ICCAD Workshop, Austin, 2015

Too hot to handle? The emerging Challenge of Reliability/Variability in Self-heated FinFET, ETSOI, and GAA-FET

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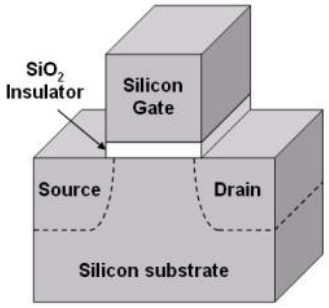
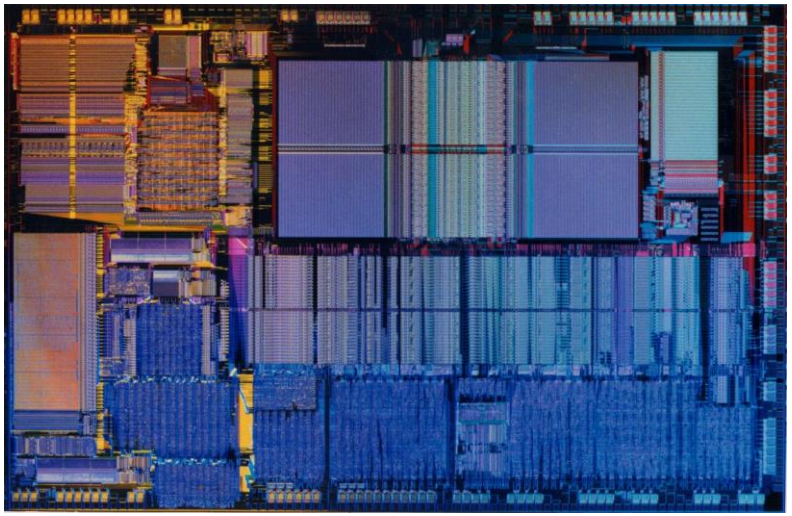
Uniformity of Components in Large Systems

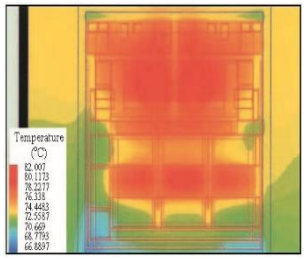


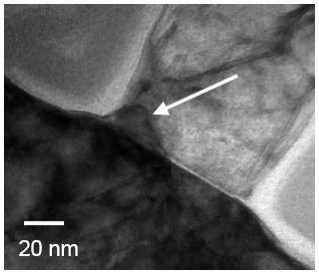


Building large systems presumes uniformity of components ….

Process, Reliability, and Design

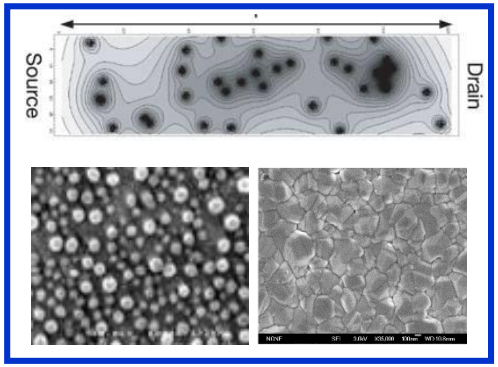
Reliability

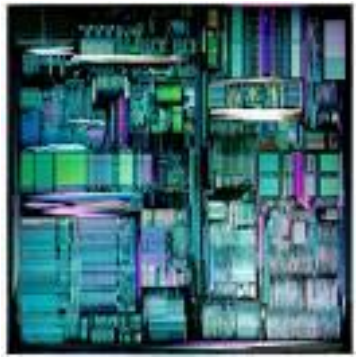


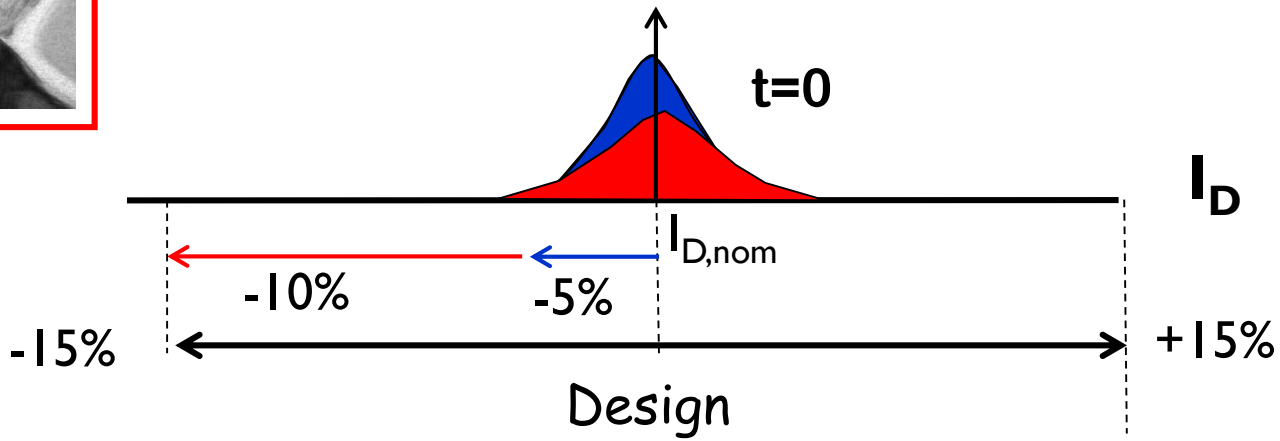


plus

Process







We do not have too much margin …

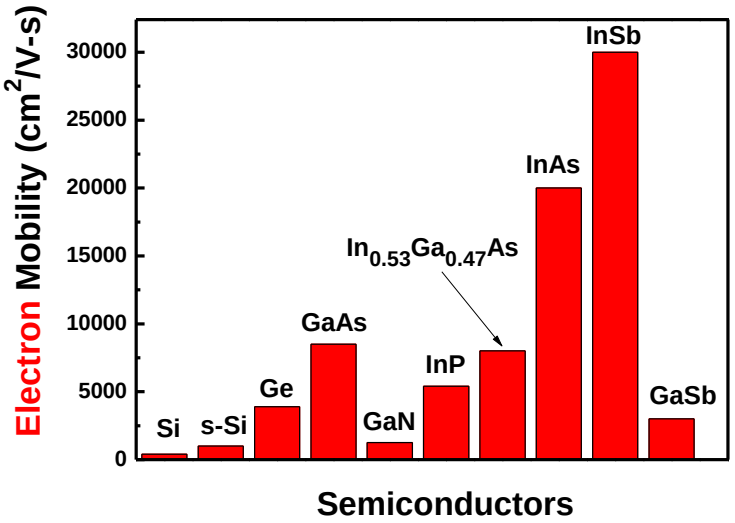
Outline

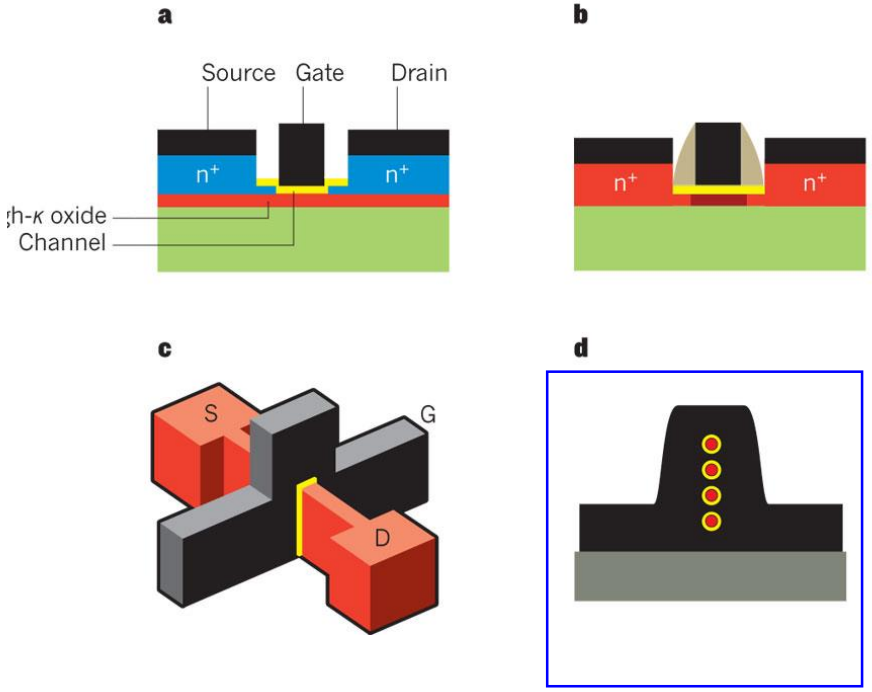
- Background: Variability/Reliability in Planar Transistors
- Self-heating in SG-FETs: An Emerging Issue
- Channel Width/Length dependence
- Reliability correlated to Variability: New Channels for MOSFET Degradation
- Conclusions

