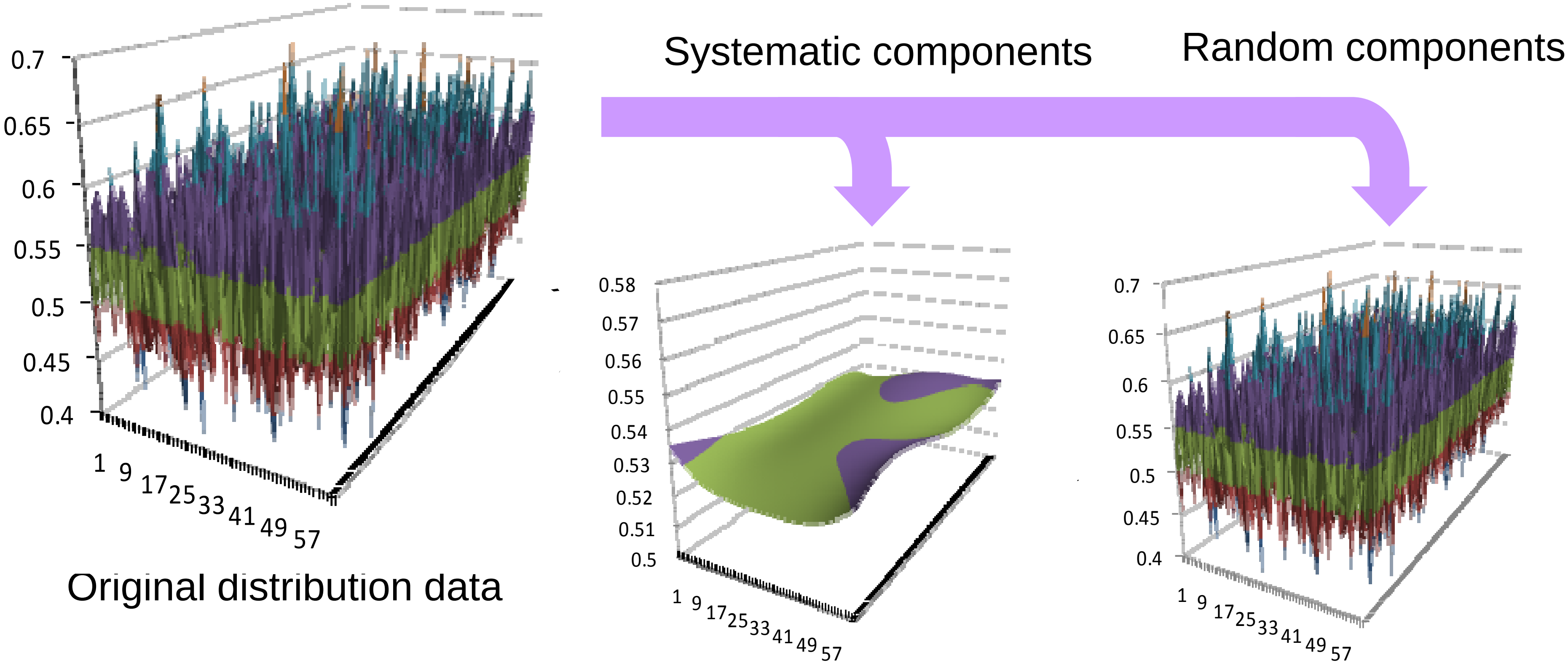
Within Wafer Variation

65nm Technology
L = 60nm
W = 140nm



T. Hiramoto et al., MIRAI Project Meeting, 2007.

Systematic and Random Components

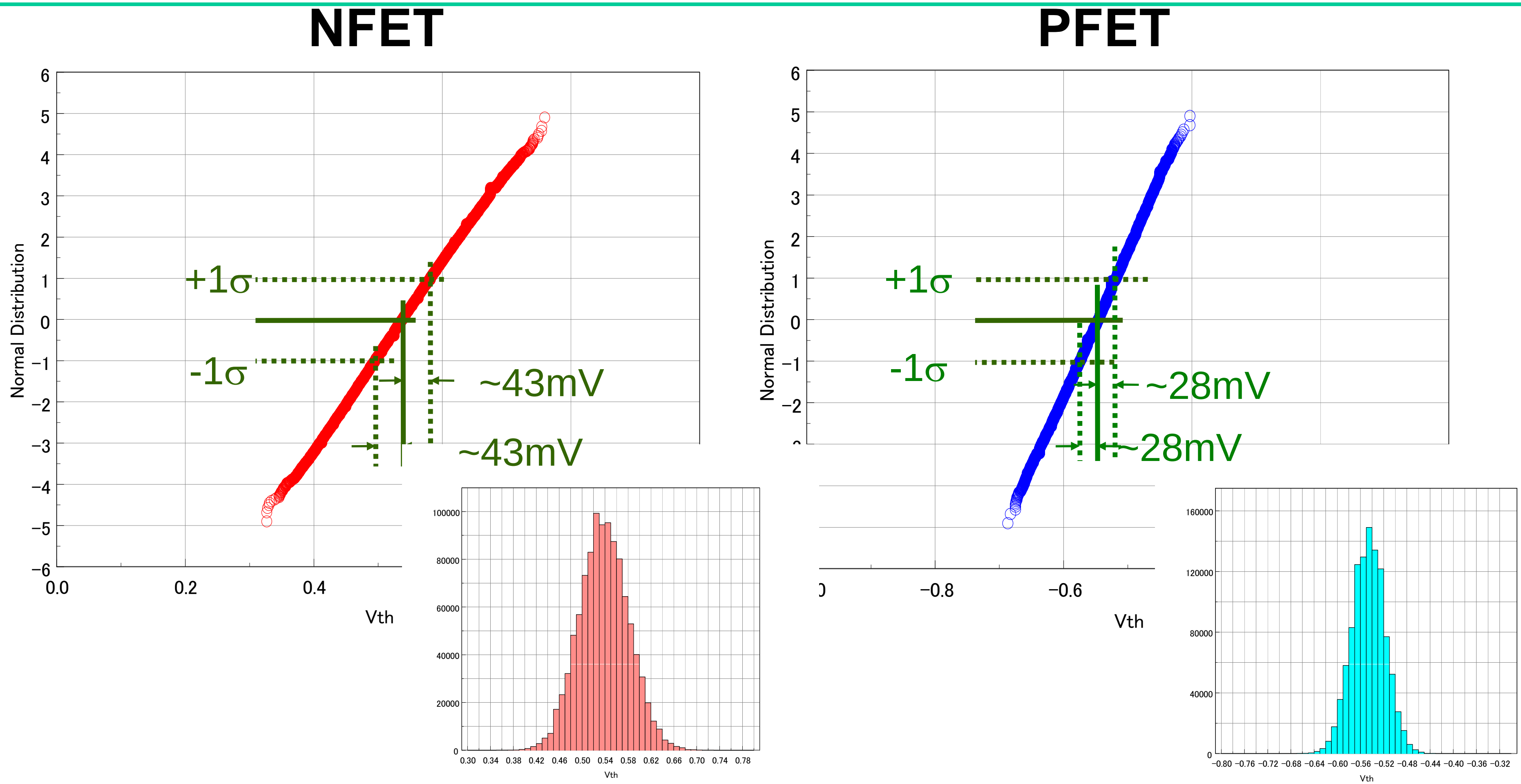


1. Random variation is dominant.

2. Systematic variation is negligible in DMA-TEG.

T. Hiramoto et al., MIRAI Project Meeting, 2007.

Vth Distribution of 1 Million Transistors



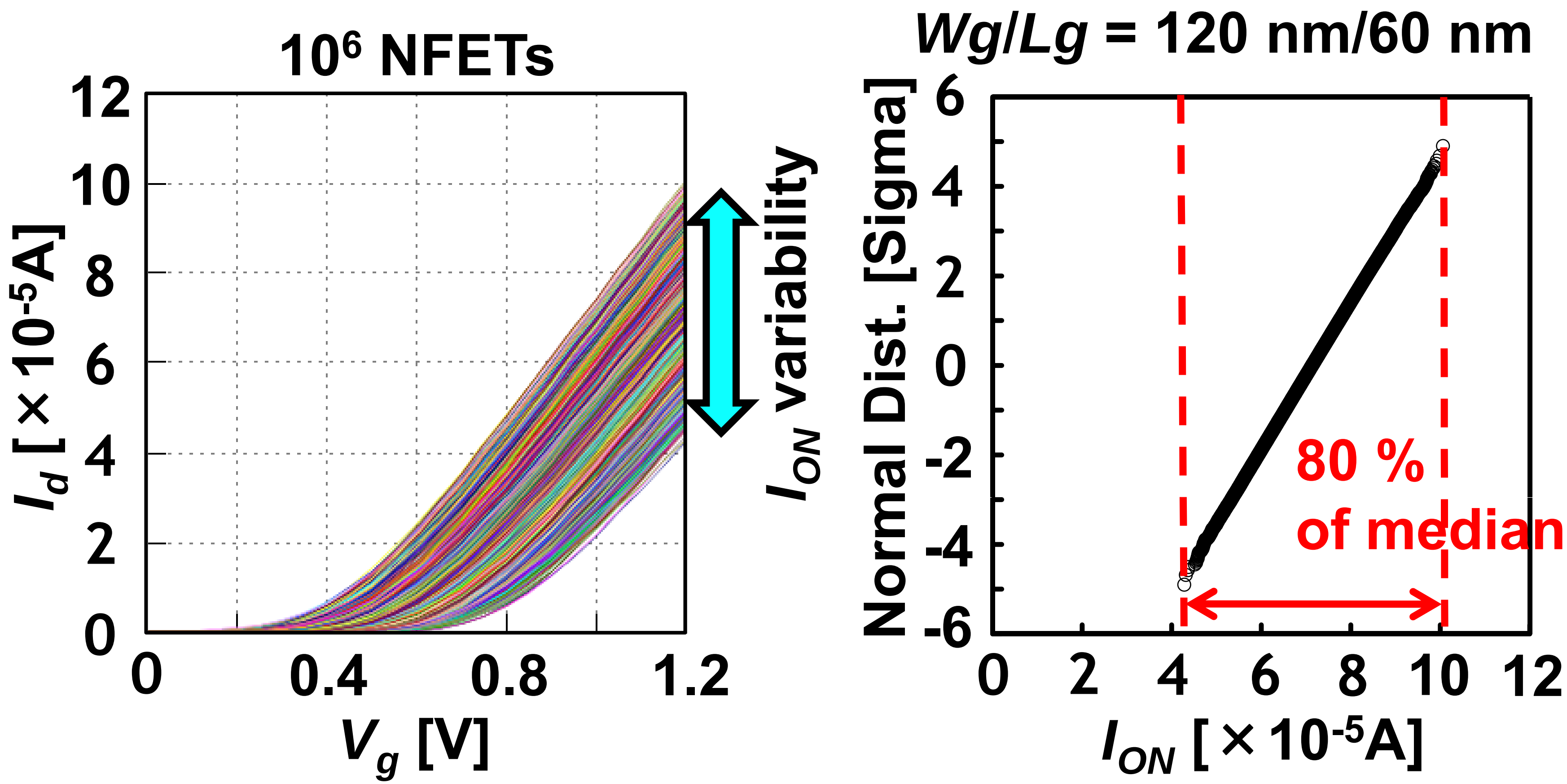
1. Normal distribution up to ±5σ.

2. NFET has larger variations than PFET.

T. Tsunomura et al., VLSI Symposium, p. 156, 2008.

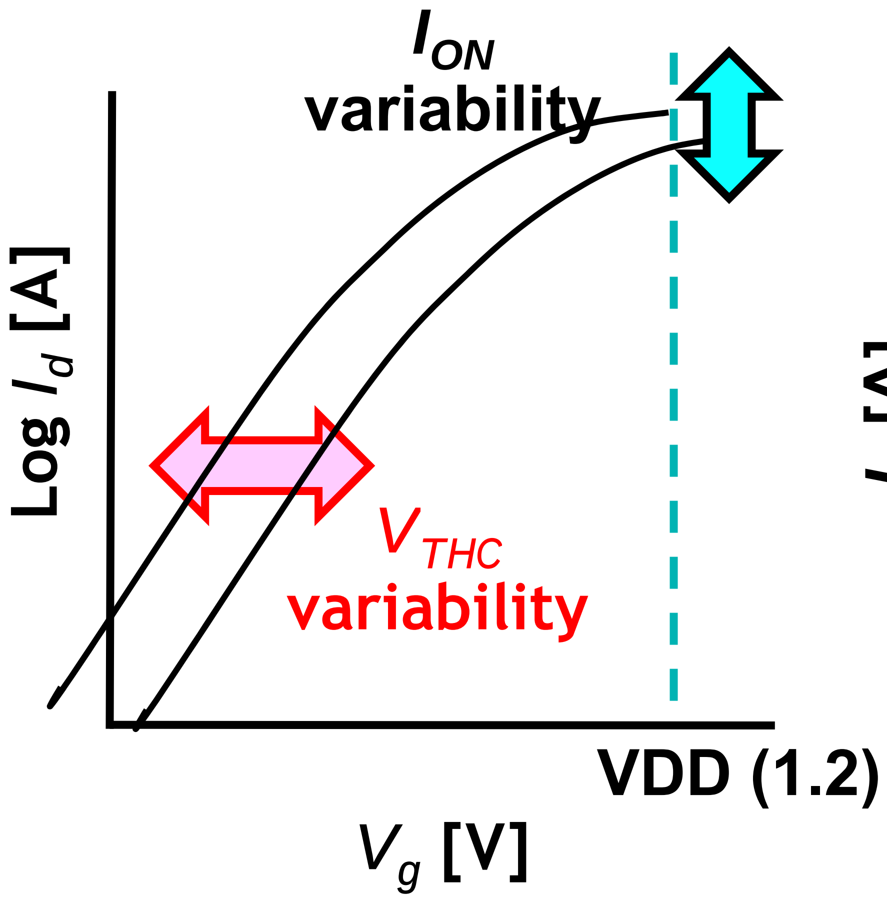
Drain Current Variability

Drain Current Variability

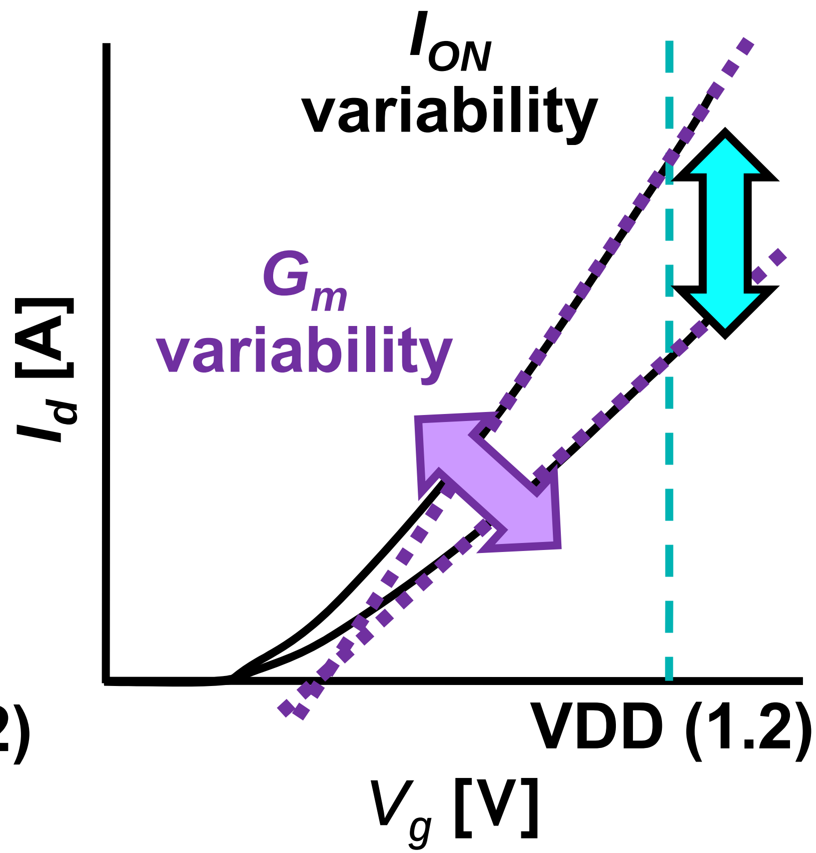


T. Tsunomura et al., VLSI Technology Symposium, p. 97, 2010.

Two Components (Vthc and gm)