Emergence of Surround Gate Transistors Technologies

$$I_{on} \propto C_{ox}\,\mu_n\,(V_G - V_T)$$

$$I_{off} \propto I_o e^{\frac{q(V_G+\eta V_D)}{kT}}$$



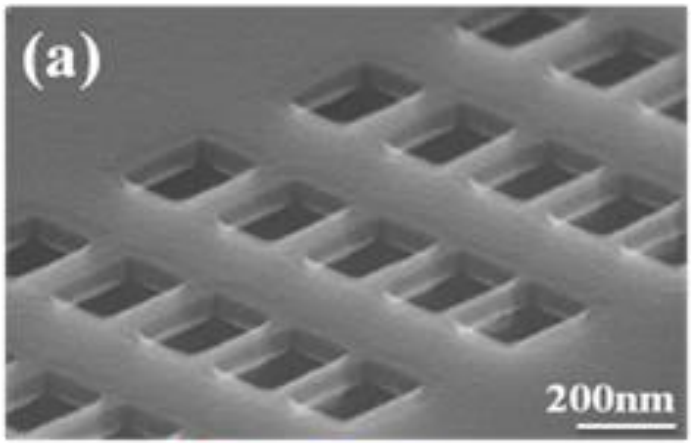


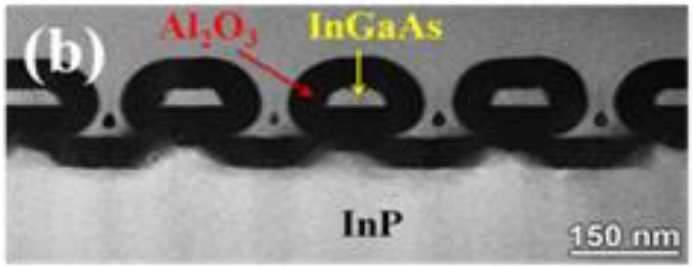
Extraordinary mobility

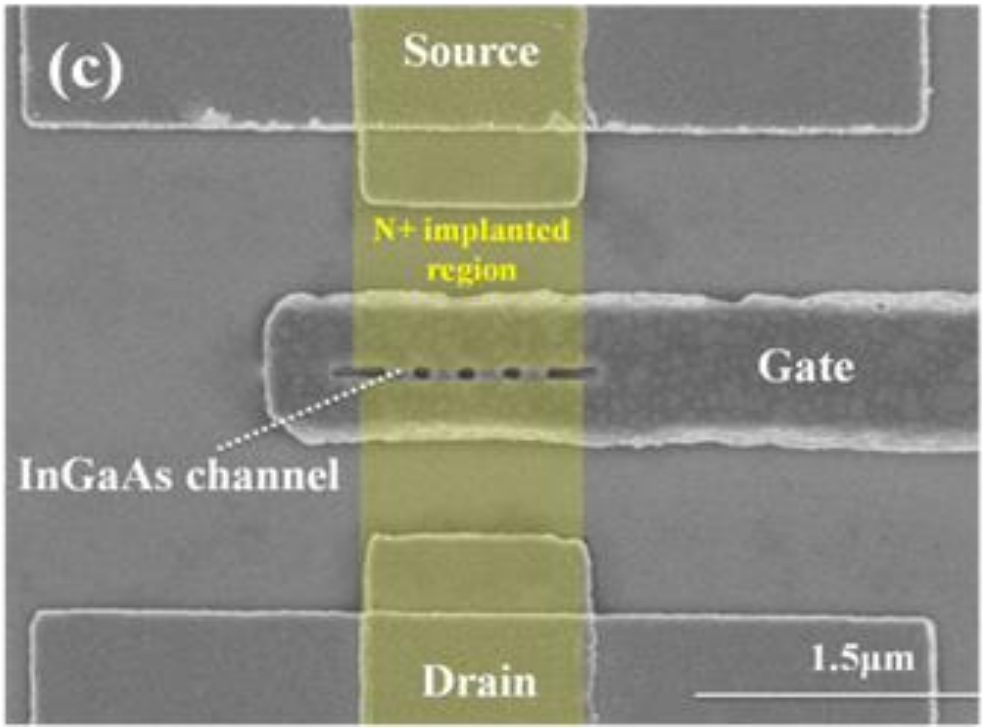
Excellent gate control

A Very High Performance MOSFET

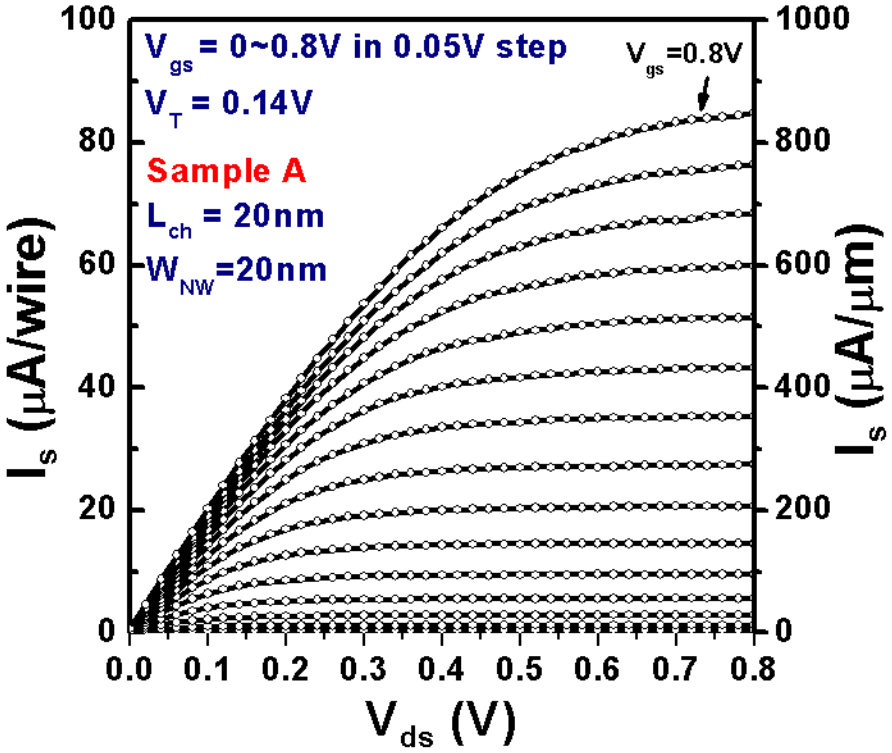
Jiangjiang Gu, IEDM 2012

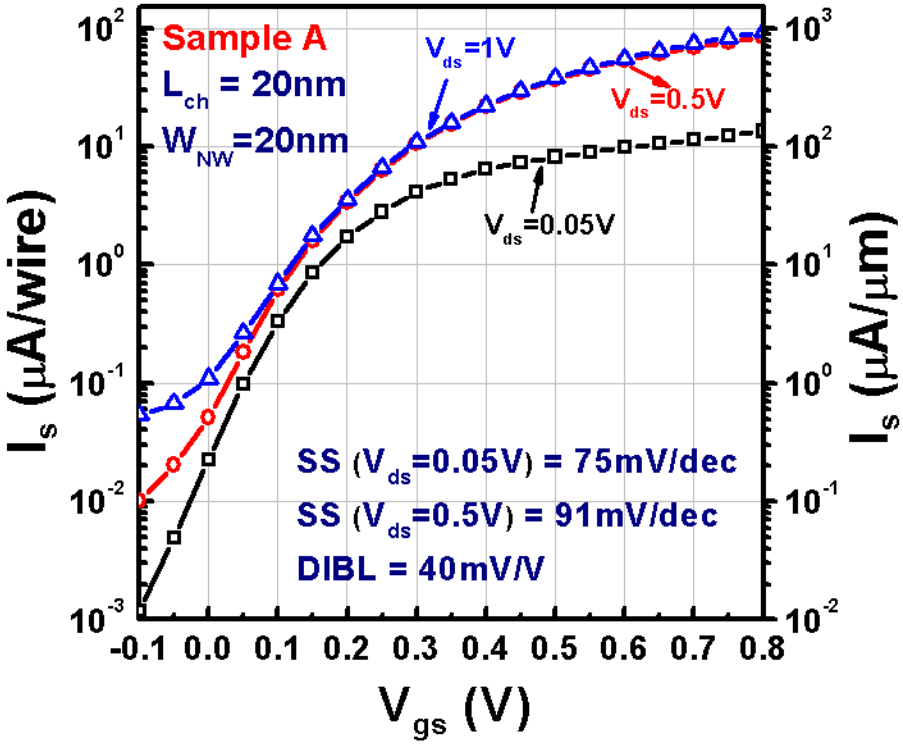






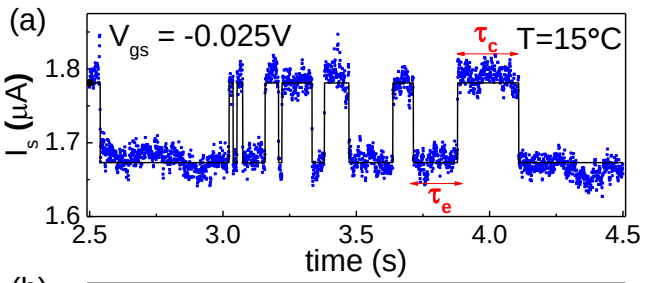
Performance is classical …



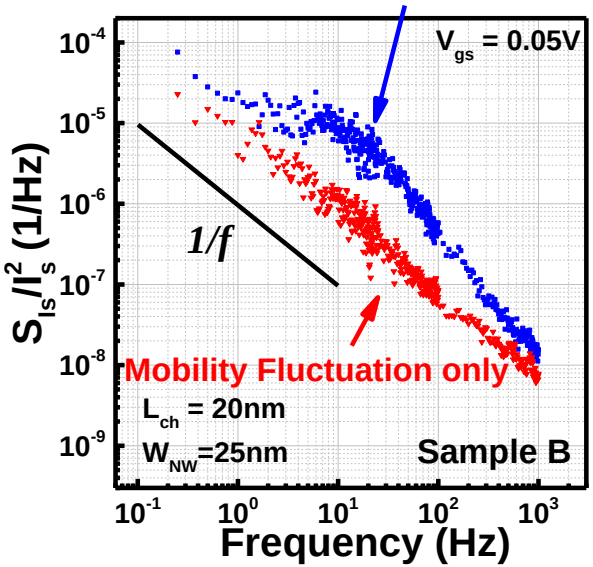


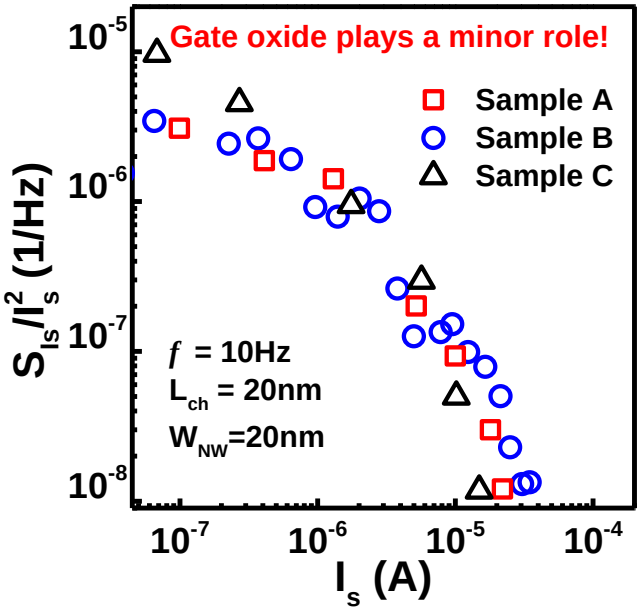
- Lch=20nm, EOT=1.2 nm,
- I_{ON} = 0.57mA/μm, g_m = 1.65mS/μm @ $V_{ds} = V_{gs} - V_T$ = 0.5V
- SS = 75mV/dec, $DIBL$ = 40mV/V, $V_{T,lin}$ = 0.14V

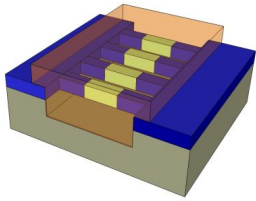
… with good noise performance

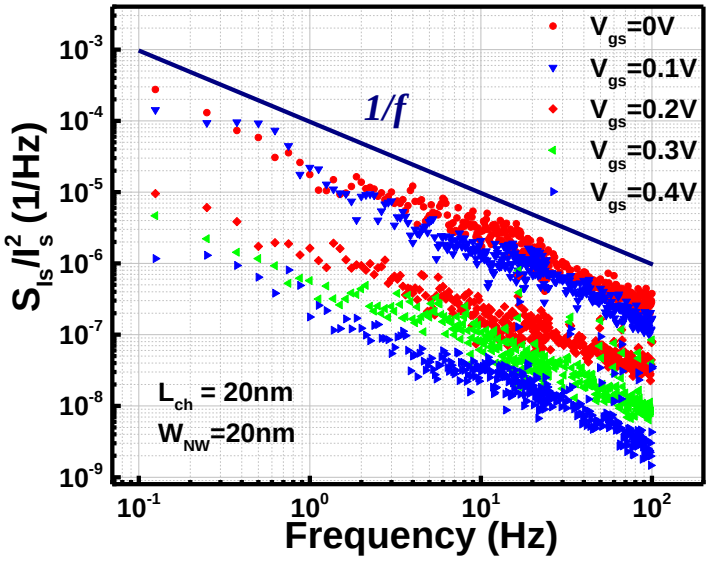


(RTN+Mobility Fluctuation)



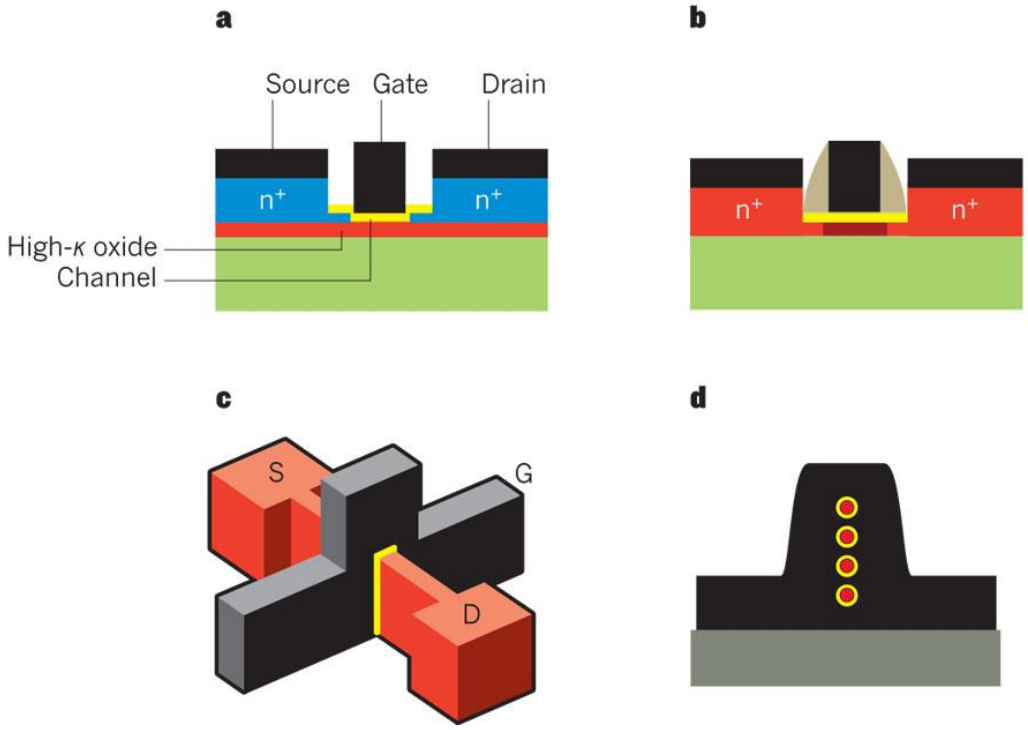




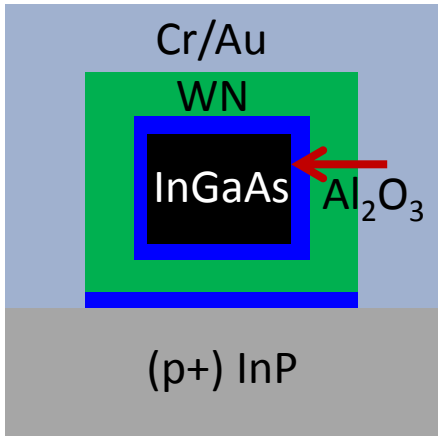


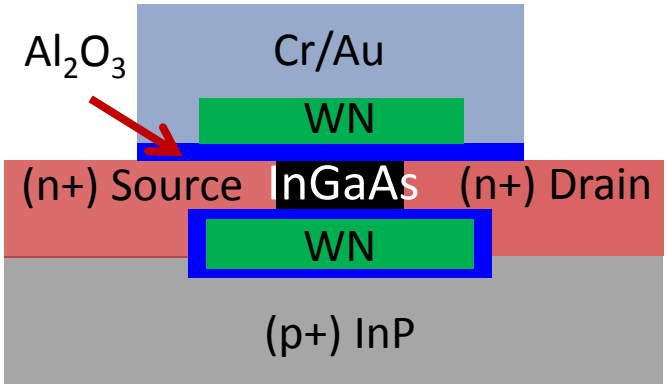
Power vs. self-heating

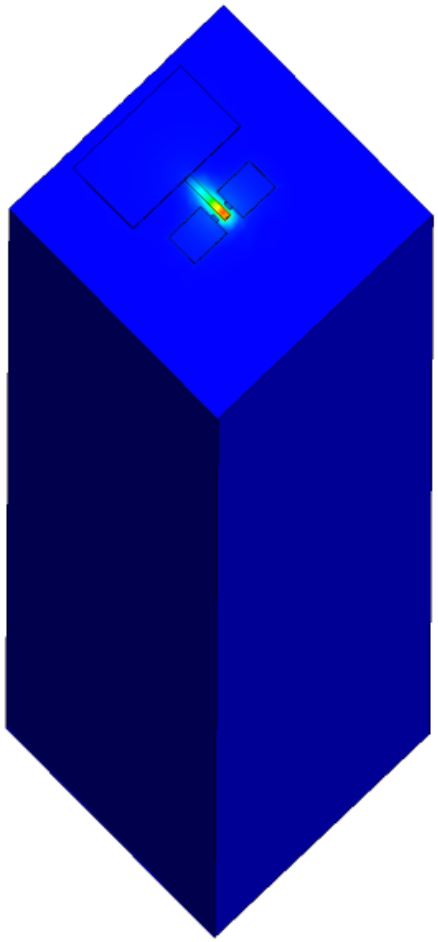
$$\Delta T \equiv T - T_a = P \times R_{th}$$