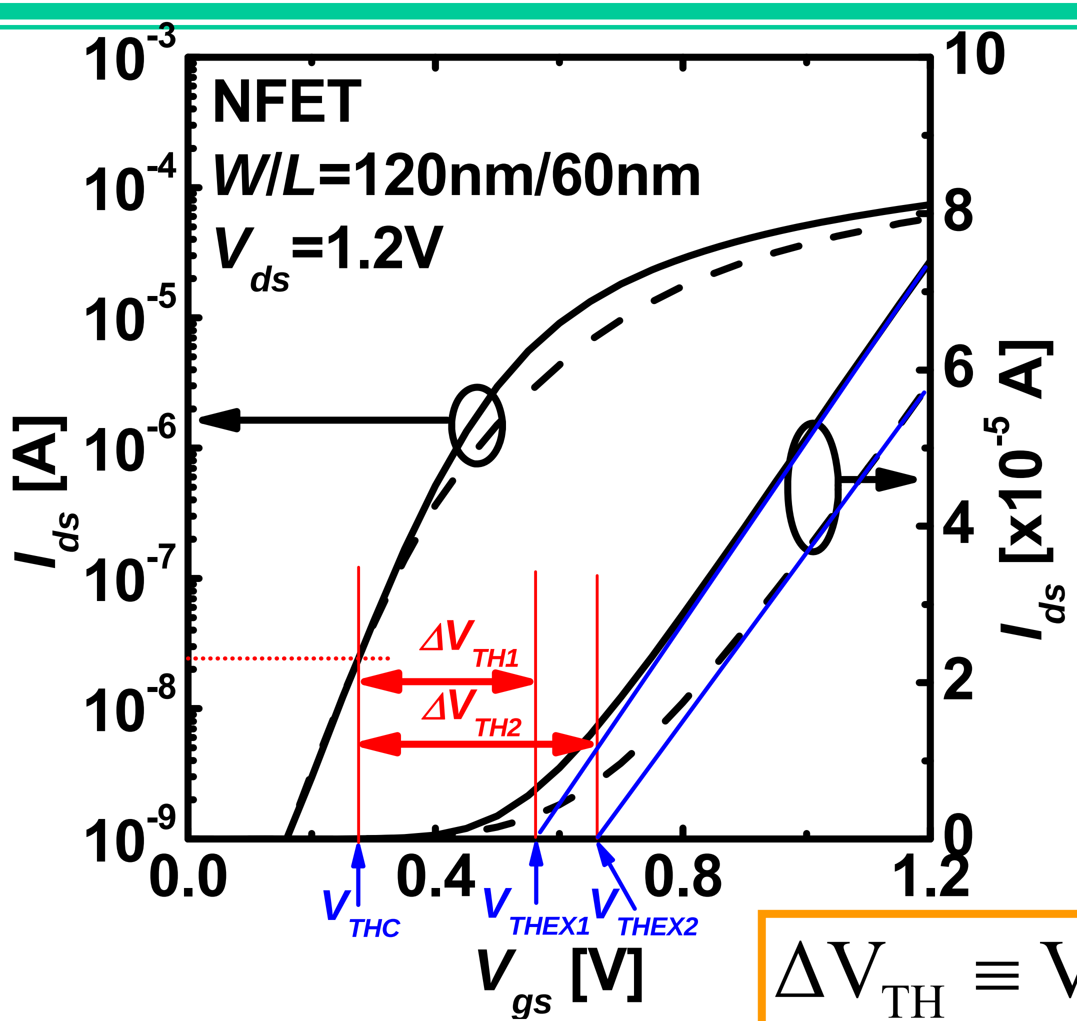
V_{THC} Component



G_m Component

T. Tsunomura et al., VLSI Technology Symposium, p. 97, 2010.

Two Transistors with same Vthc and gm



$$\Delta V_{TH} \equiv V_{THEX} - V_{THC}$$

"Current-Onset Voltage"

T. Tsunomura et al., VLSI Technology Symposium, p. 97, 2010.

Definition of Current Onset Voltage ΔV_{TH}

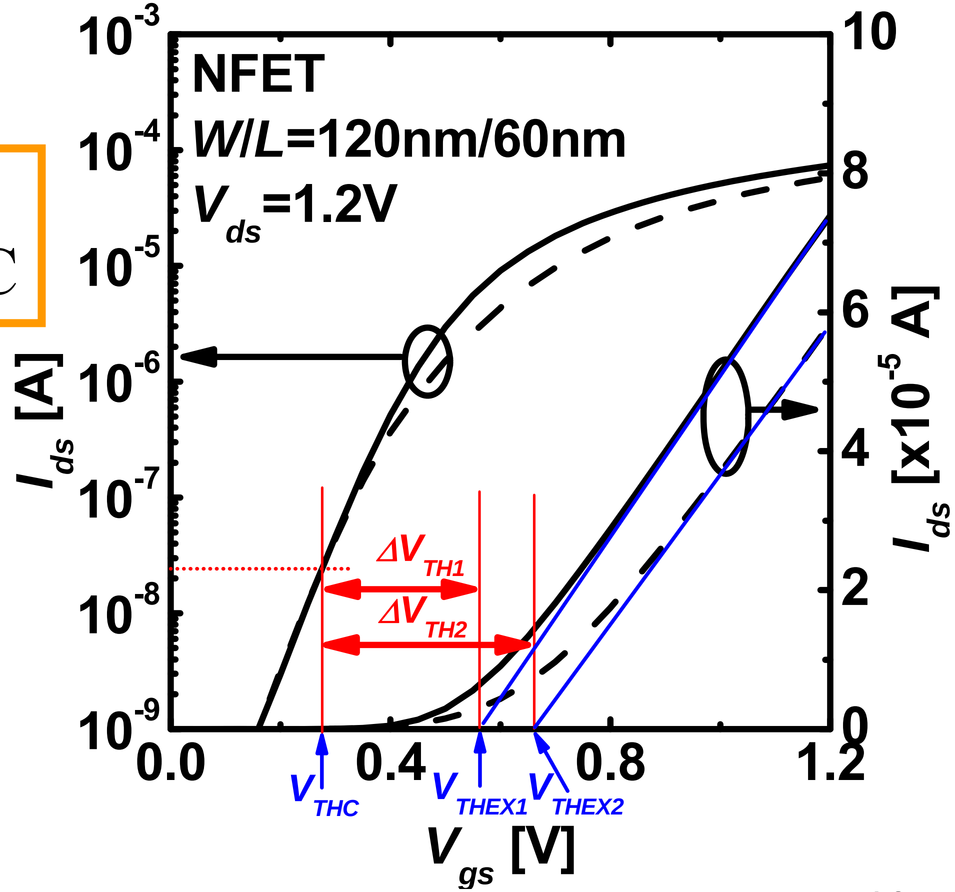
The 3rd Component of Drain Current Variability

"Current-Onset Voltage"

$$\Delta V_{TH} \equiv V_{THEX} - V_{THC}$$

Extrapolated Vth

Subthreshold Constant Current Vth



T. Tsunomura et al., VLSI Technology Symposium, p. 97, 2010.

Independent Three Components

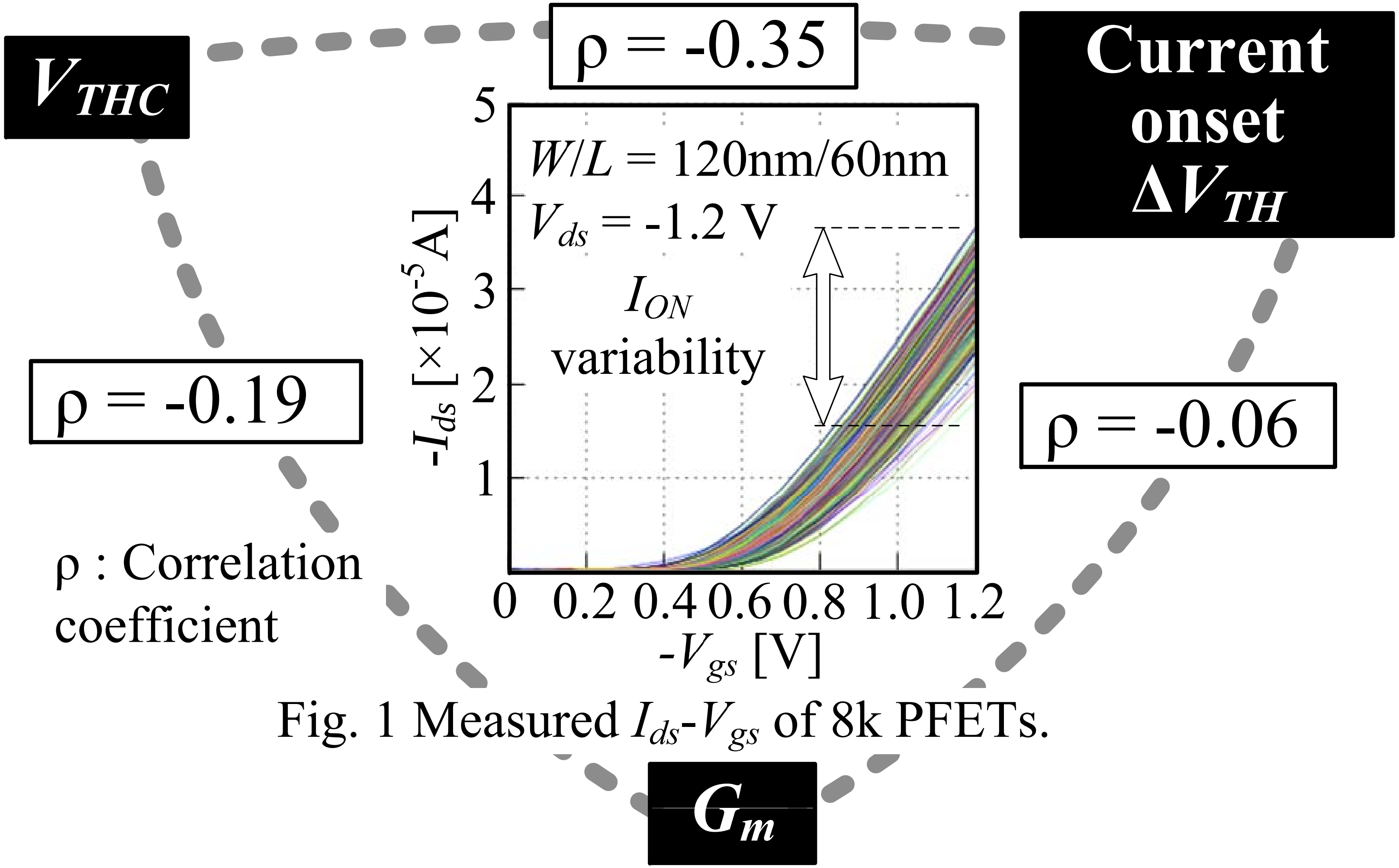
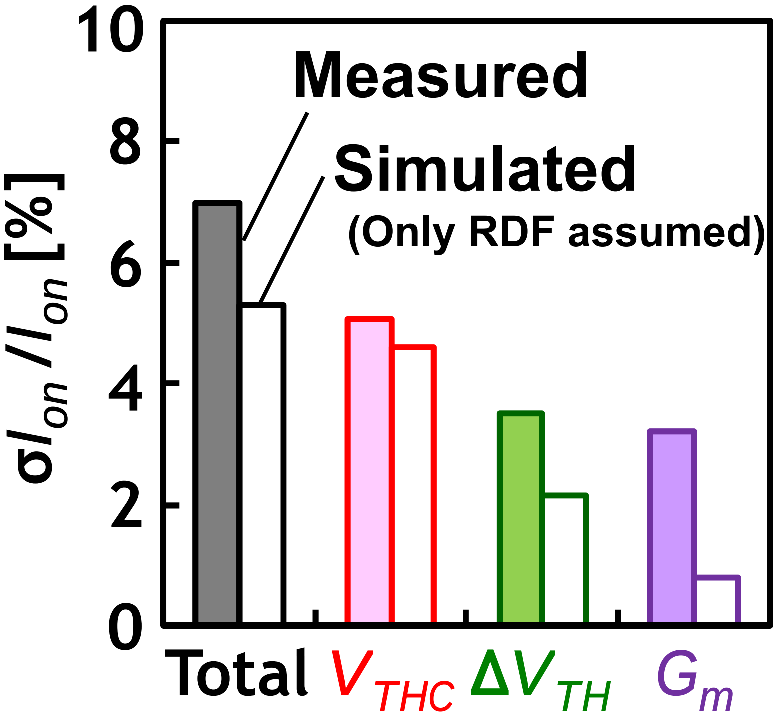


Fig. 1 Measured I_{ds}-V_{gs} of 8k PFETs.

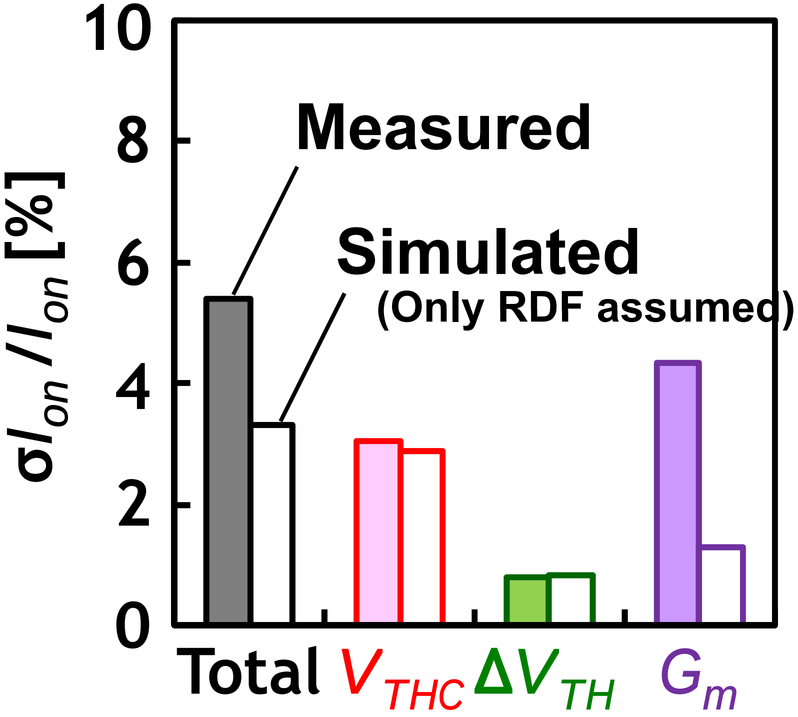
T. Tsunomura et al., VLSI Technology Symposium, p. 97, 2010.