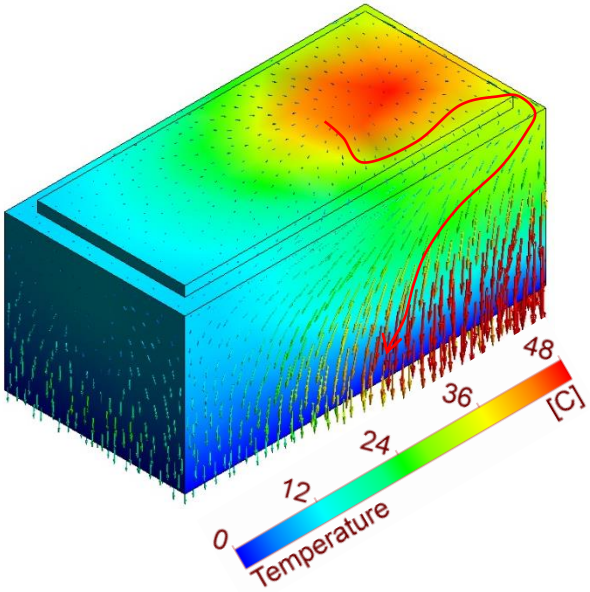


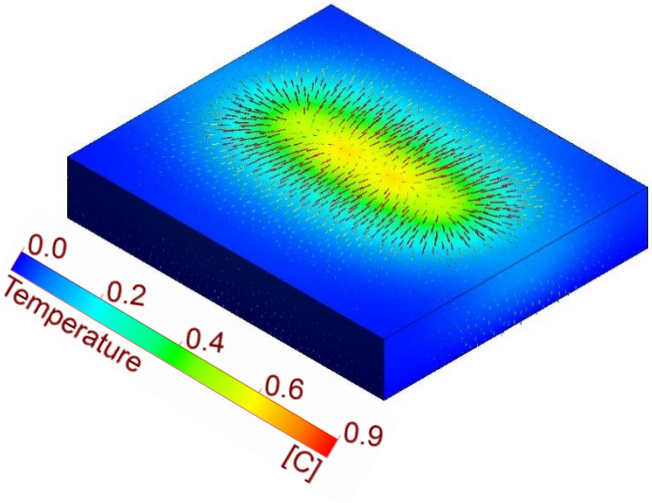
Process complexity & Thermal Bottleneck





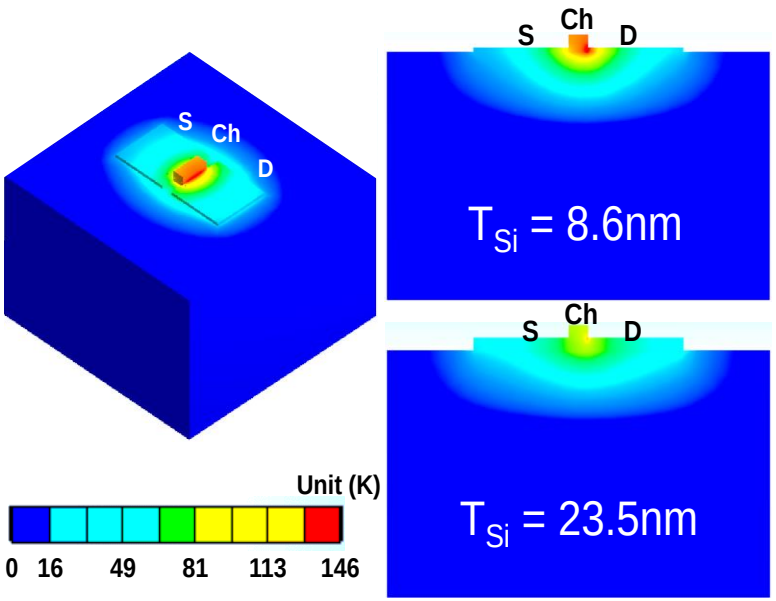




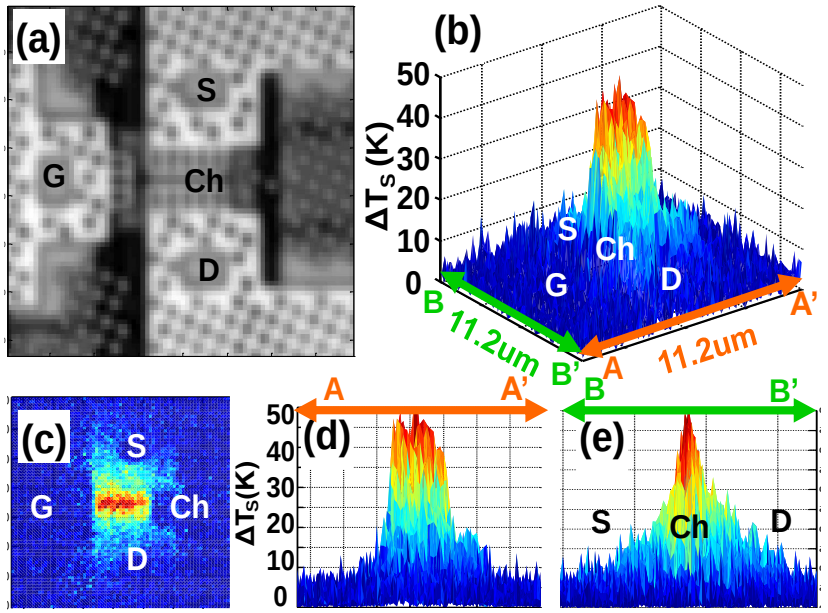


Self-heating and body thickness

Simulation

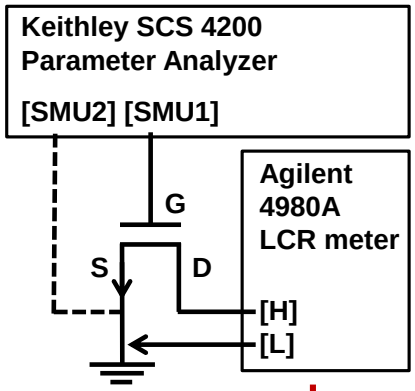


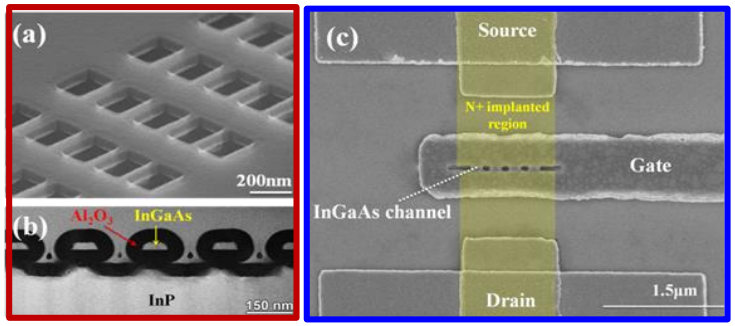
Experiment

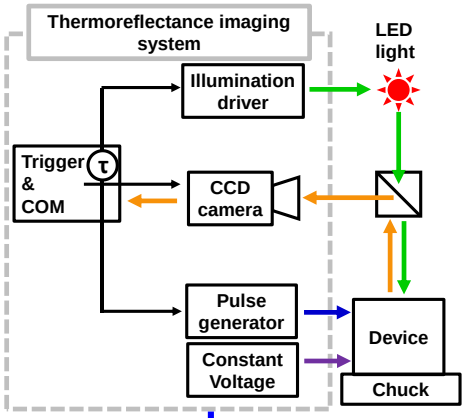


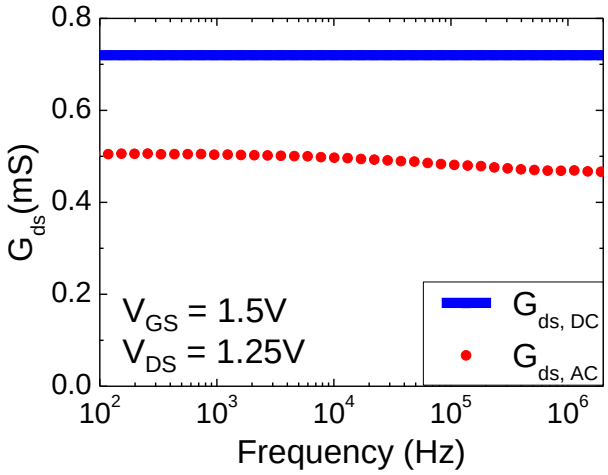
$$\Delta T \equiv T - T_a = P \times R_{th}$$