Contributions of Three Components

PFET



W_g / L_g = 120 nm/60 nm,
V_d = -1.2 V

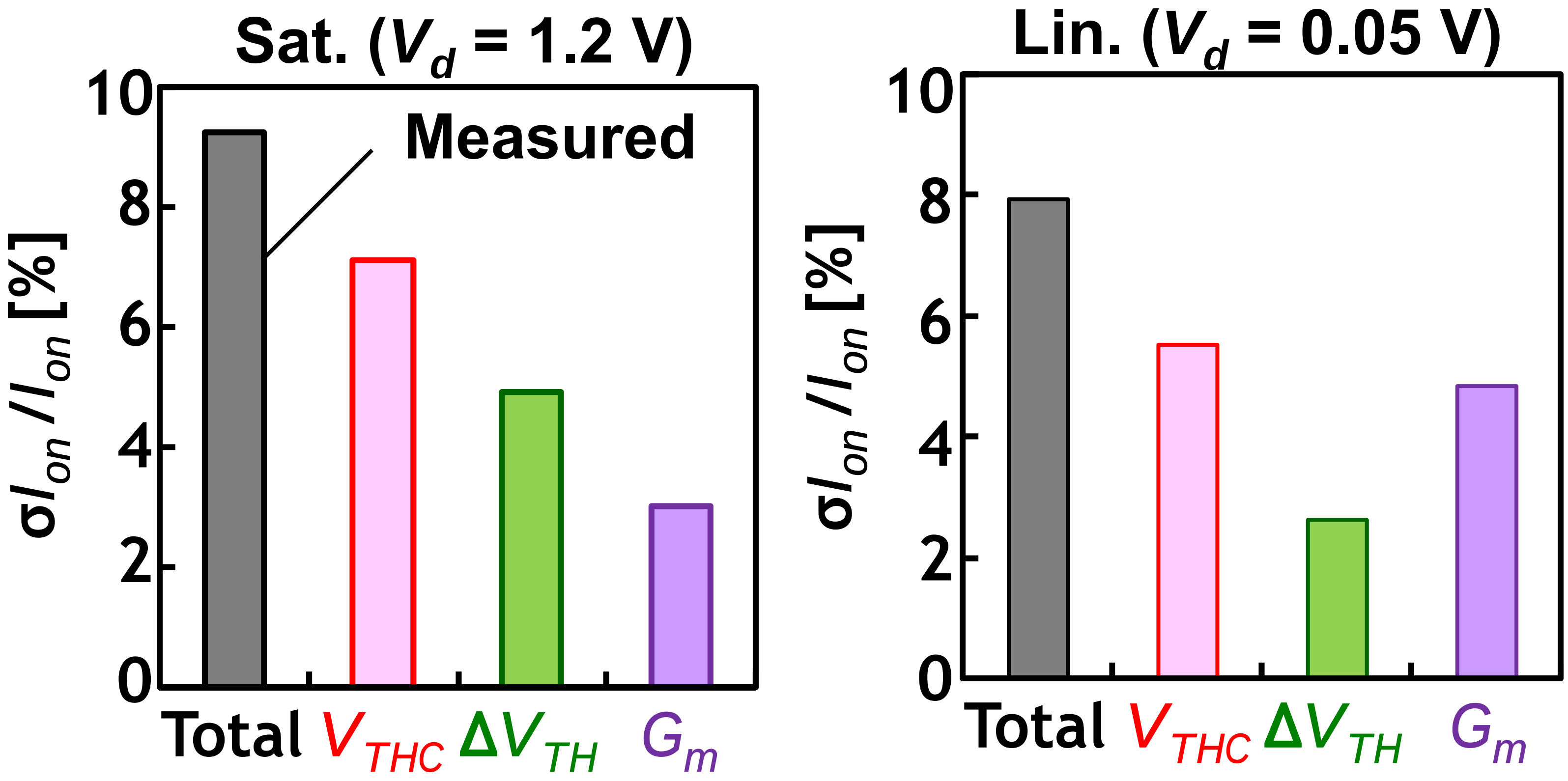


W_g / L_g = 120 nm/60 nm,
V_d = -0.05 V

T. Tsunomura et al., VLSI Technology Symposium, p. 97, 2010.

Contributions of Three Components

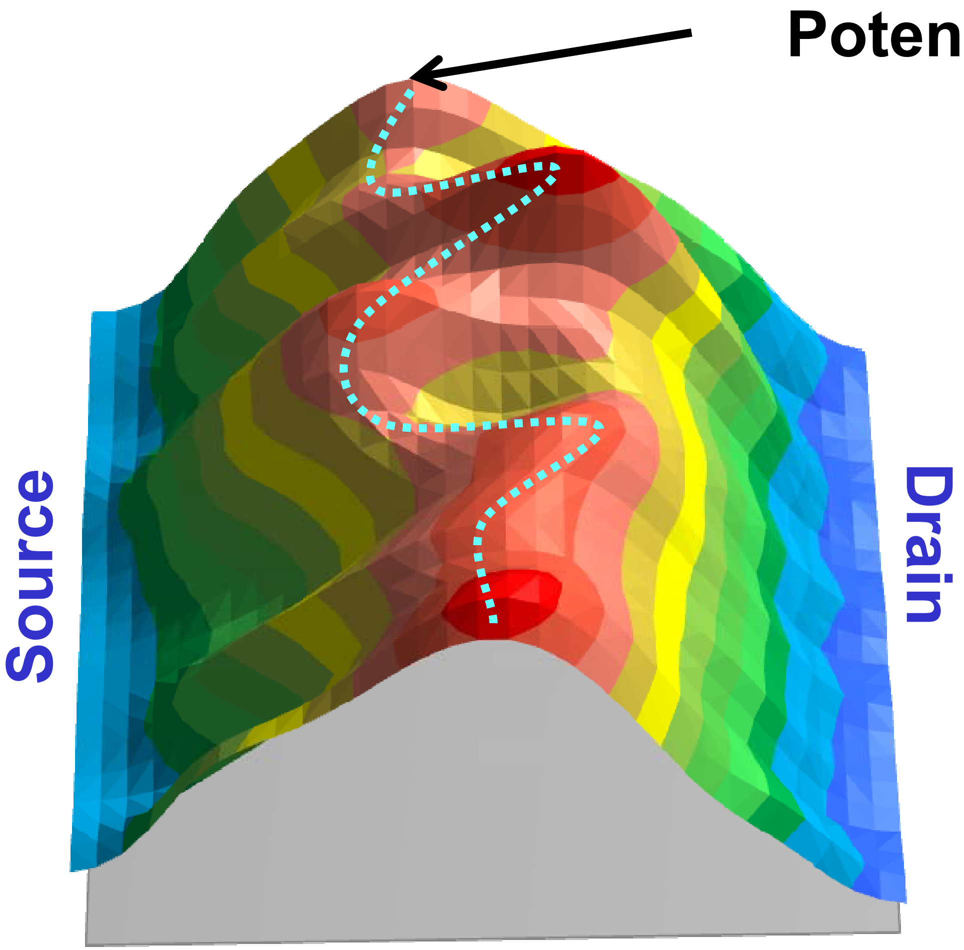
NFET



W_g / L_g = 120 nm/60 nm

T. Tsunomura et al., VLSI Technology Symposium, p. 97, 2010.

The Origin of ΔV_{TH}

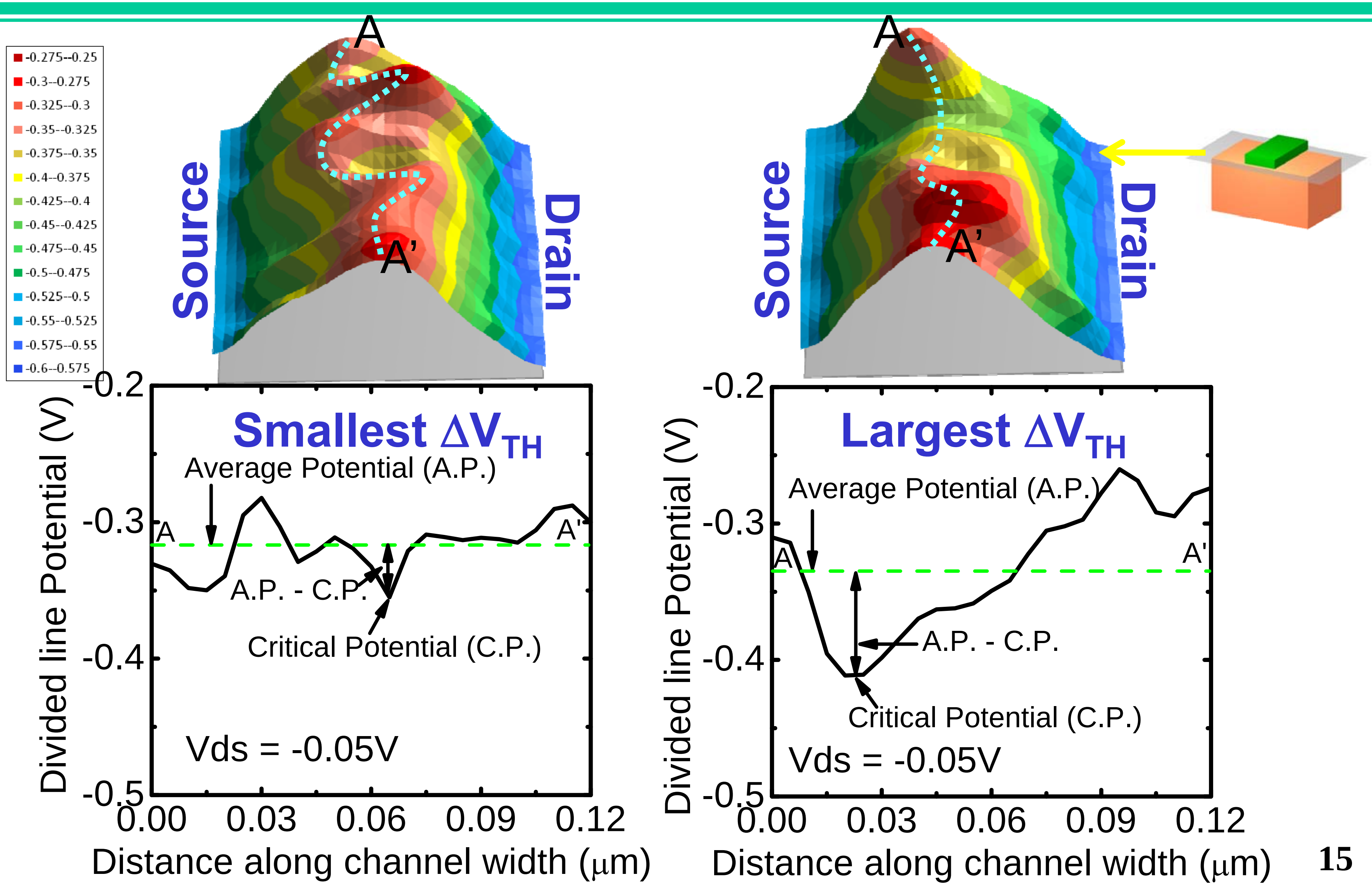


V_{THC}: Subthreshold region
Determined by the minimum potential on the divided line?

V_{THEX}: Strong inversion
Average potential?

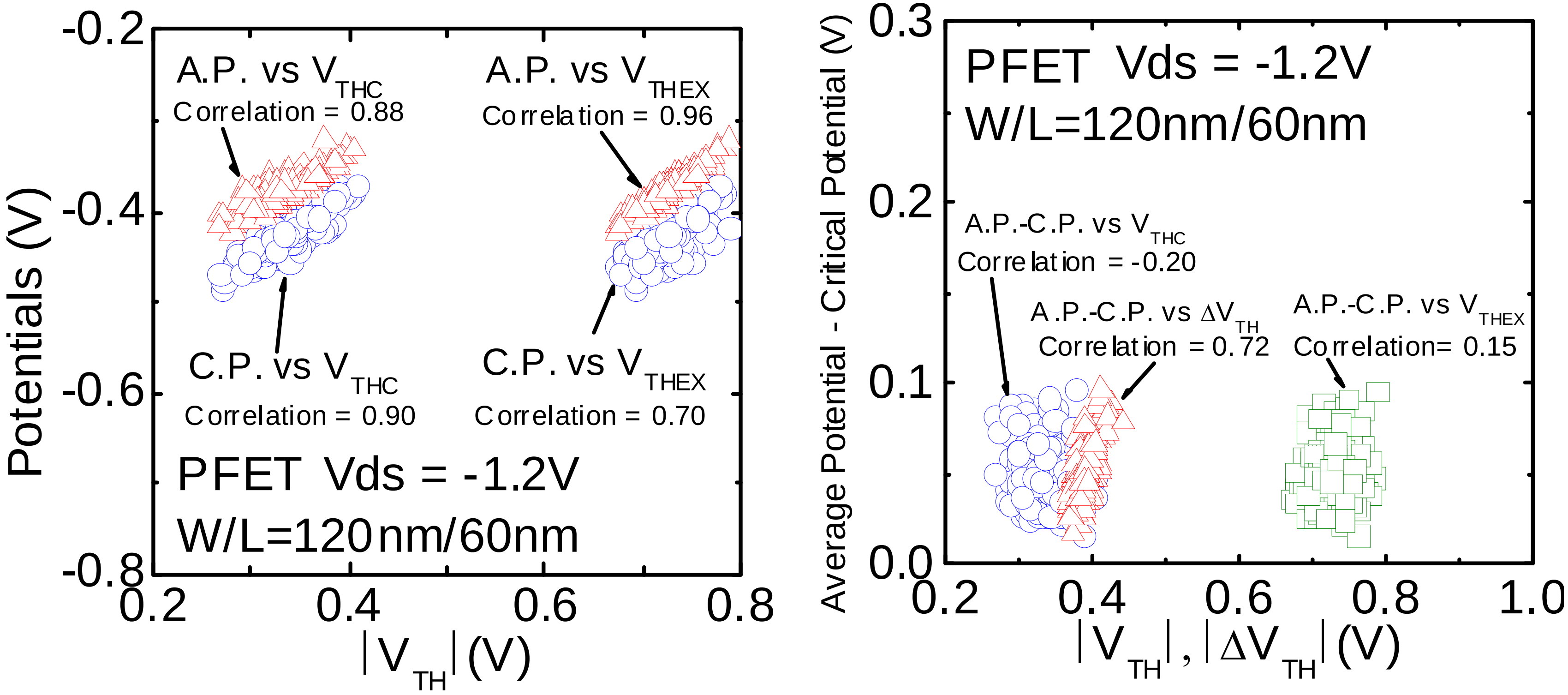
A. Kumar et al., Silicon Nanoelectronics Workshop, p. 7, 2010.

Simulated Potential Profile



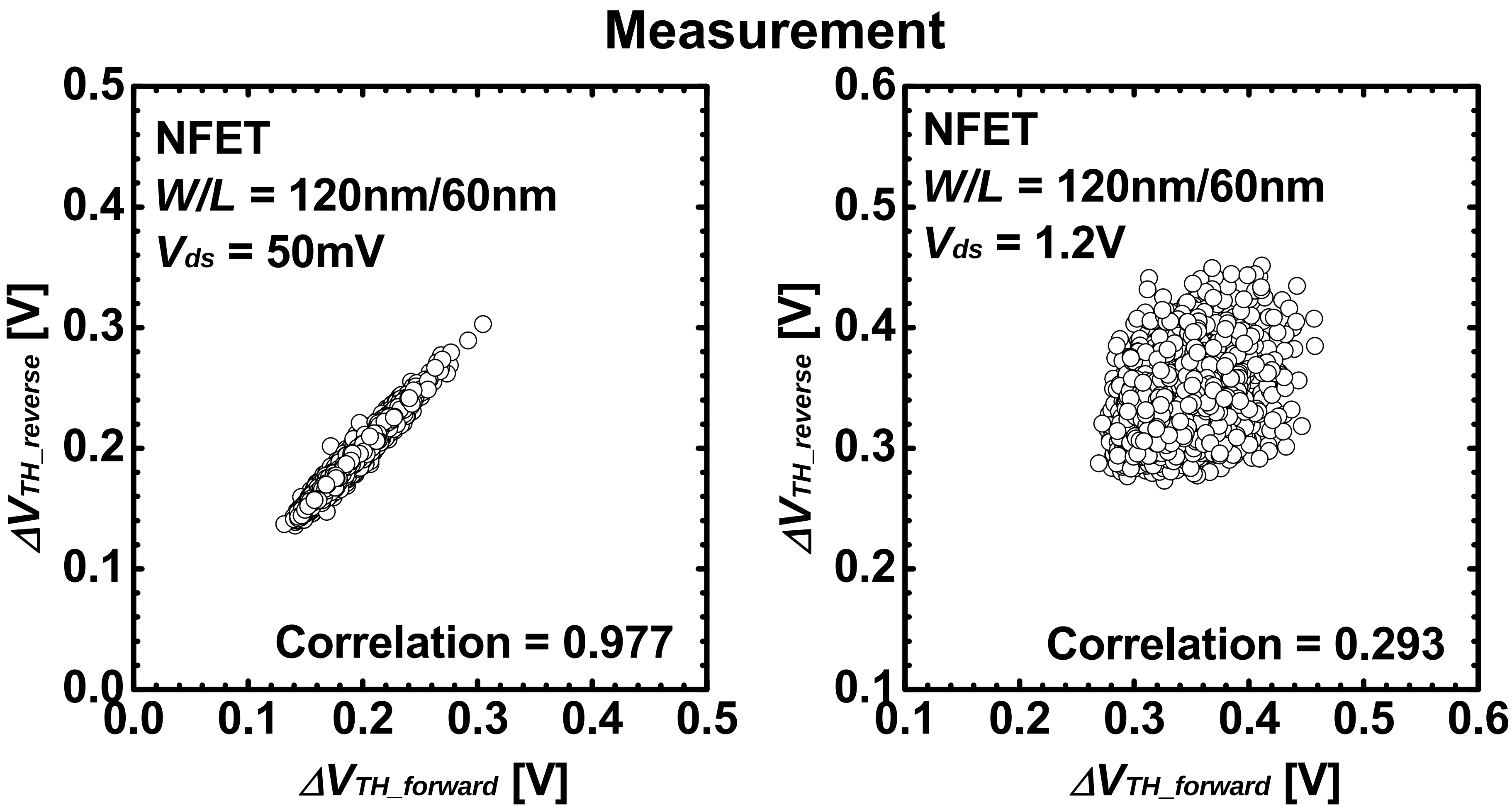
Correlation between ΔV_{TH} and V_{TH}'s

Simulation



A. Kumar et al., Silicon Nanoelectronics Workshop, p. 7, 2010.

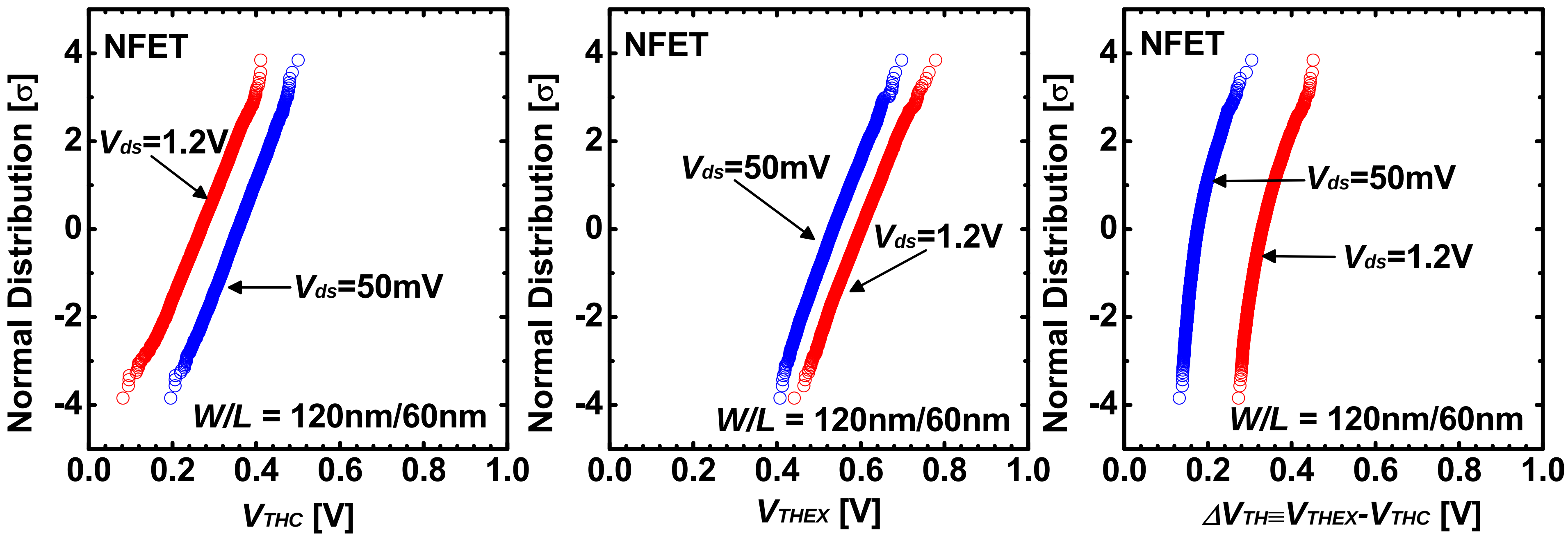
Reversed S/D



T. Mizutani et al., Silicon Nanoelectronics Workshop, p. 81, 2010.

Cumulative Distribution

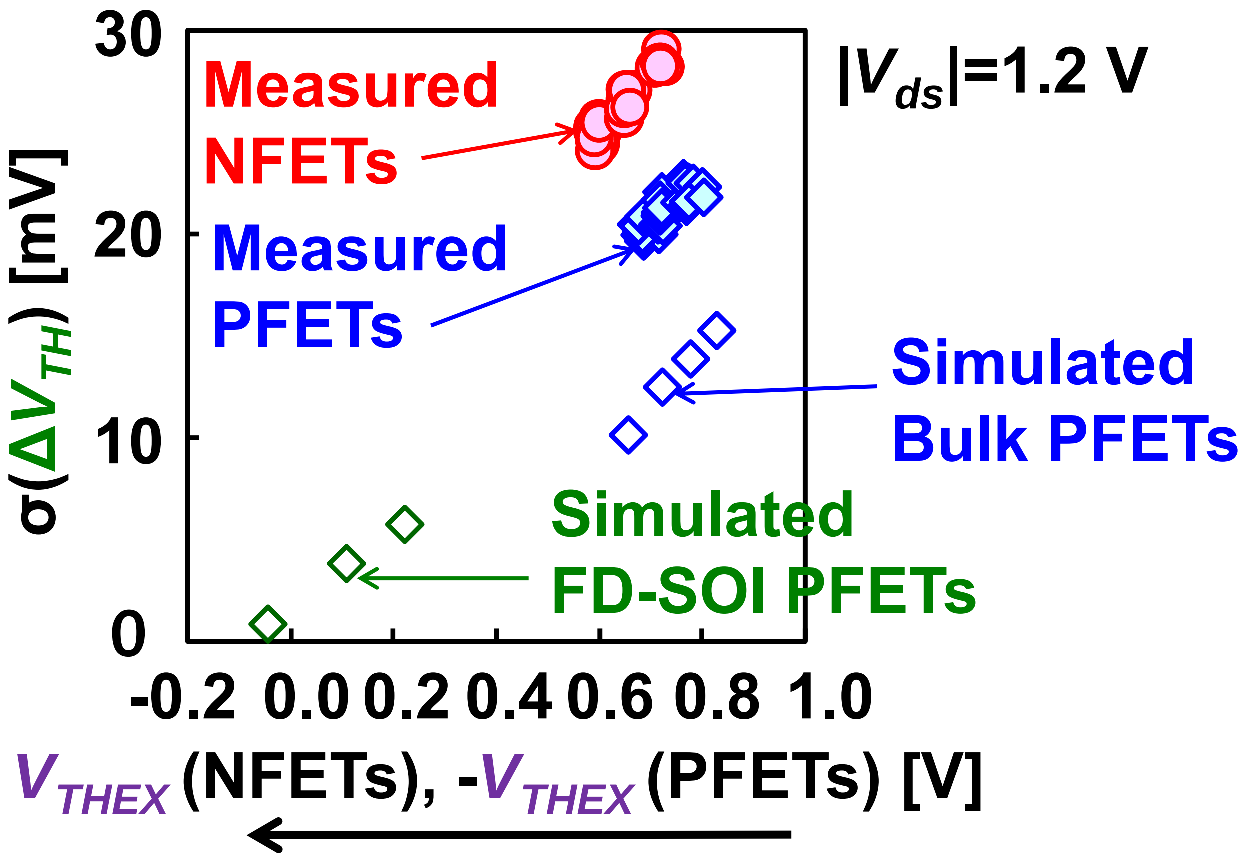
Measurement



V_{THC} V_{THEX} ΔV_{TH}

T. Mizutani et al., Silicon Nanoelectronics Workshop, p. 81, 2010.

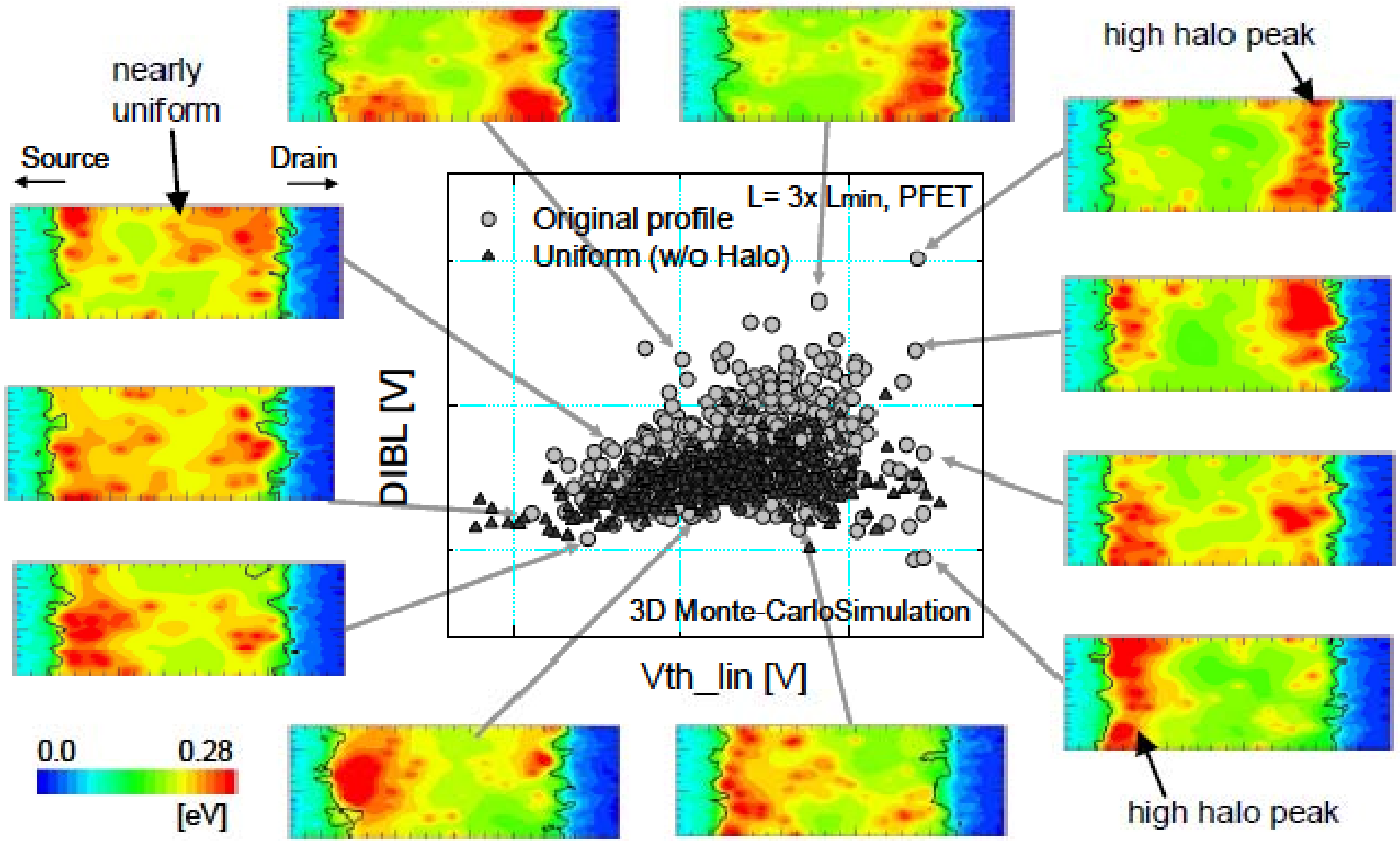
Dopant Density v.s. σ(ΔVTH)



• V_{THEX} is controlled by the channel dopant concentration.

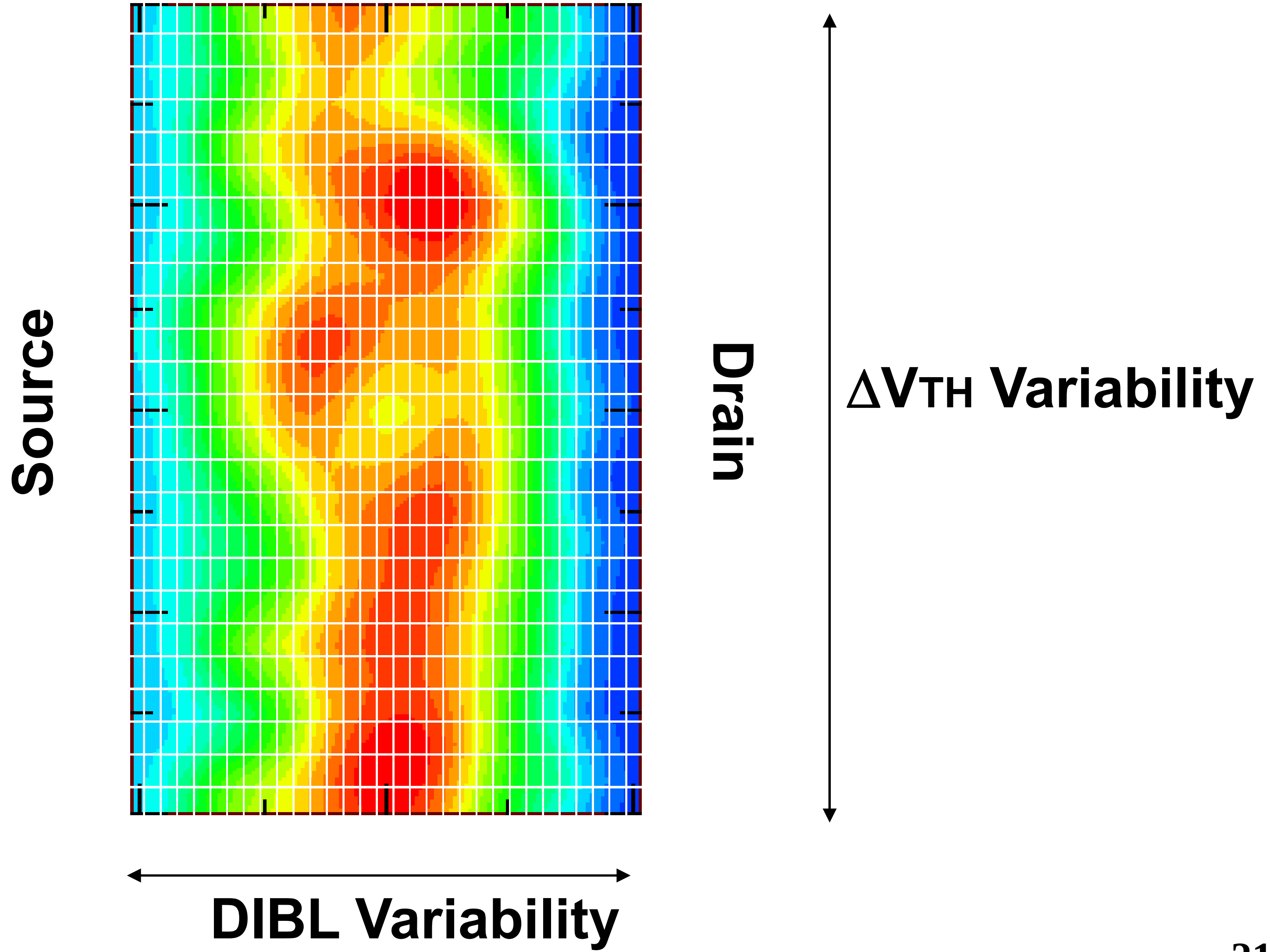
T. Tsunomura et al., VLSI Technology Symposium, p. 97, 2010.