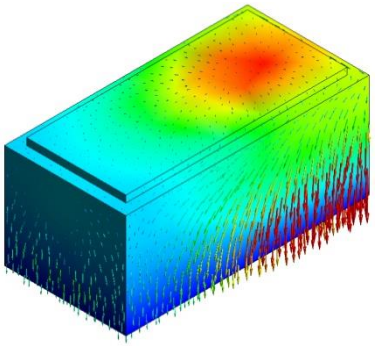
3D Mapping of Self-heating



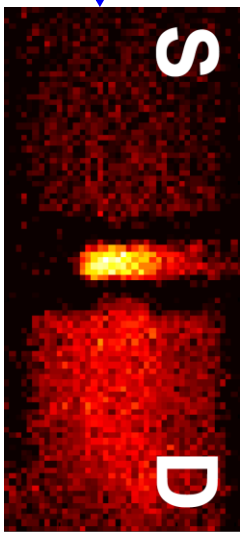






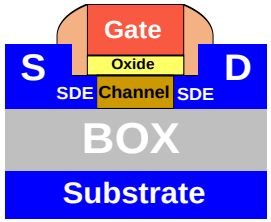


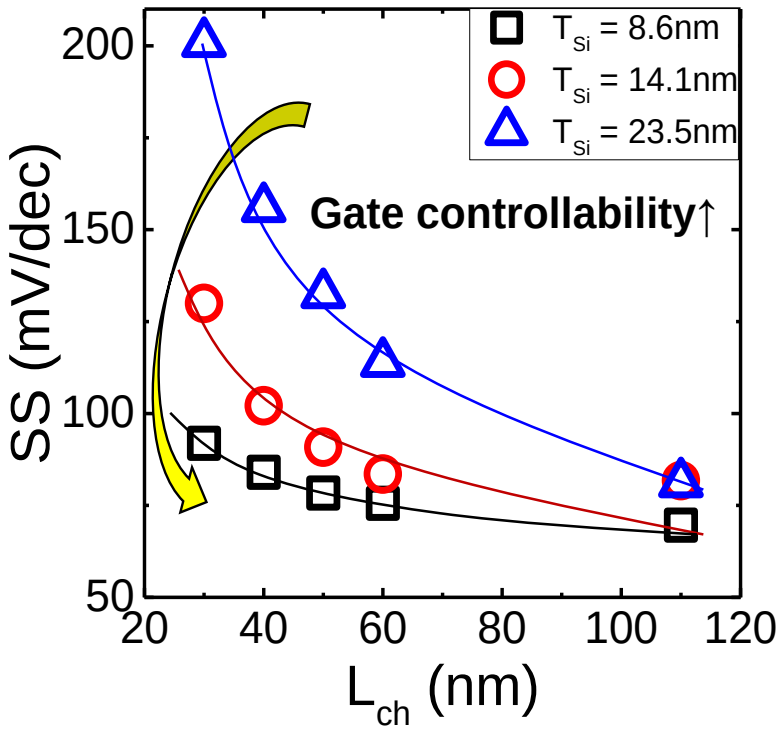
Correlate by modeling

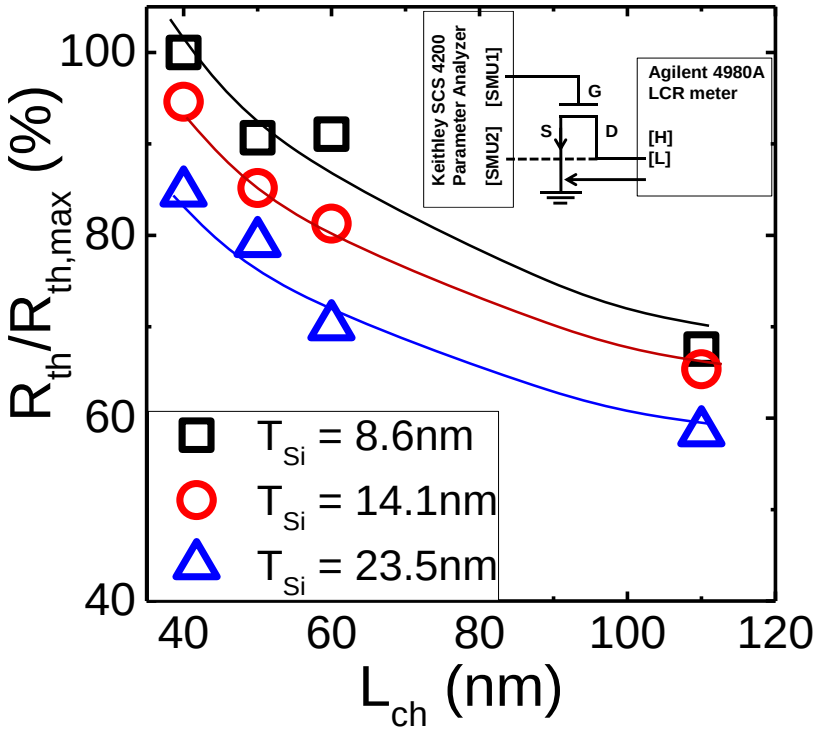


Wei Jin, TED '01, Shin, IEDM '13, Wahab, TED, 2015

Gate control vs. self-heating







Improved SS comes with higher R_{th}

Outline

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- Self-heating in SG-FETs: An Emerging Issue
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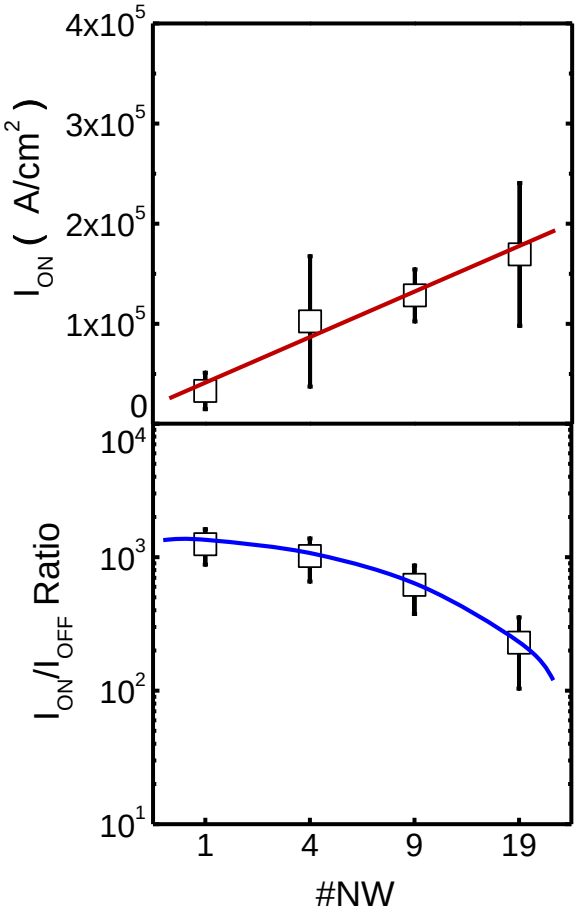
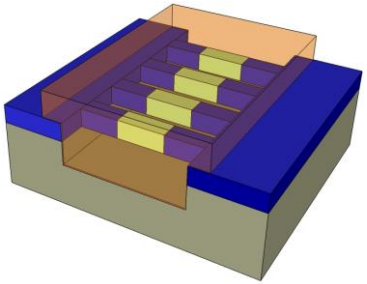
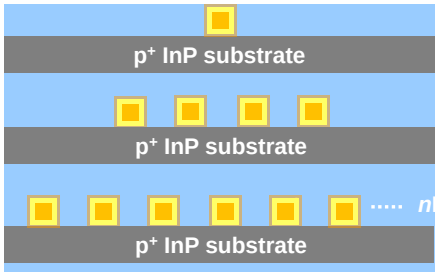
- Reliability correlated to Variability: New Channels for MOSFET Degradation
- Conclusions

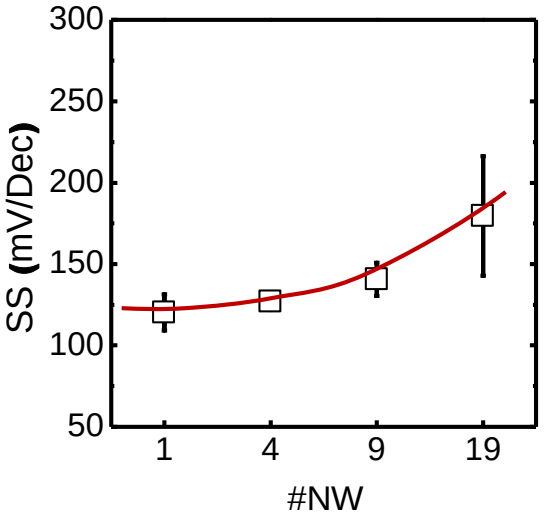
What is wrong with this picture ?

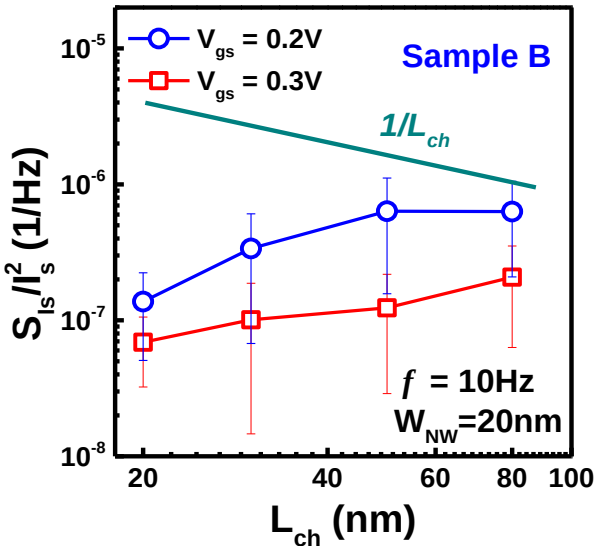
(1) On current does not scale ….







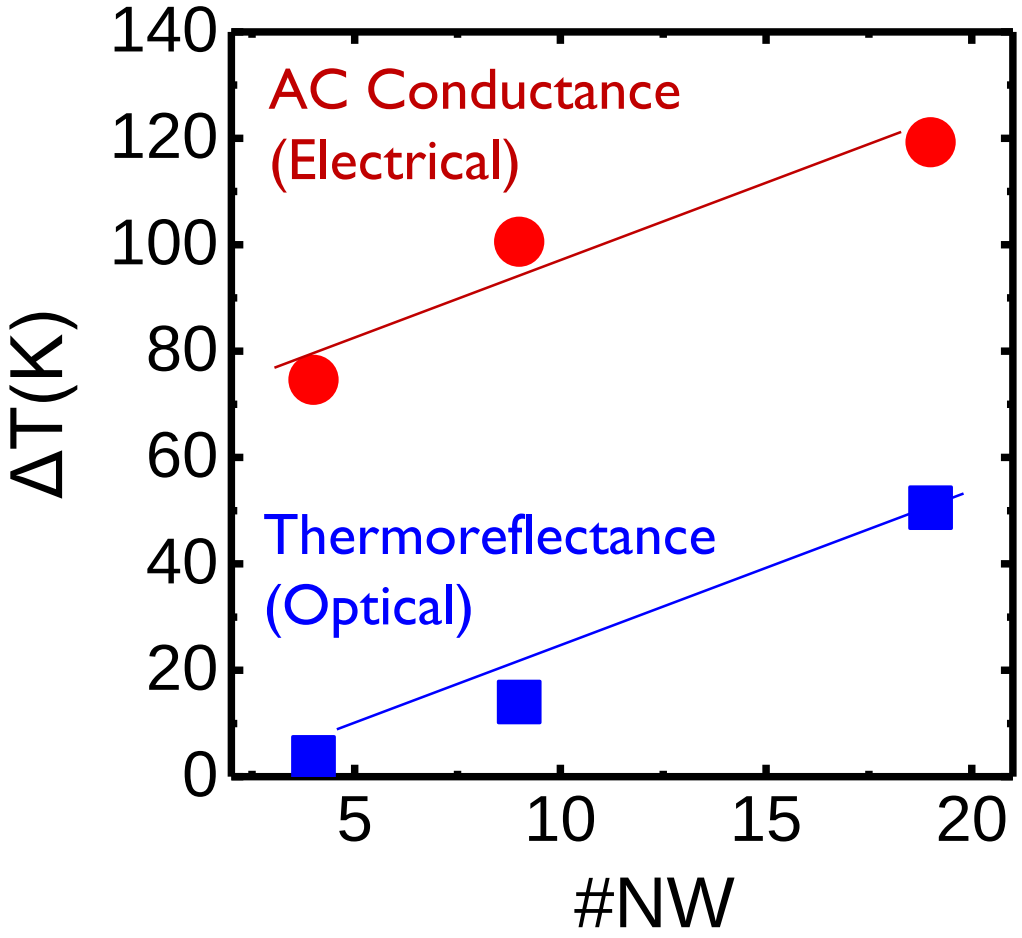


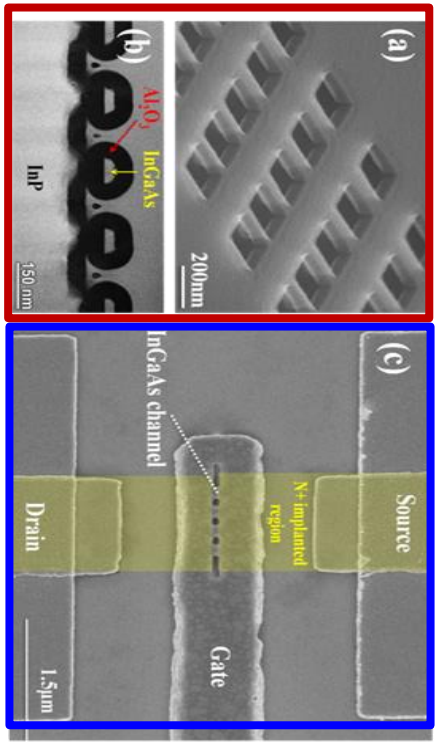


(2) Variable on/off ratio & SS slope..

(3) Noise reduces with Lch!

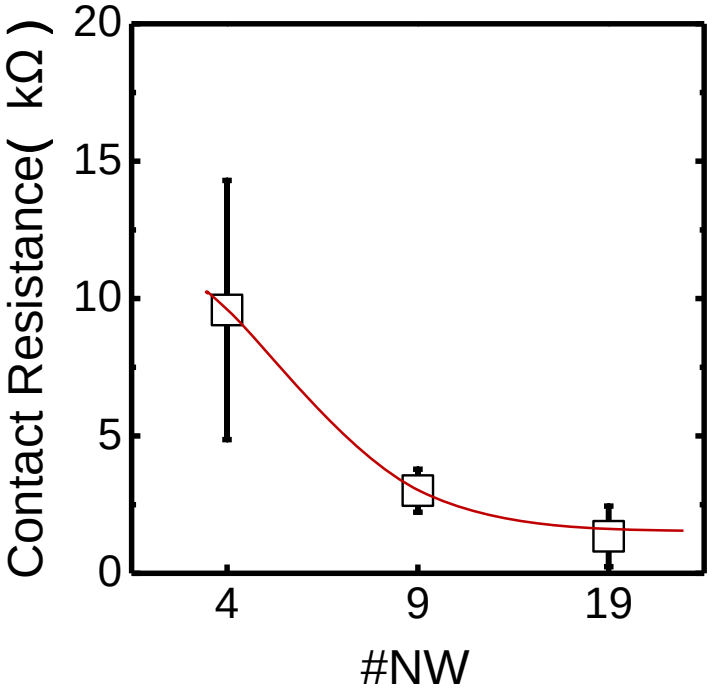
Evidences of Significant Self-heating

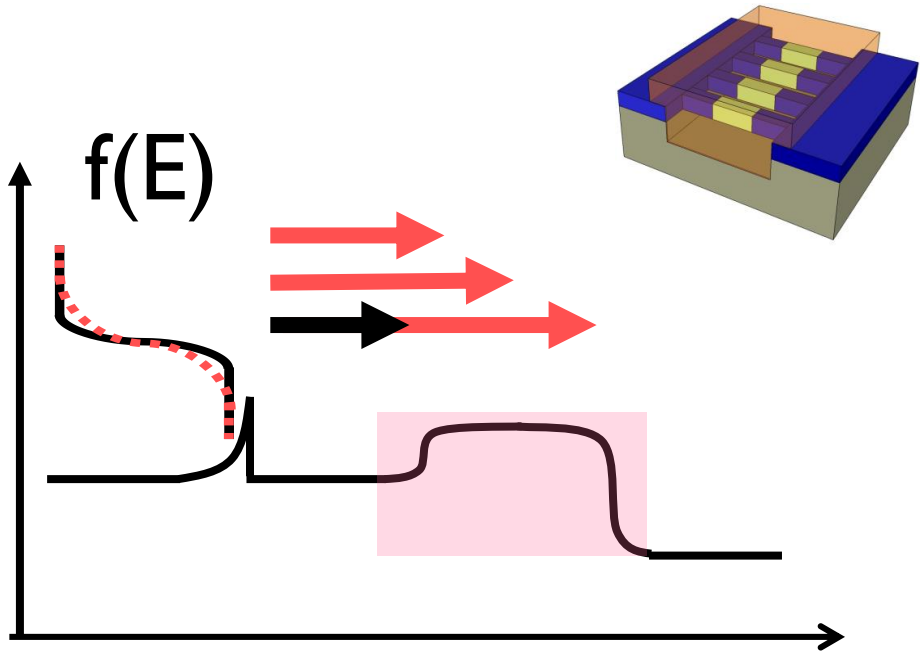




(4) Self heating (80-120), Surface T = 60-70 lower. Why?