DIBL and Potential Profile



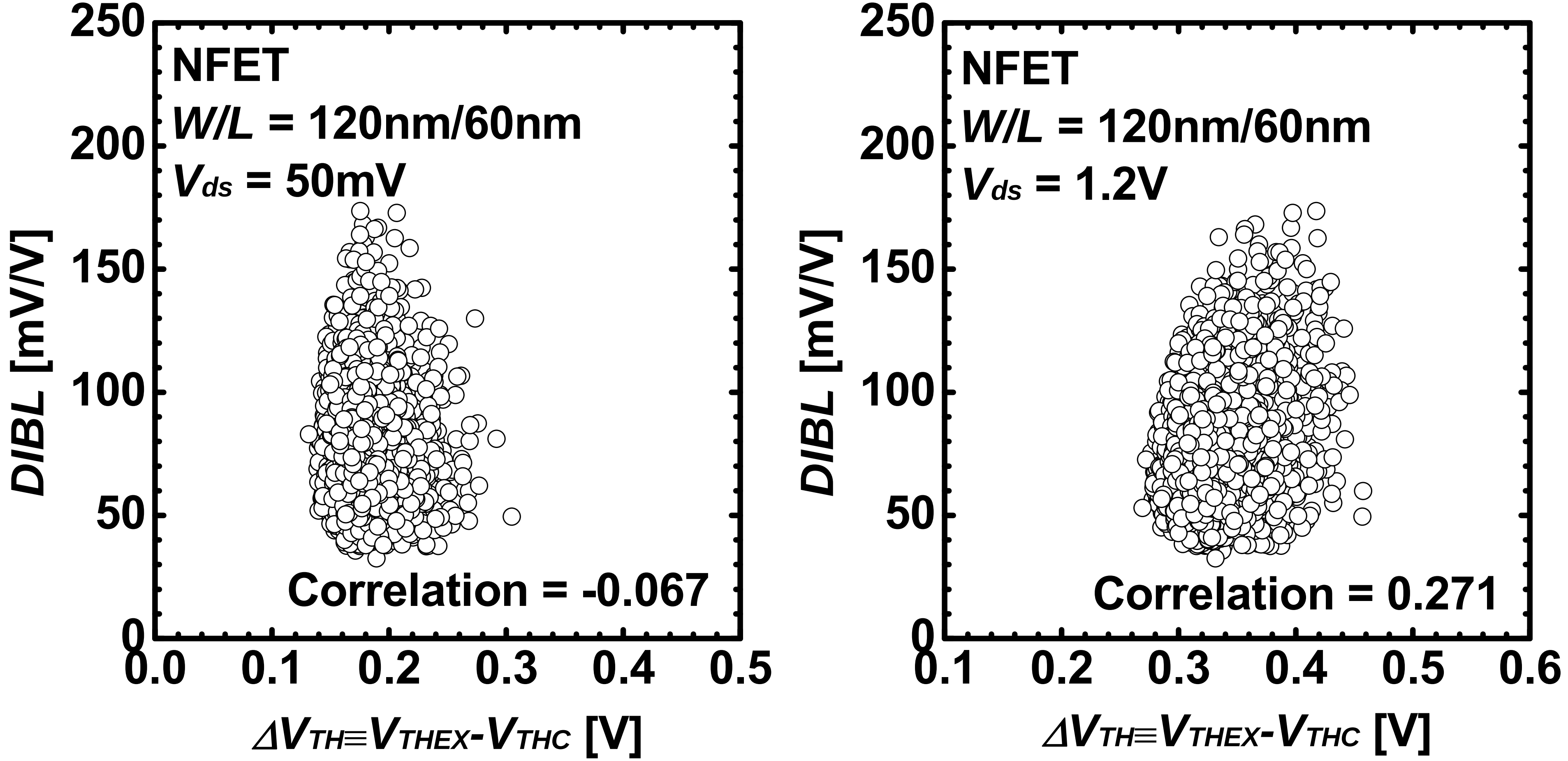
M. Miyamura et al., IEDM, p.447, 2008.

ΔV_{TH} Variability and DIBL Variability



Correlation between ΔV_{TH} and DIBL

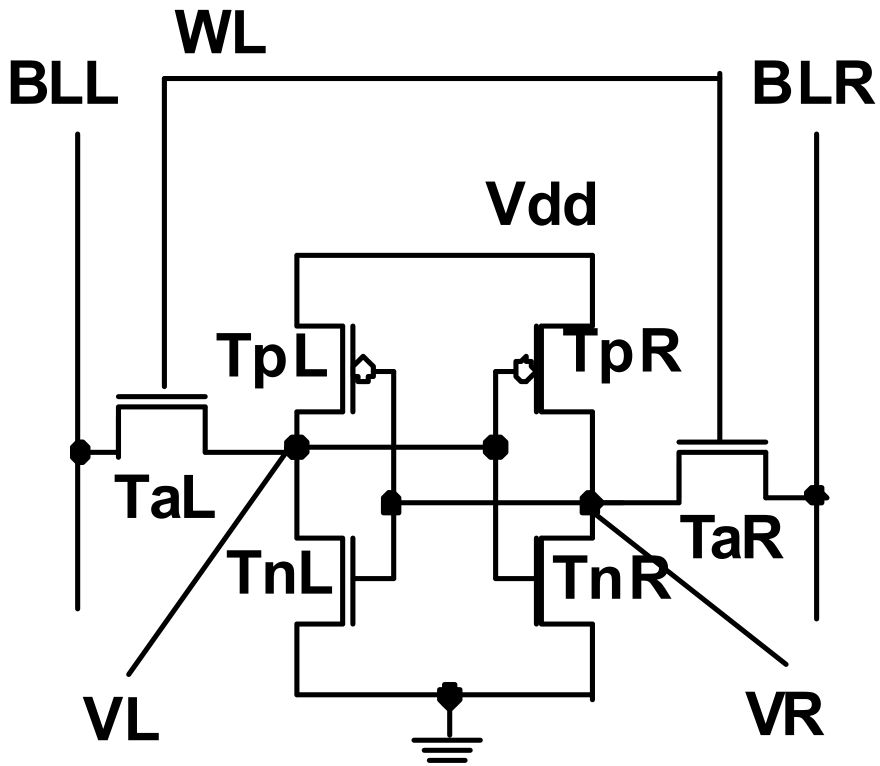
Measurement

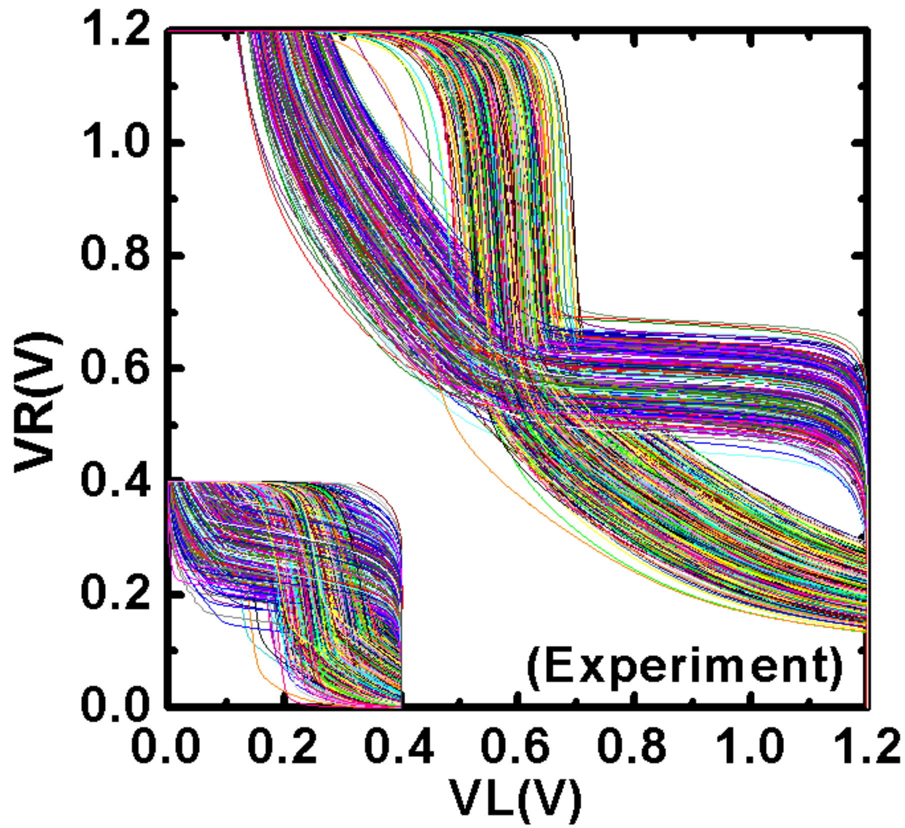


T. Mizutani et al., Silicon Nanoelectronics Workshop, p. 81, 2010.

SRAM Variability

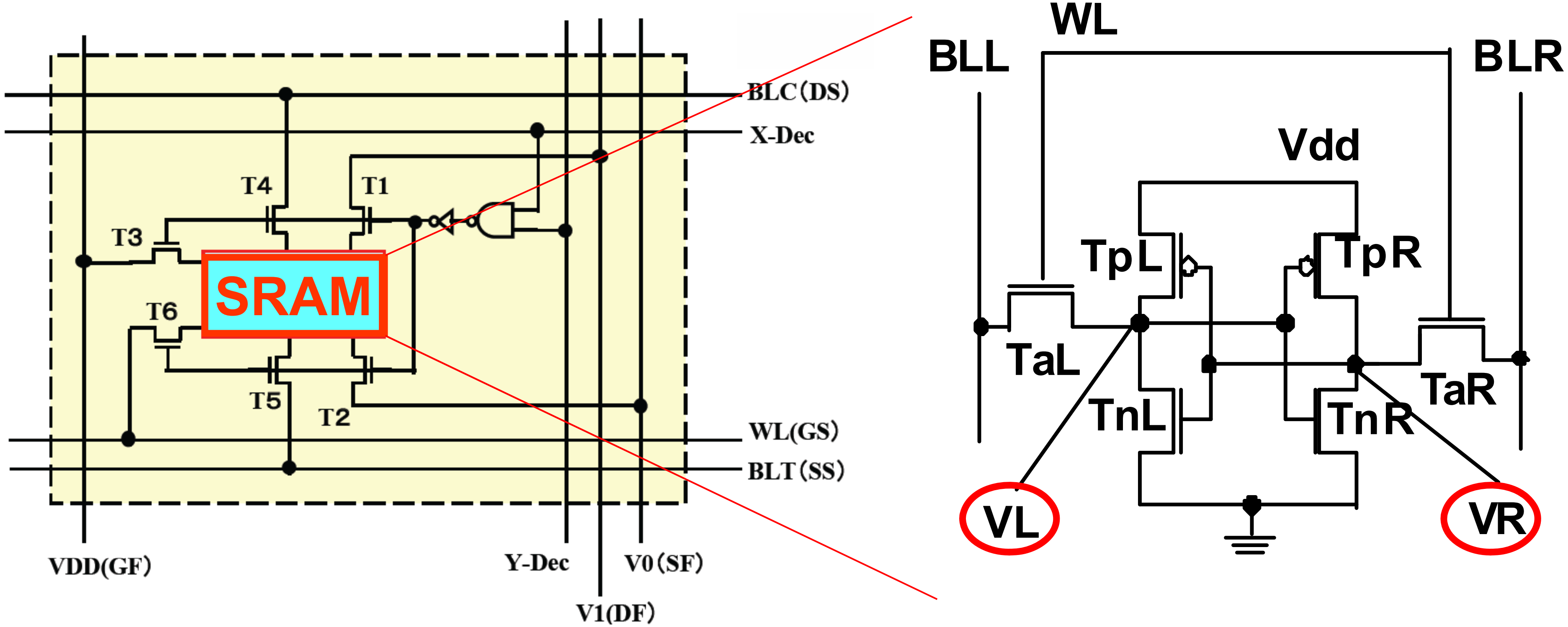
SRAM





M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.

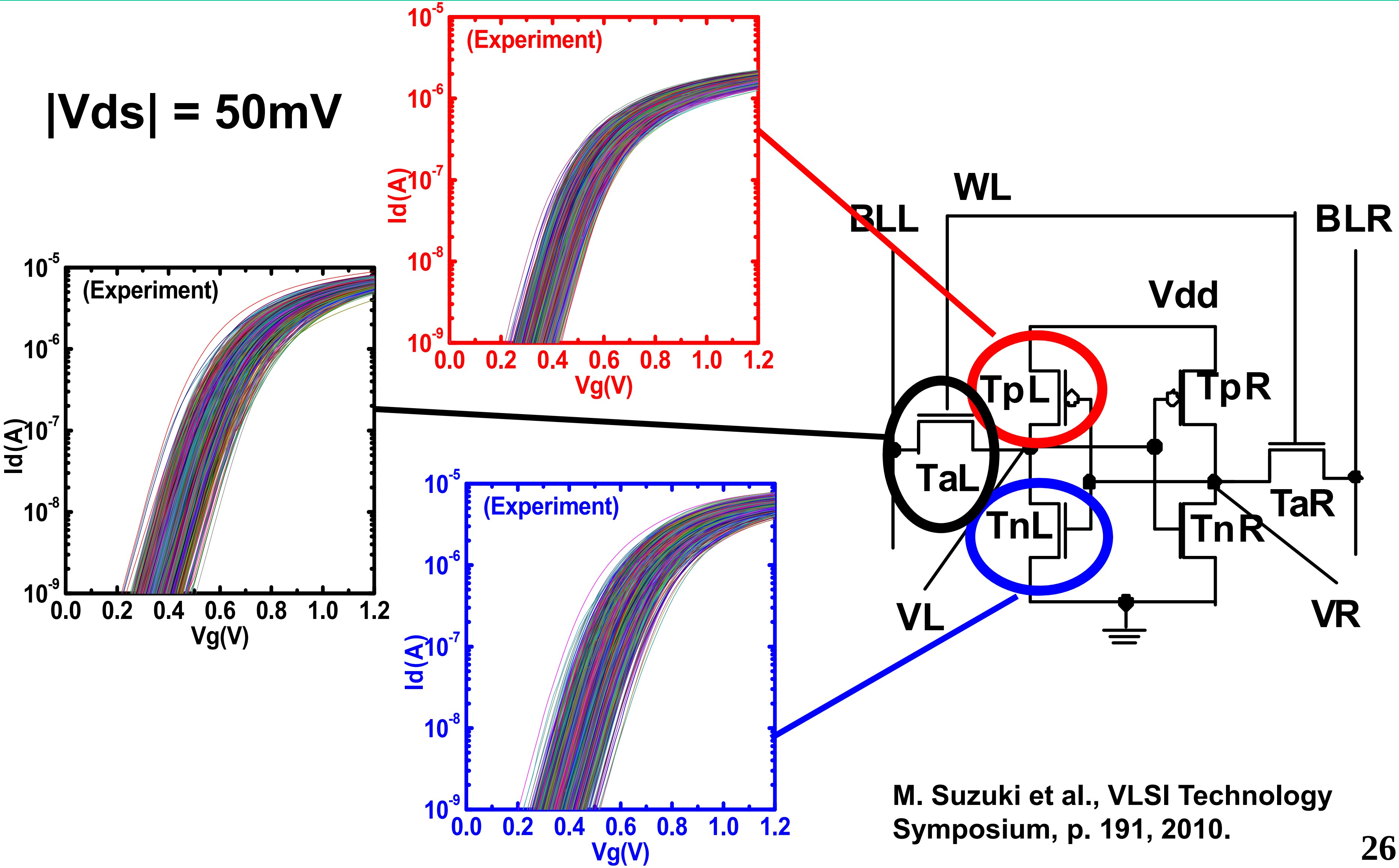
16k SRAM DMA TEG



M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.