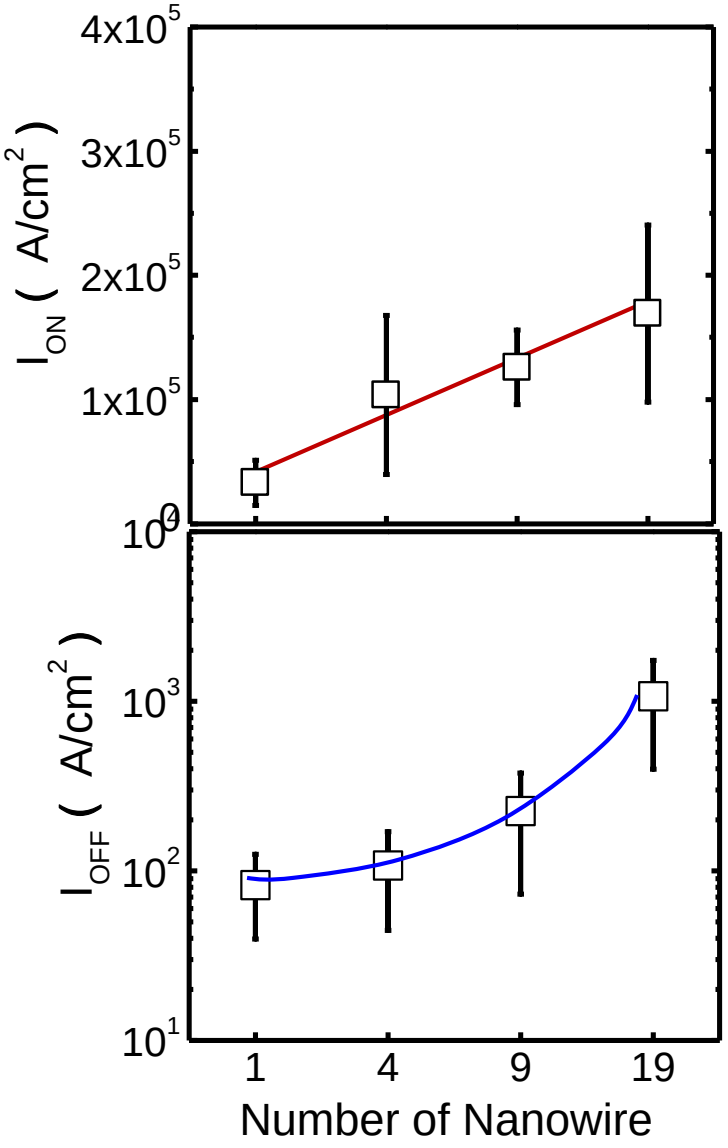
Self heating reduces series resistance!

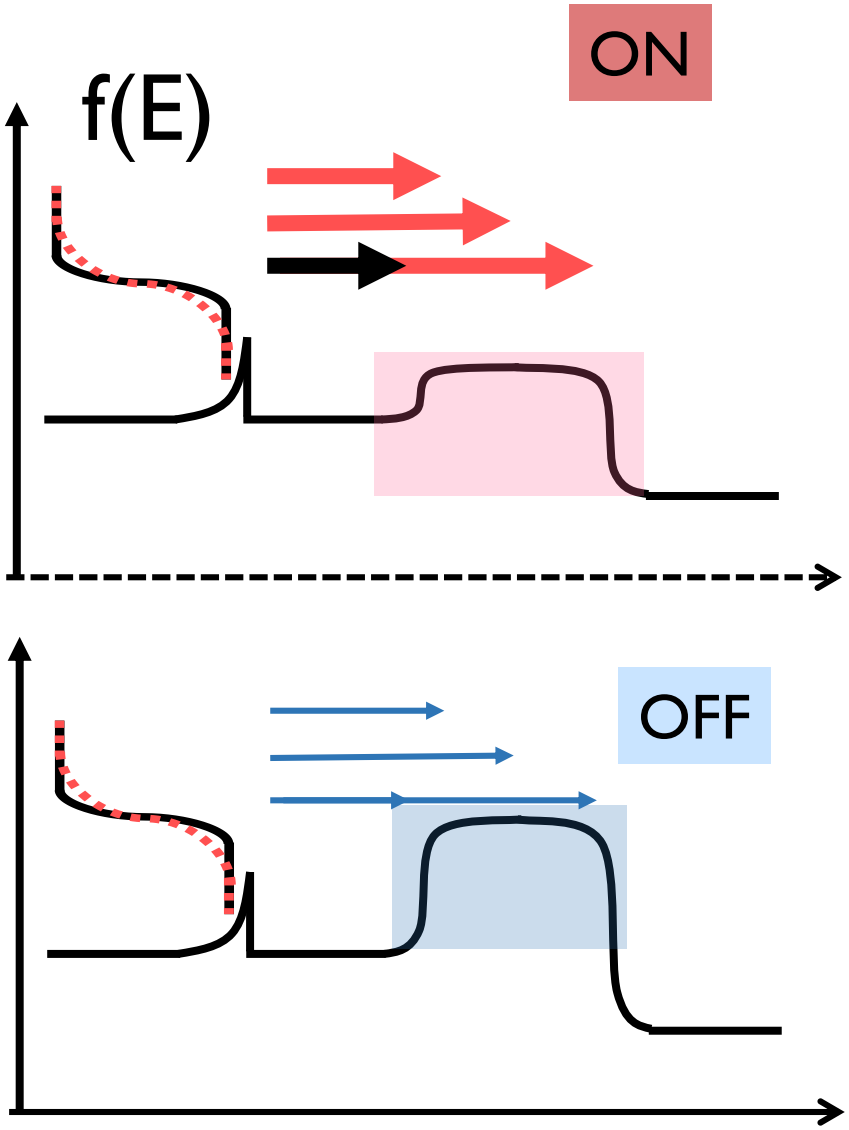




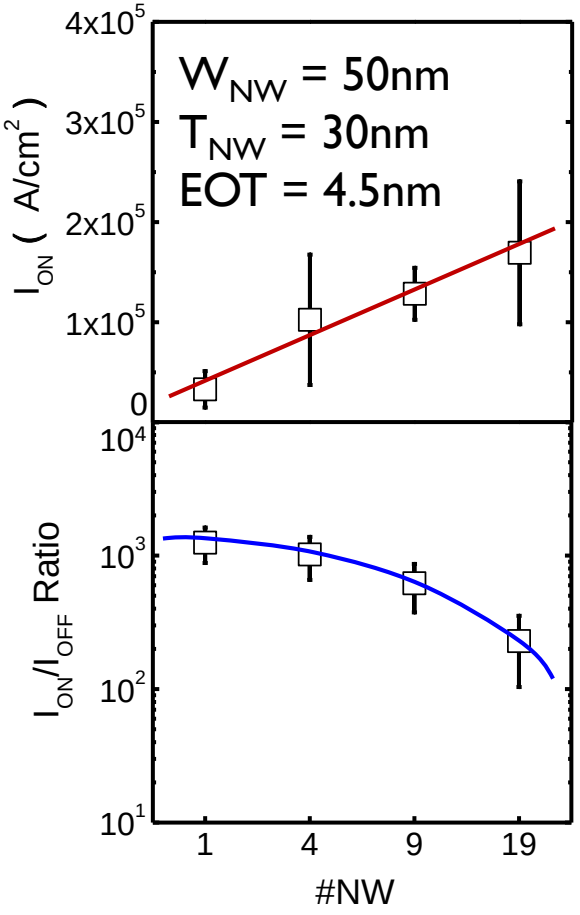
- Self-heating improves performance by reducing R_C, and hence improves Ion.
- Temperature dependence of channel resistance has the opposite sign.