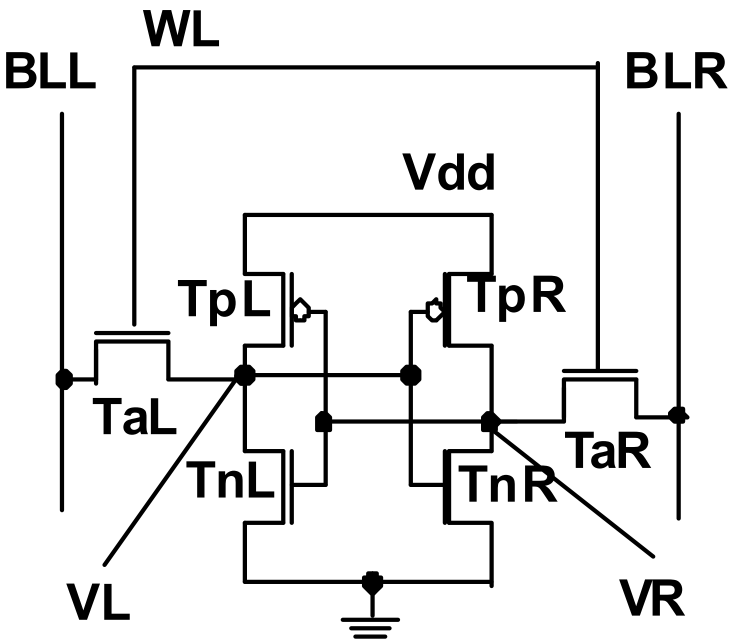
Measured I-V in Individual Transistors

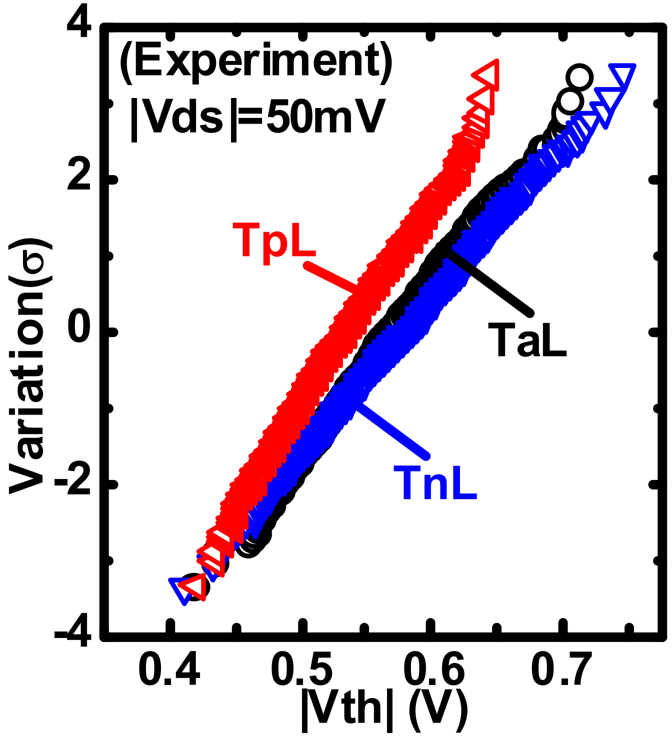
|Vds| = 50mV



M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.

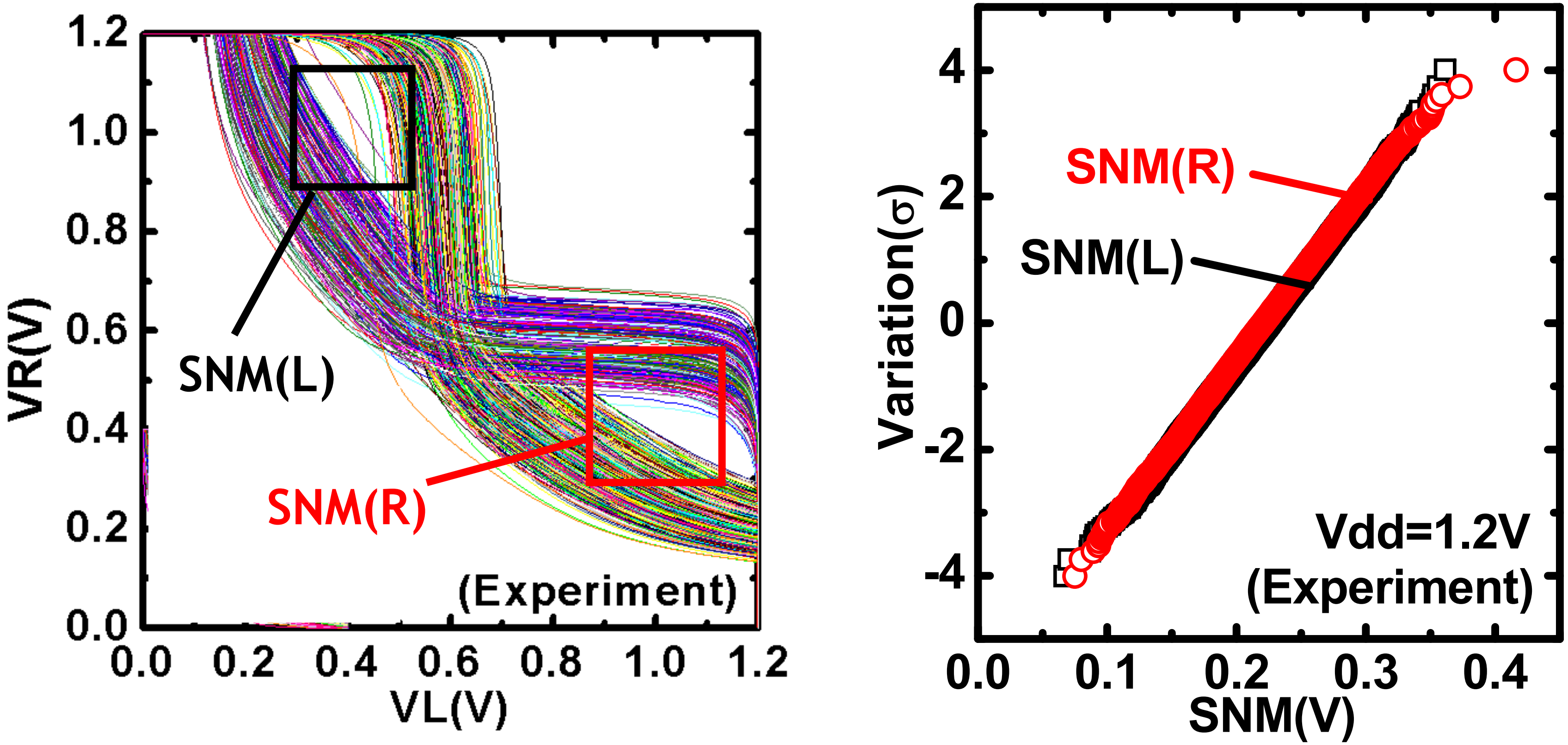
16k SRAM DMA TEG





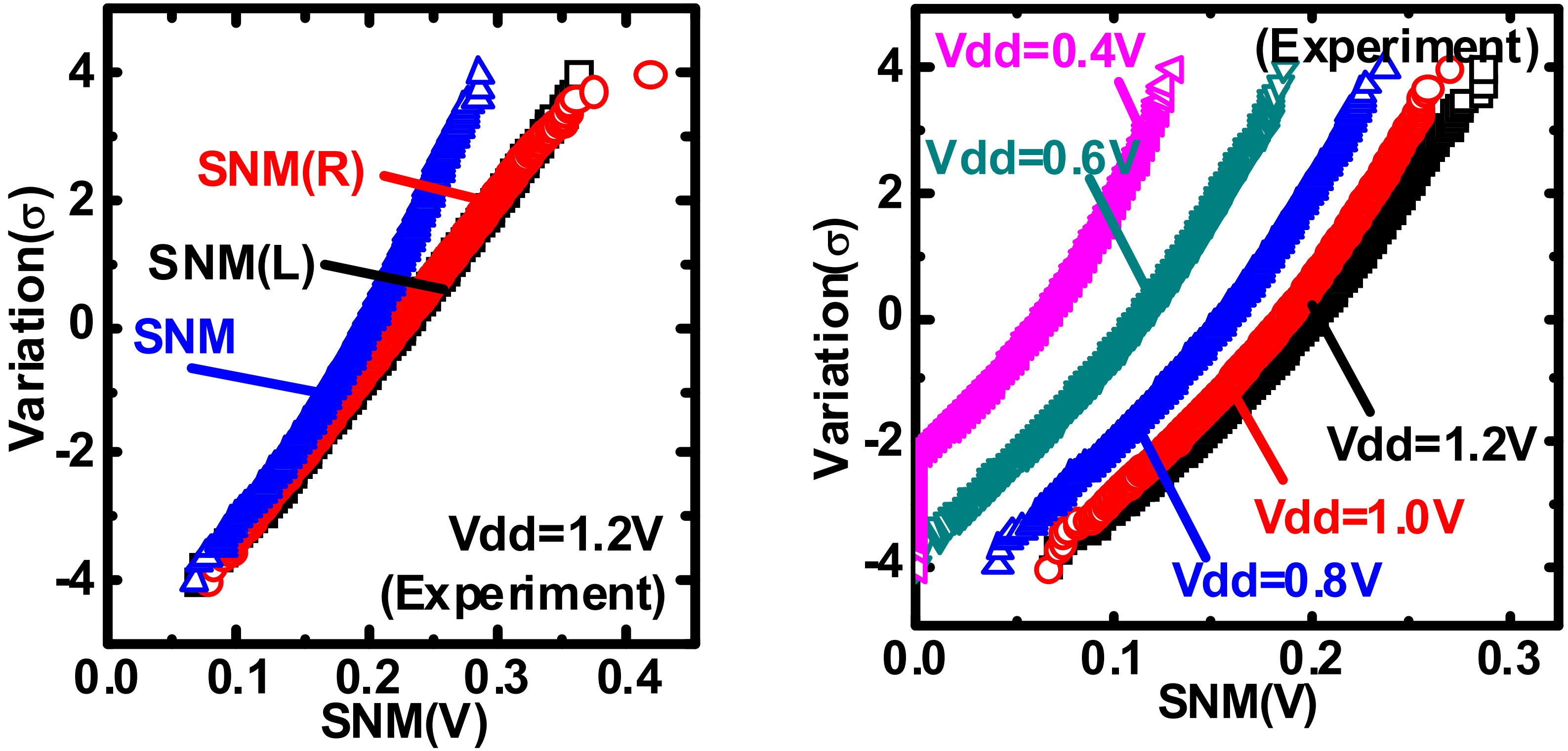
M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.

One-Side SNM



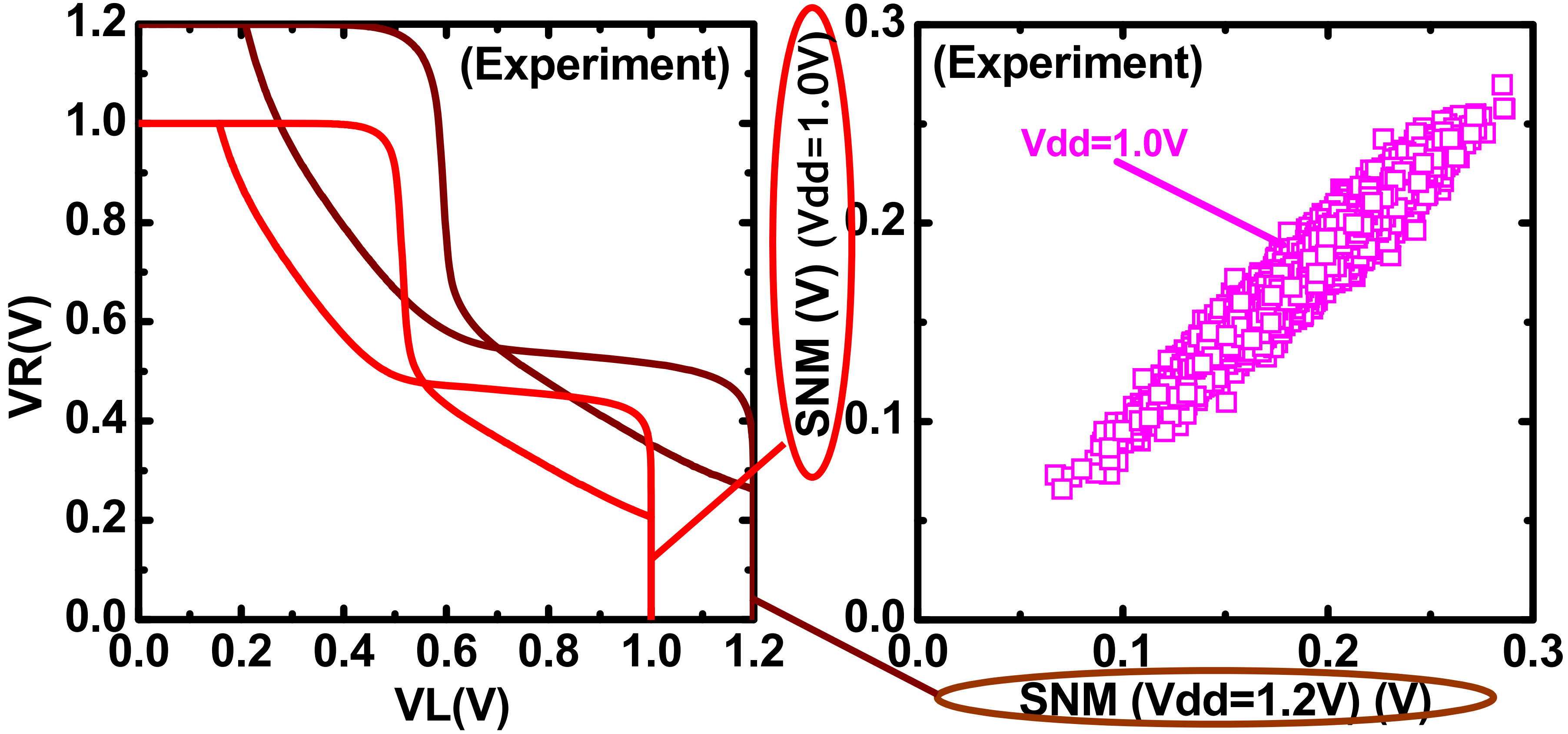
M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.

Distribution of SNM



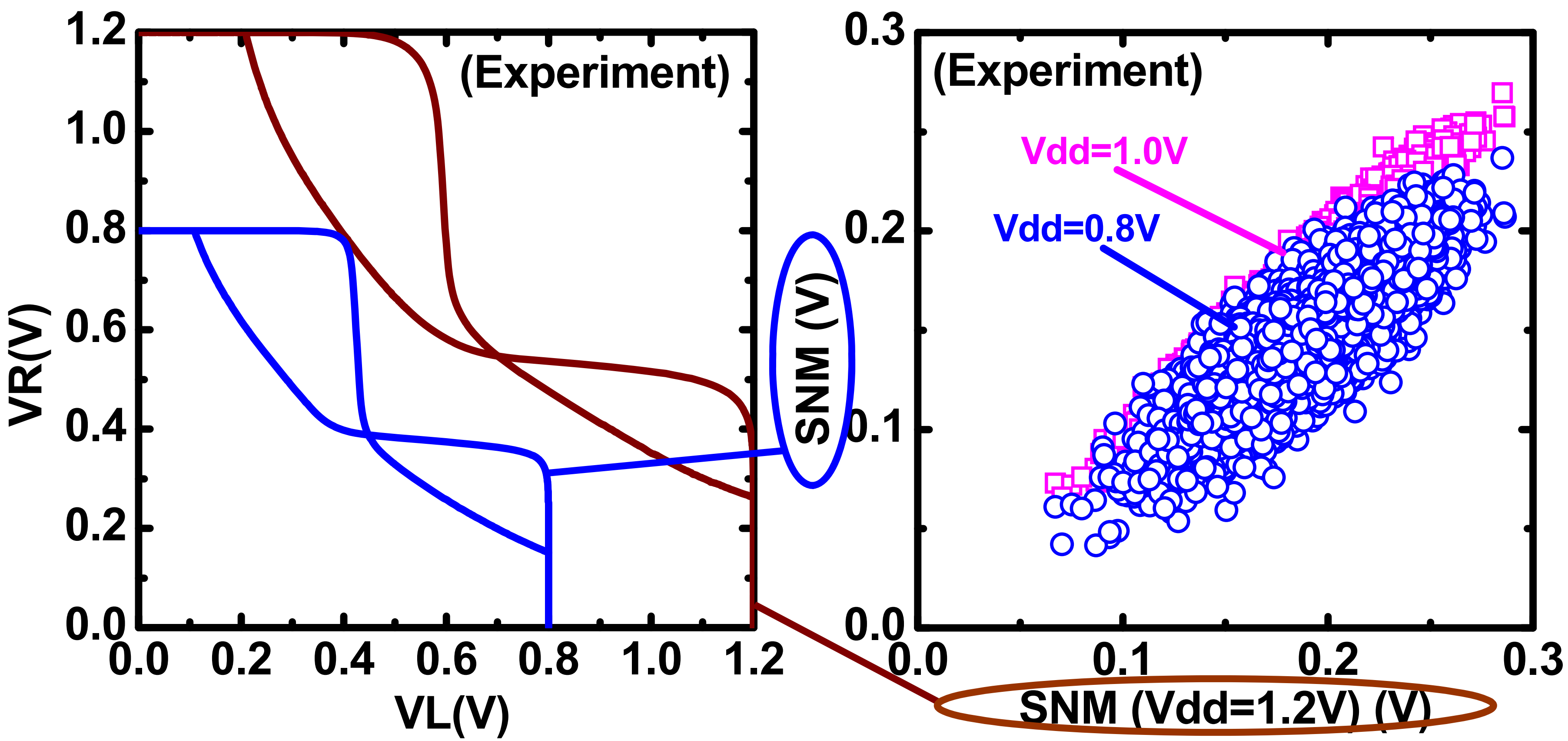
M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.

Correlation of SNM at Different Vdd



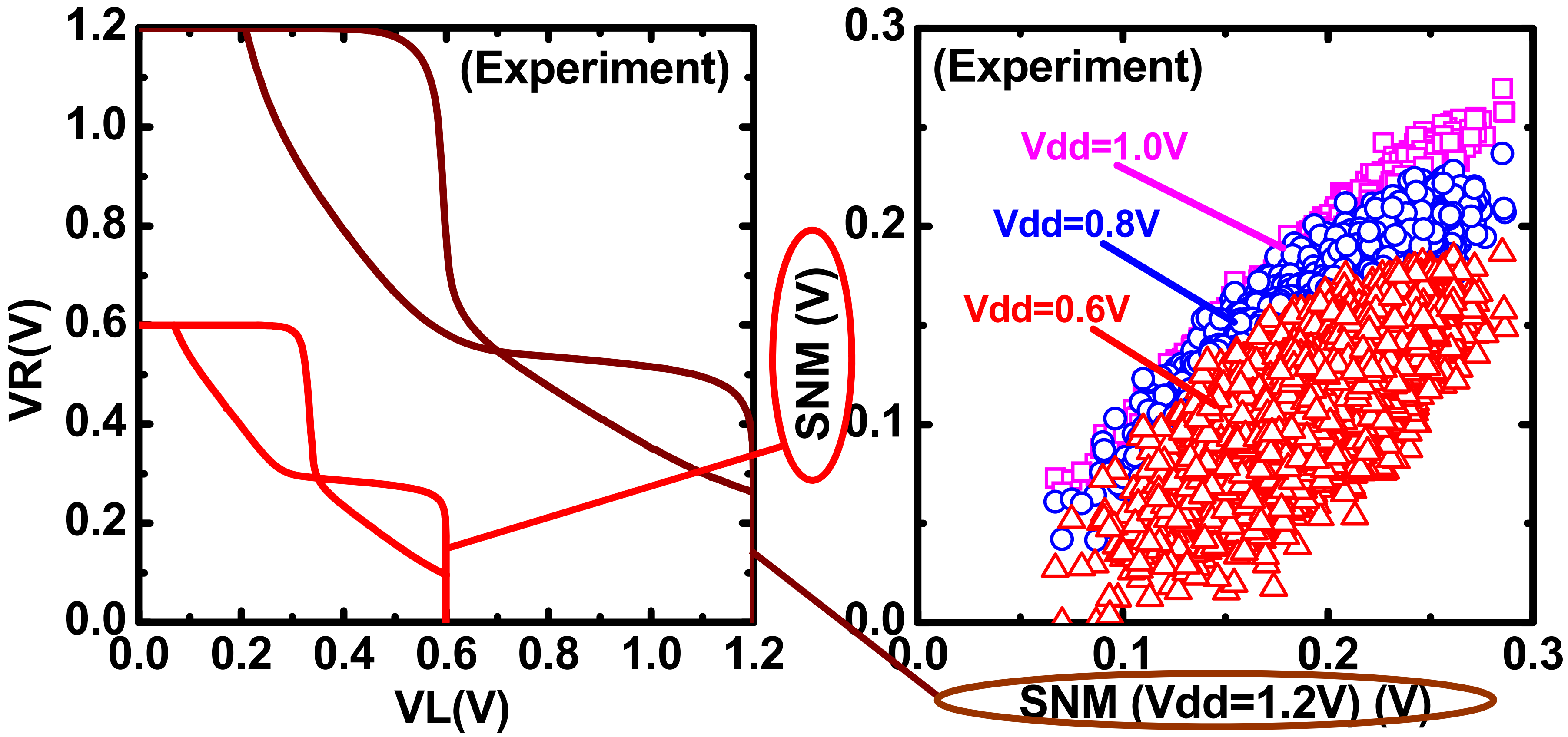
M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.

Correlation of SNM at Different Vdd



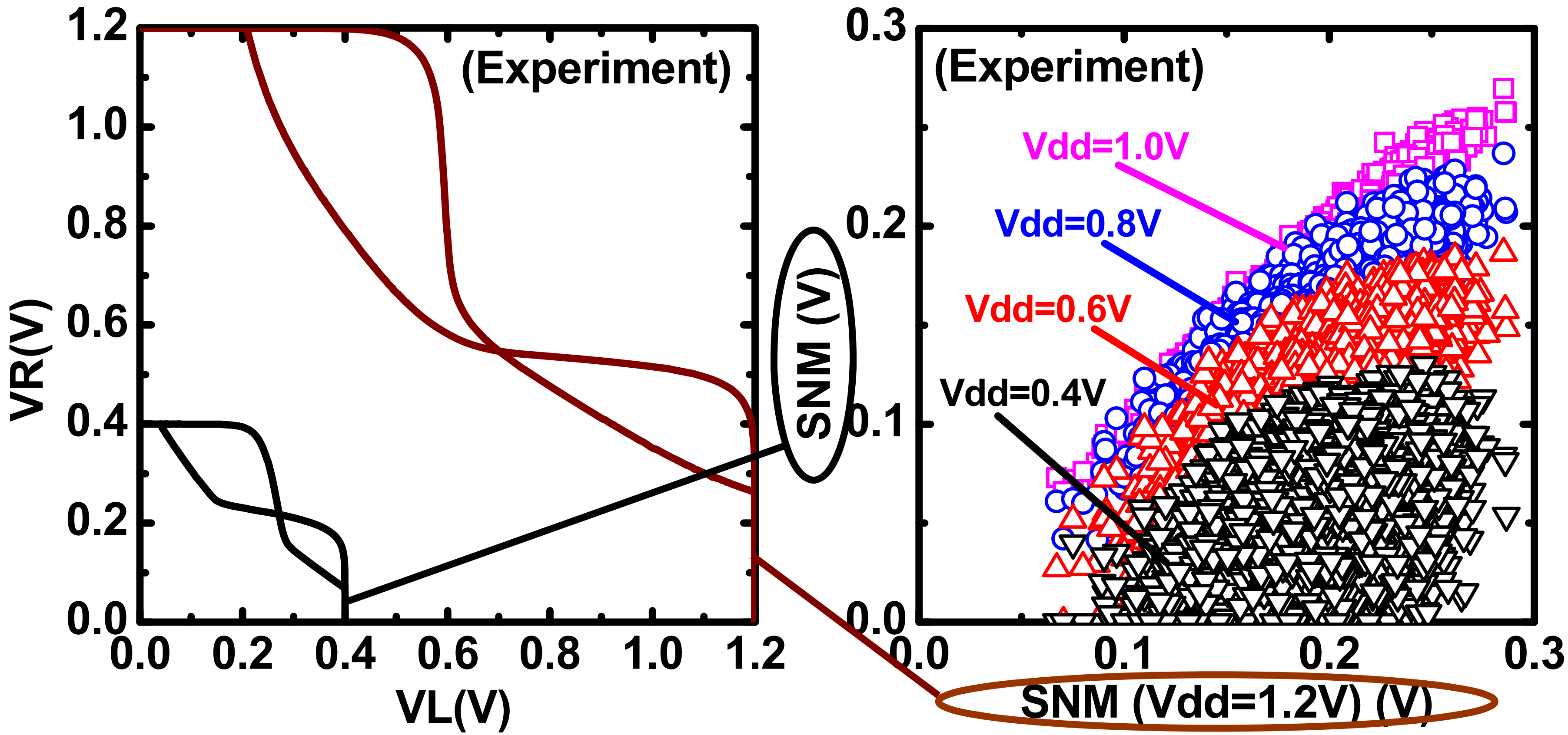
M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.

Correlation of SNM at Different Vdd



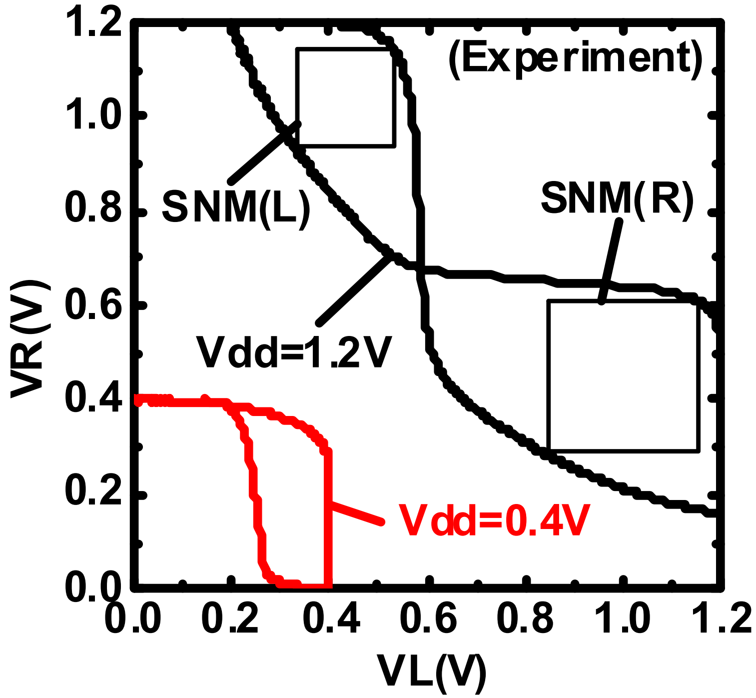
M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.

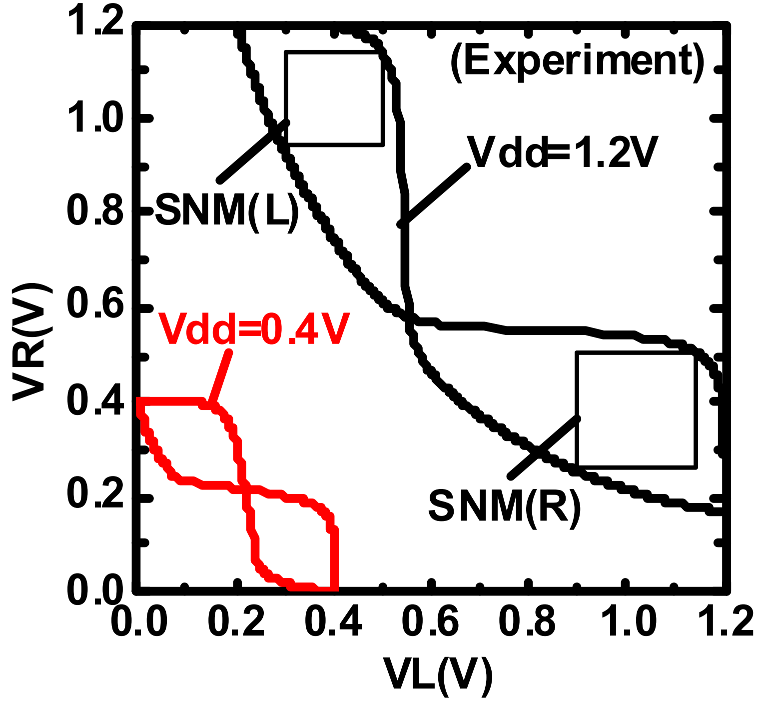
Correlation of SNM at Different Vdd



M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.

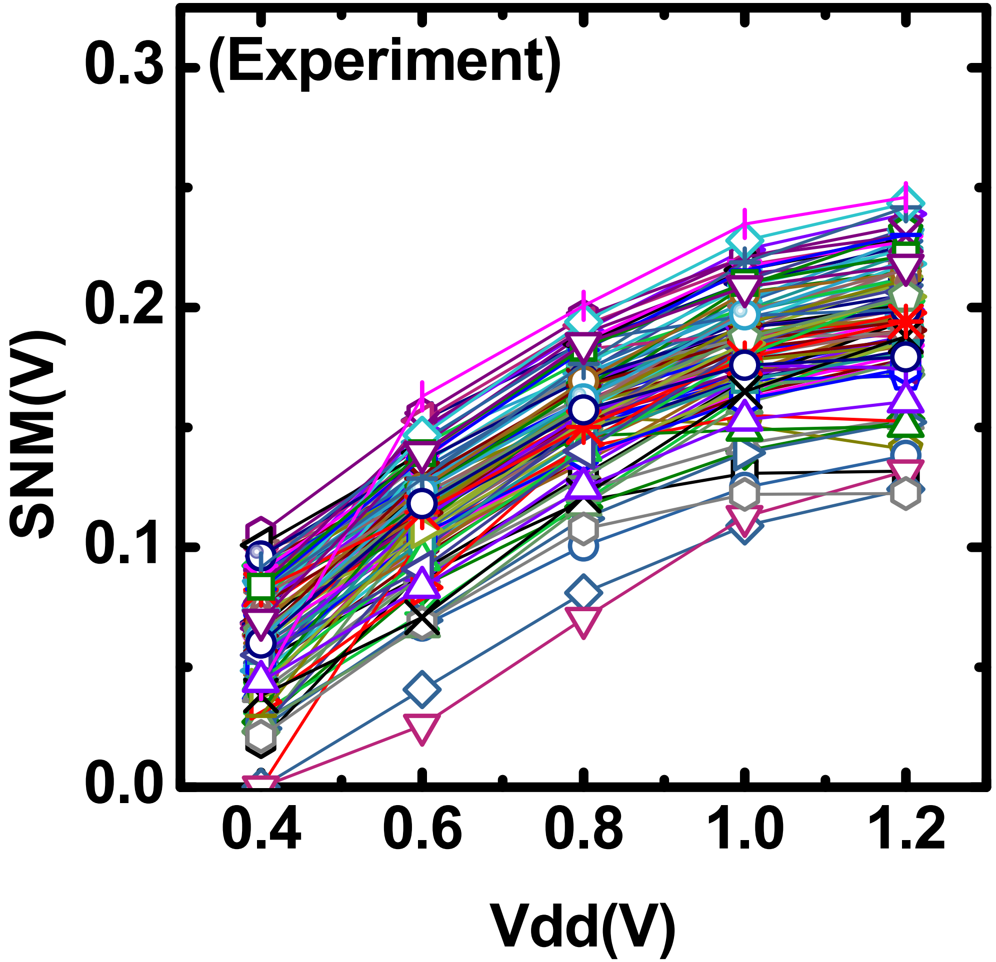
Two Cells with the Same SNM at 1.2V





M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.

Vdd Dependence of SNM



M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.