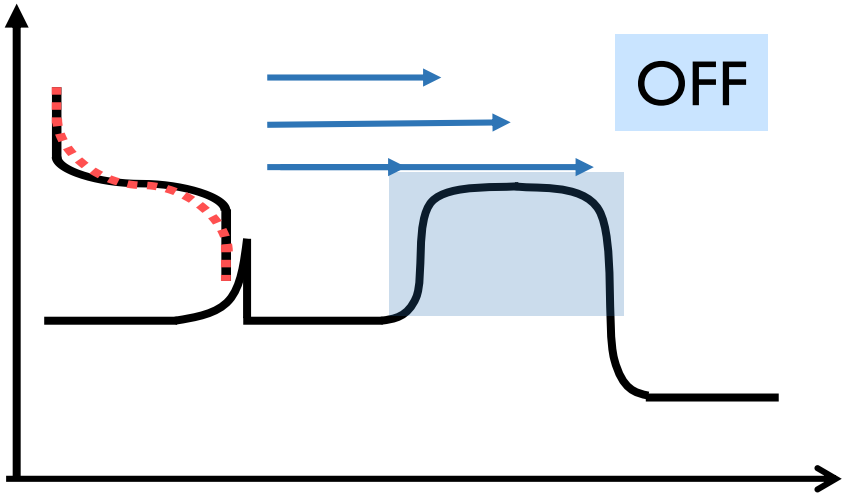
Self-heating for On & Off currents

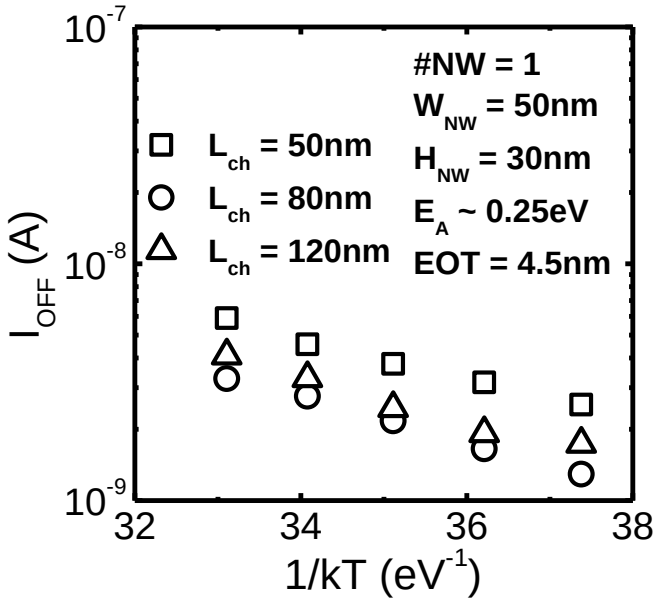




Self-heating explains on/off puzzle

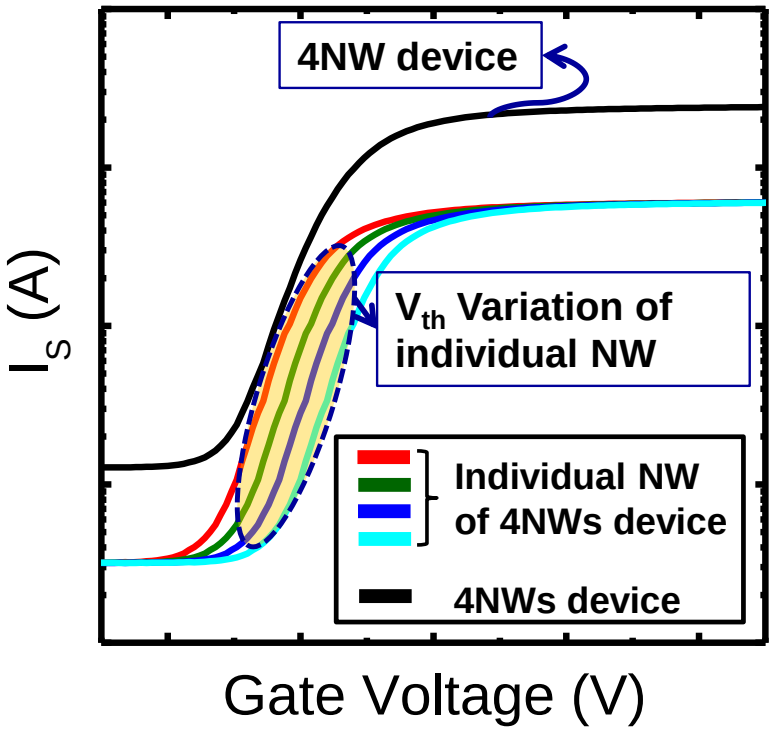


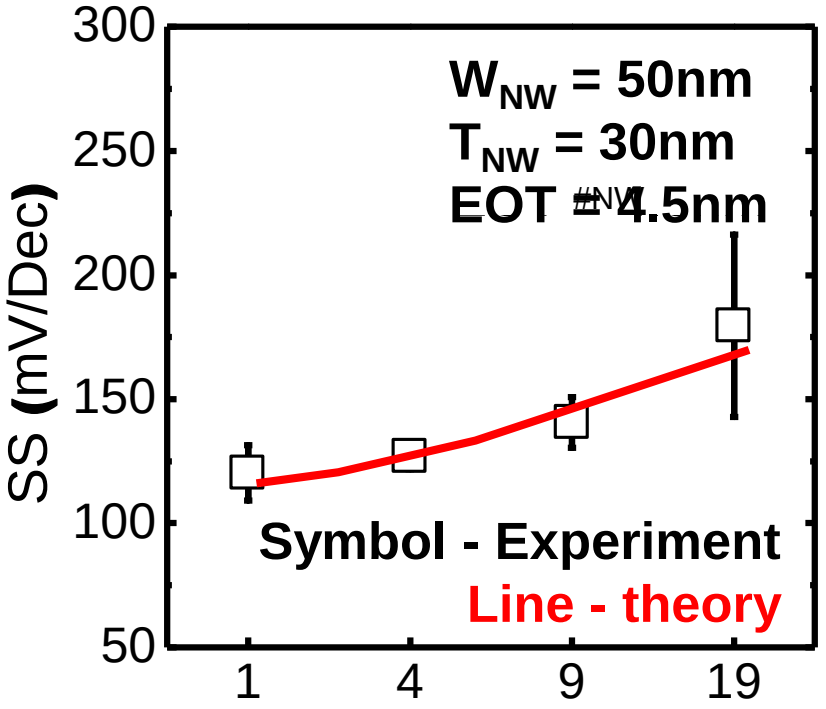




Variable on off ratio ..

SS depends on Variability/Self-heating





- I_S-V_{gs} of 4NW = summation of 4*(I_S-V_{gs} of 1NW)
- 4NW with variability of V_{th} → Widening I_s-V_{gs}
- SS increases with Variability & Self heating

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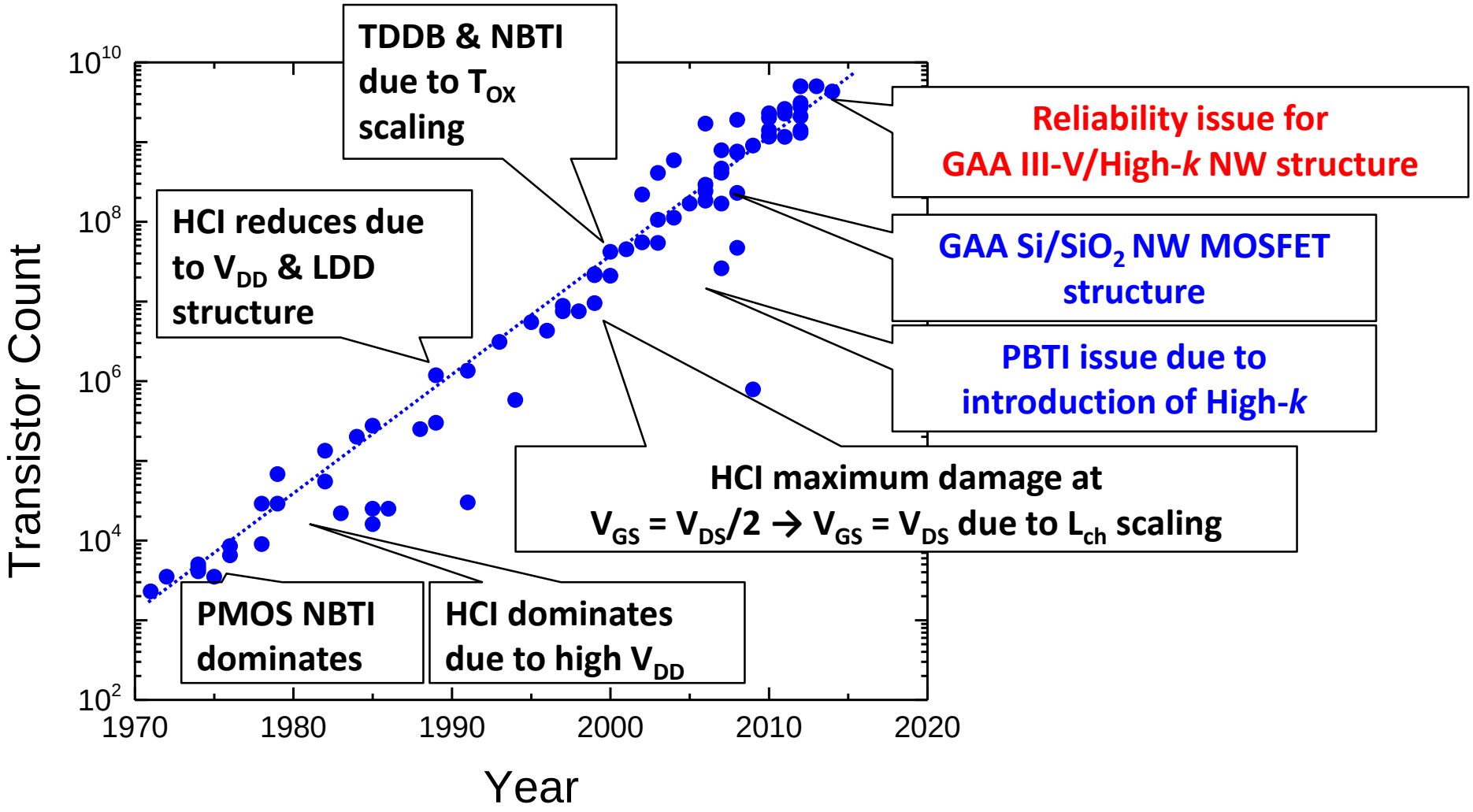
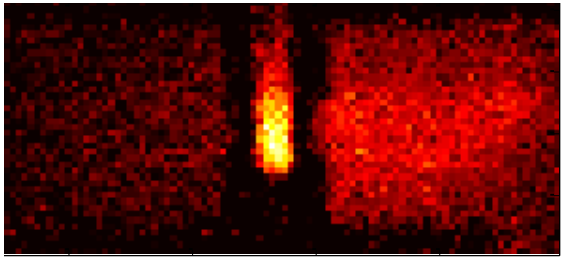
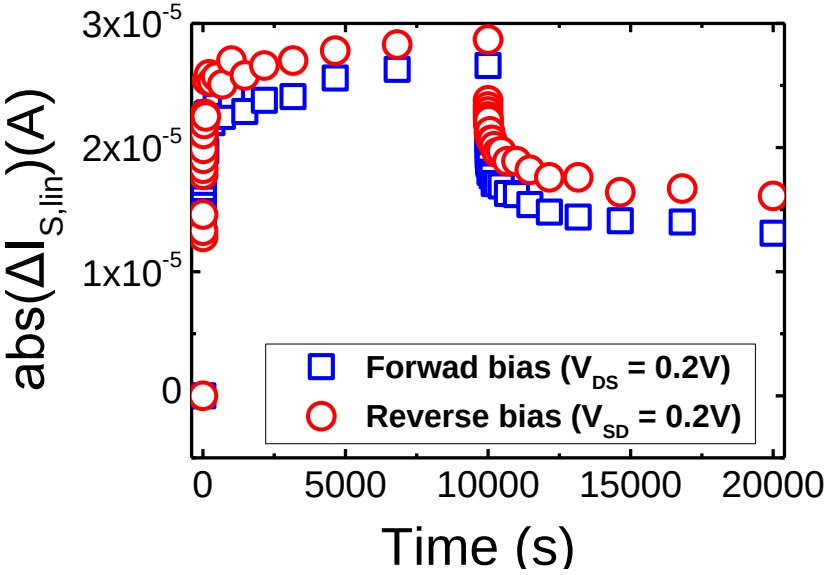
A Short History of Reliability