Simulation Using Measured Vth

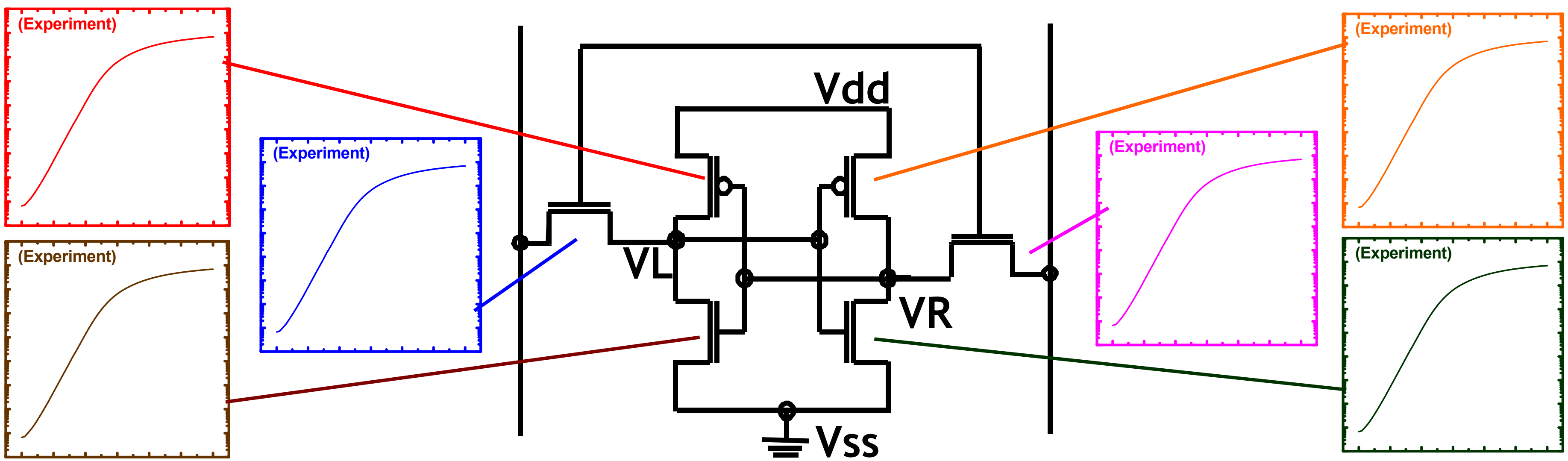
Measurement data

Measured Vth (CC method)

HSPICE Simulation

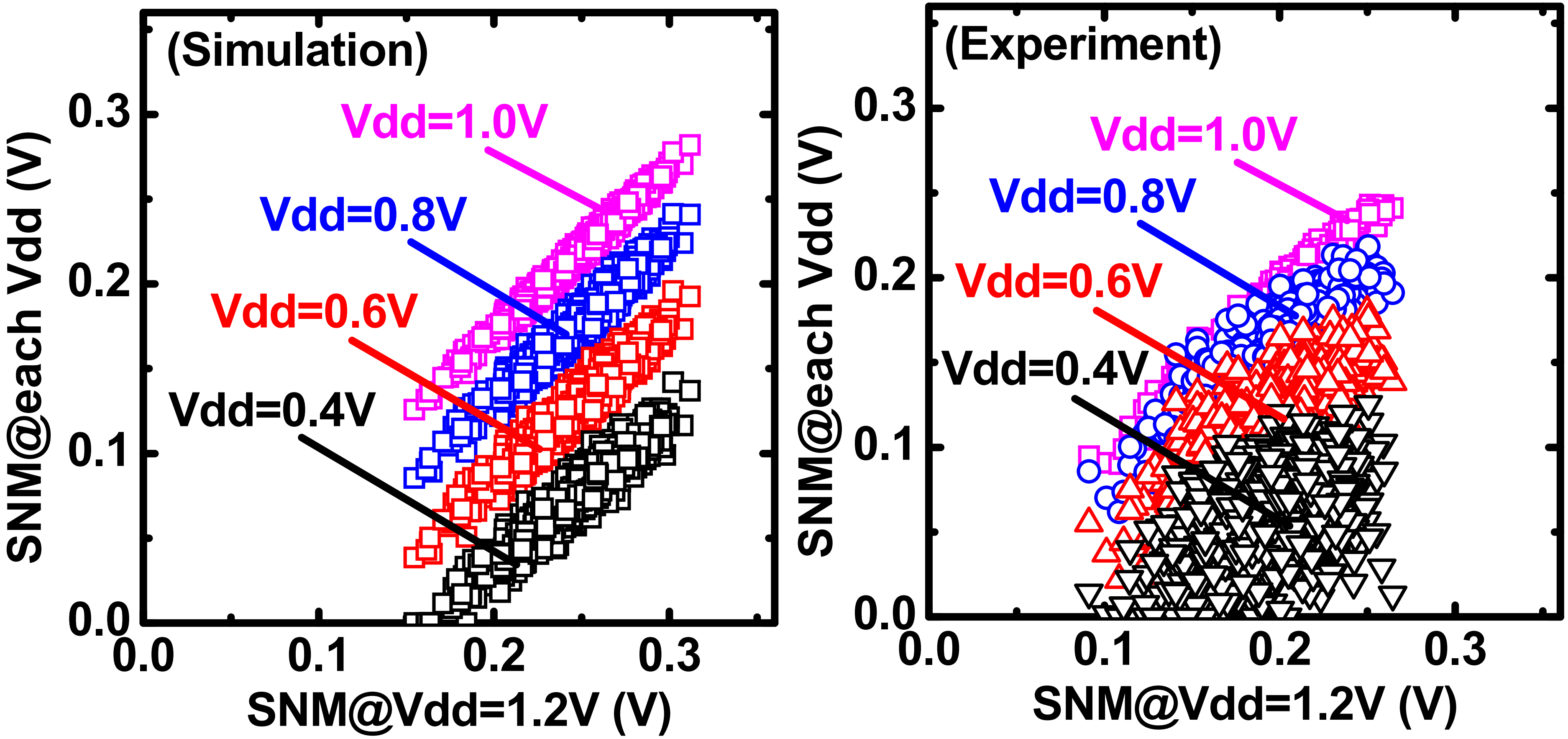
Measured Vth (CC method)

Calculation of SNM



M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.

Comparison between Sim and Meas (1k)



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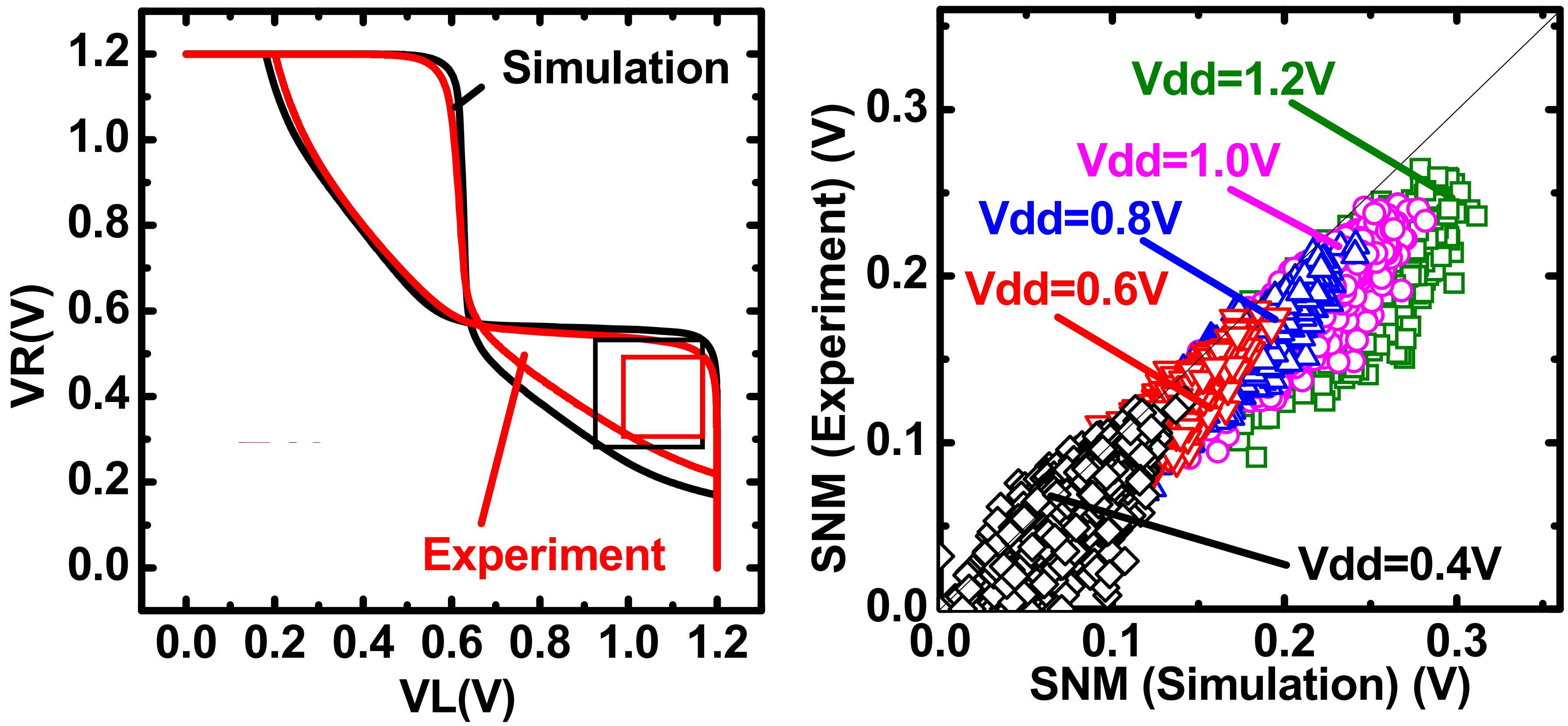
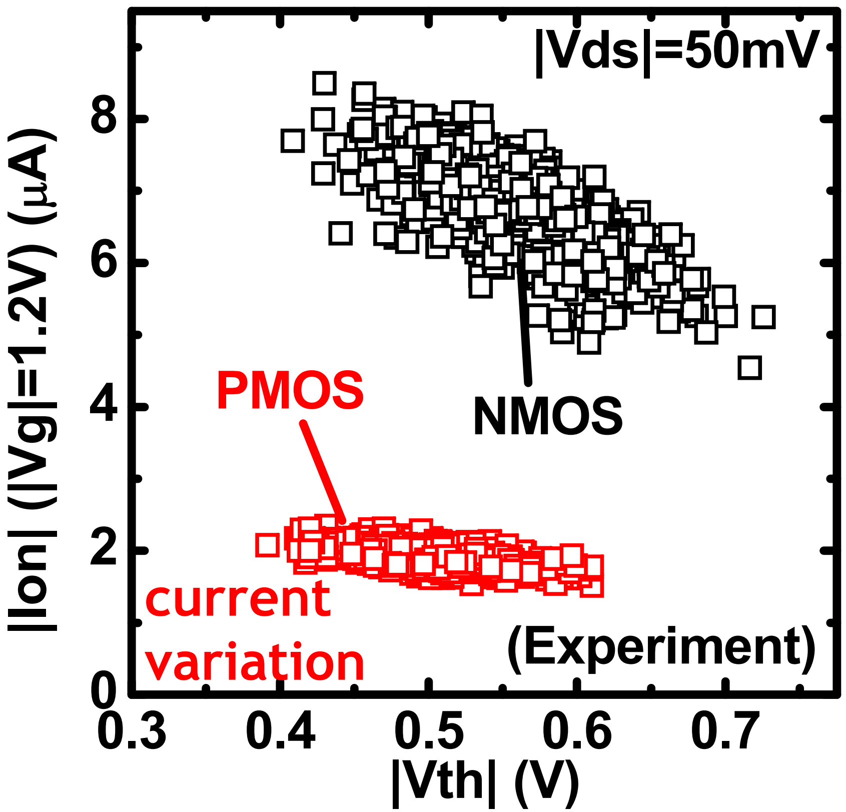
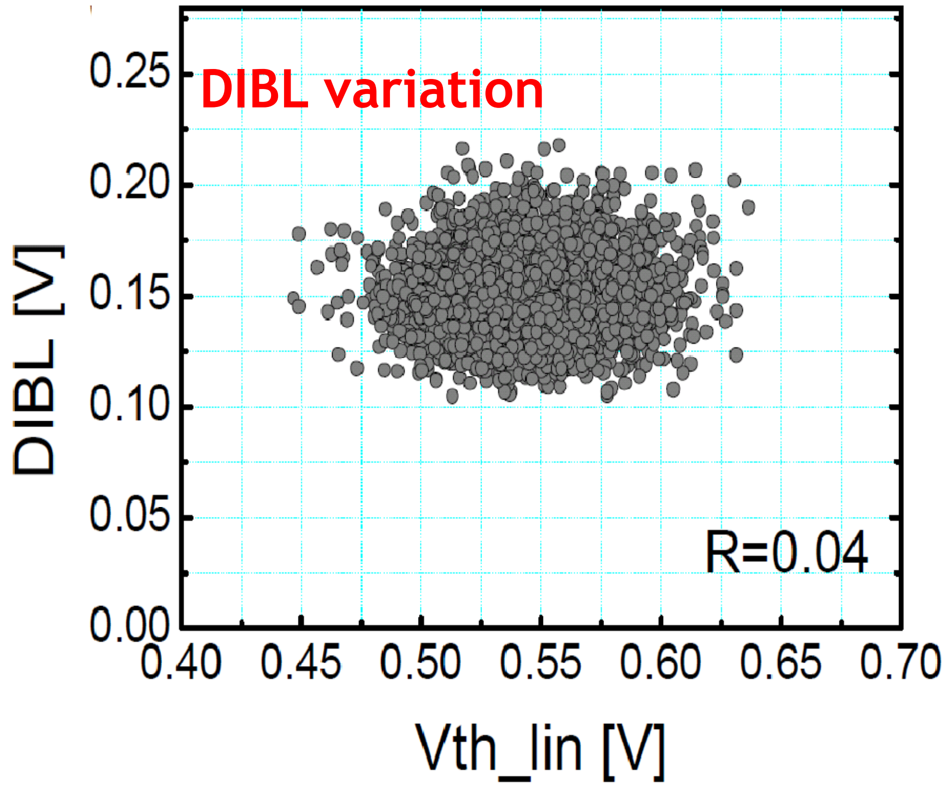


M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.

Reasons for Disagreement



M. Suzuki et al., VLSI Technology Symposium, p. 191, 2010.



M. Miyamura et al., IEDM, p.447, 2008.

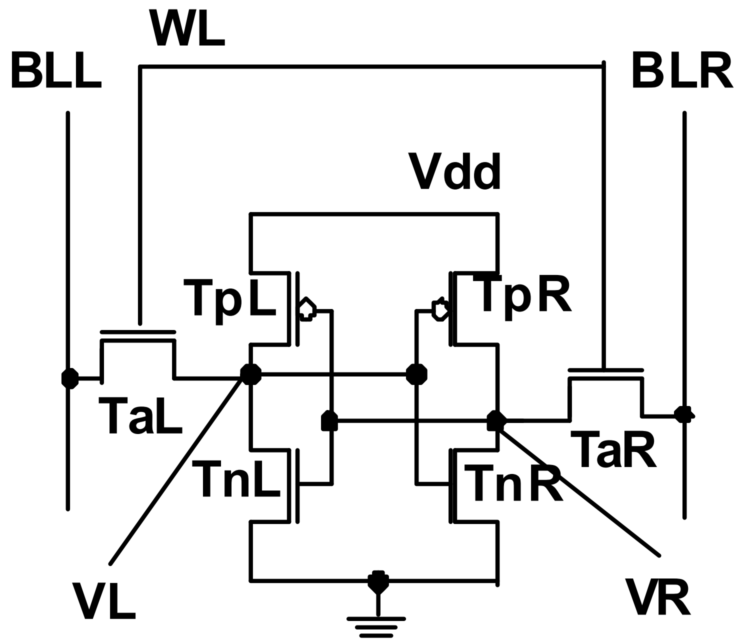
Reasons for Disagreement

(1) gm variability?

(2) DIBL variability?

(3) Body factor variability?

To be presented in 2010 IEDM



Summary

1. Drain current variability is caused by "Current Onset Voltage" Variability, which originates from potential fluctuation by RDF.
2. SNM and Vth of individual transistors are directly measured by SRAM DMA TEG. SNM variability is not explained by the Vth variability alone.

This work is performed in the MIRAI-Project supported by NEDO.