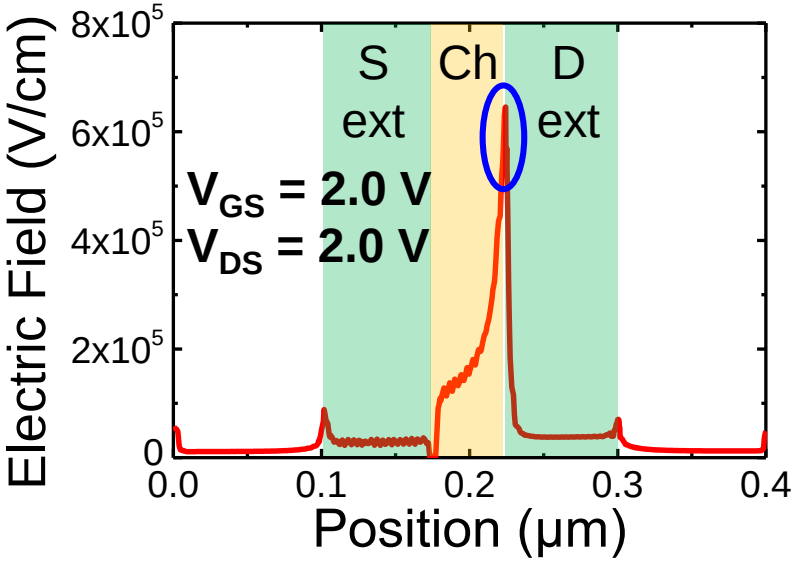


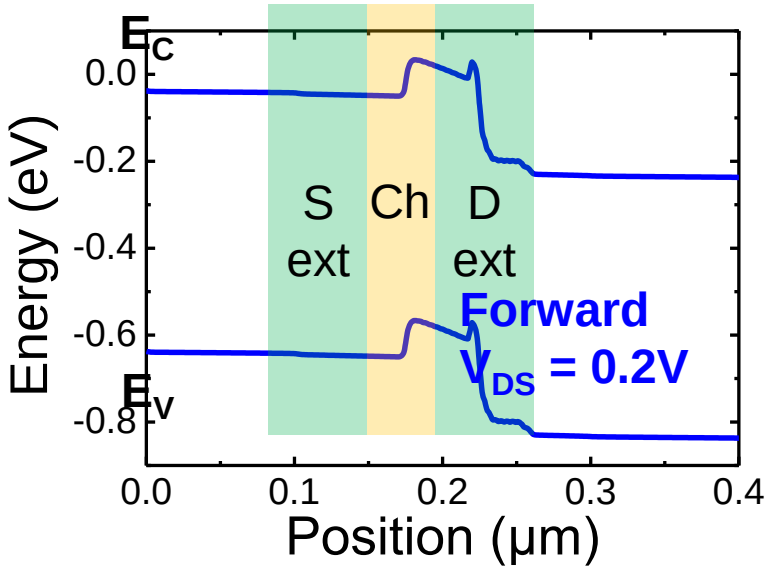
How do III-V reliability compare to the Si counterpart ?

HCI damages the drain-edge

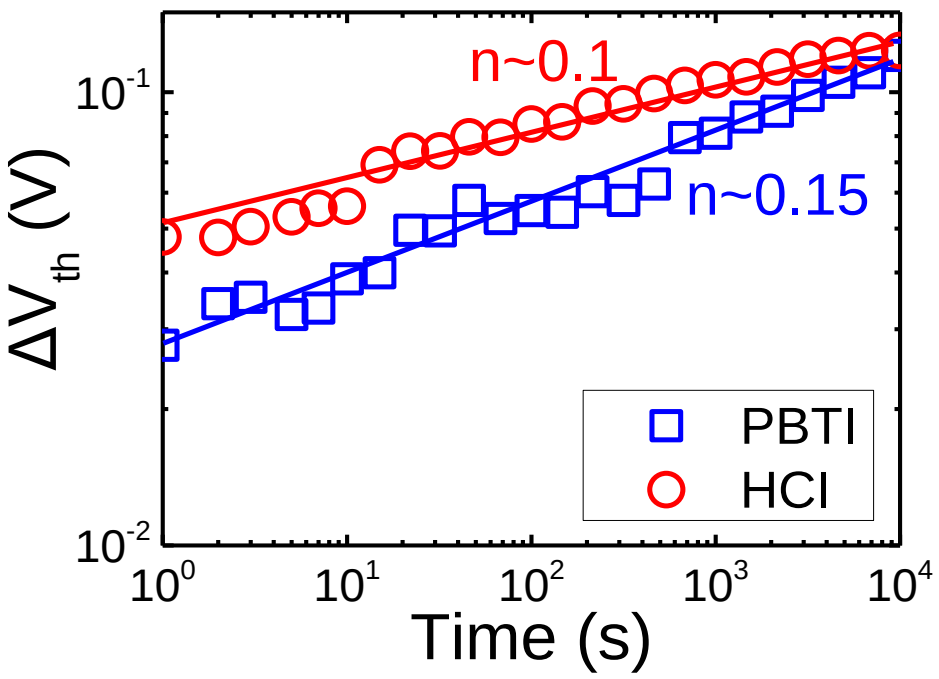


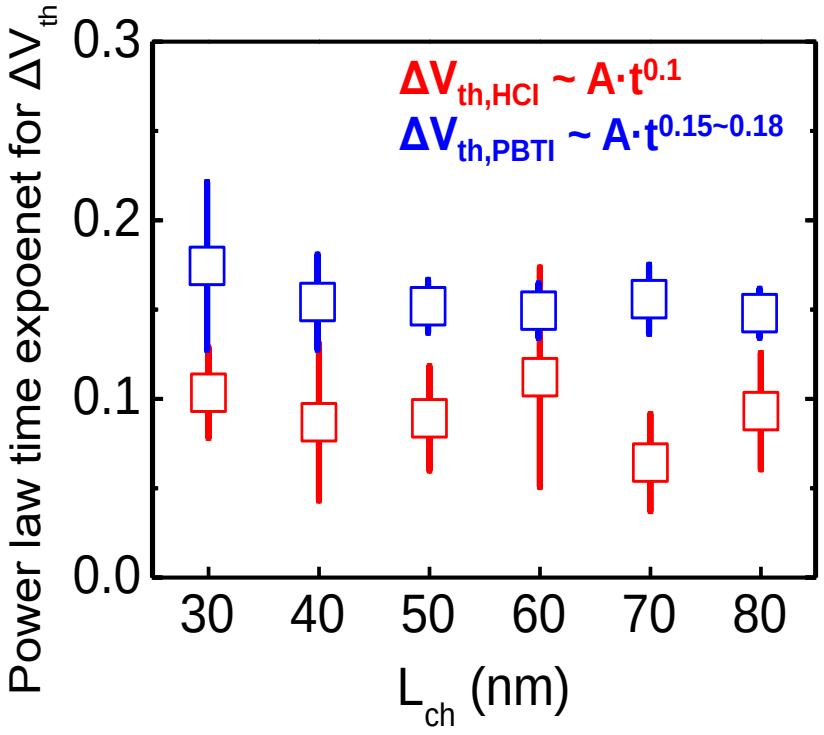






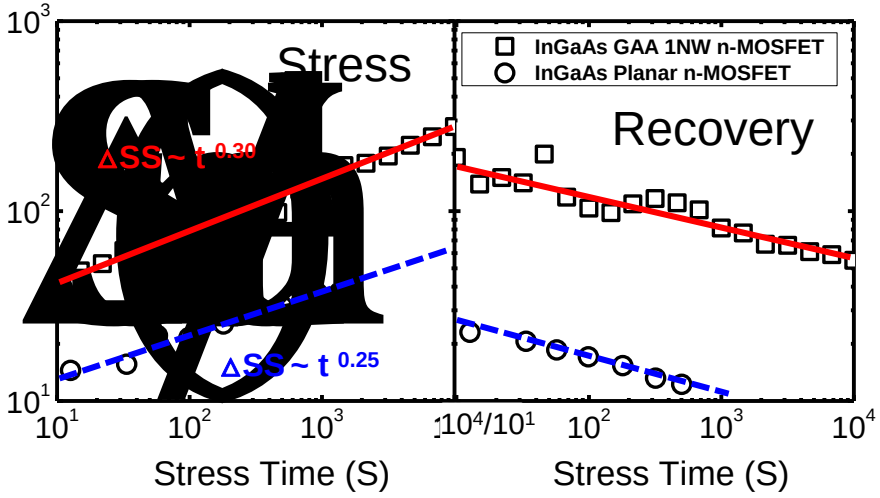
PBTI vs. HCI: ΔV_T degradation

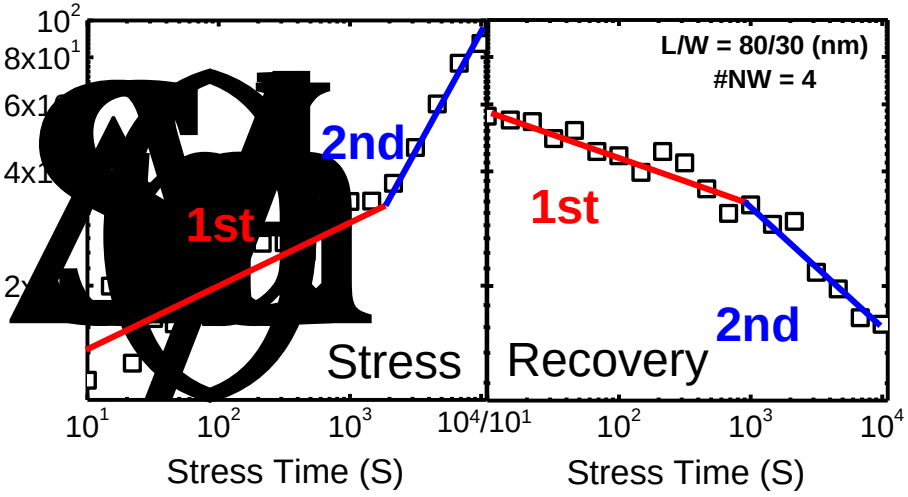




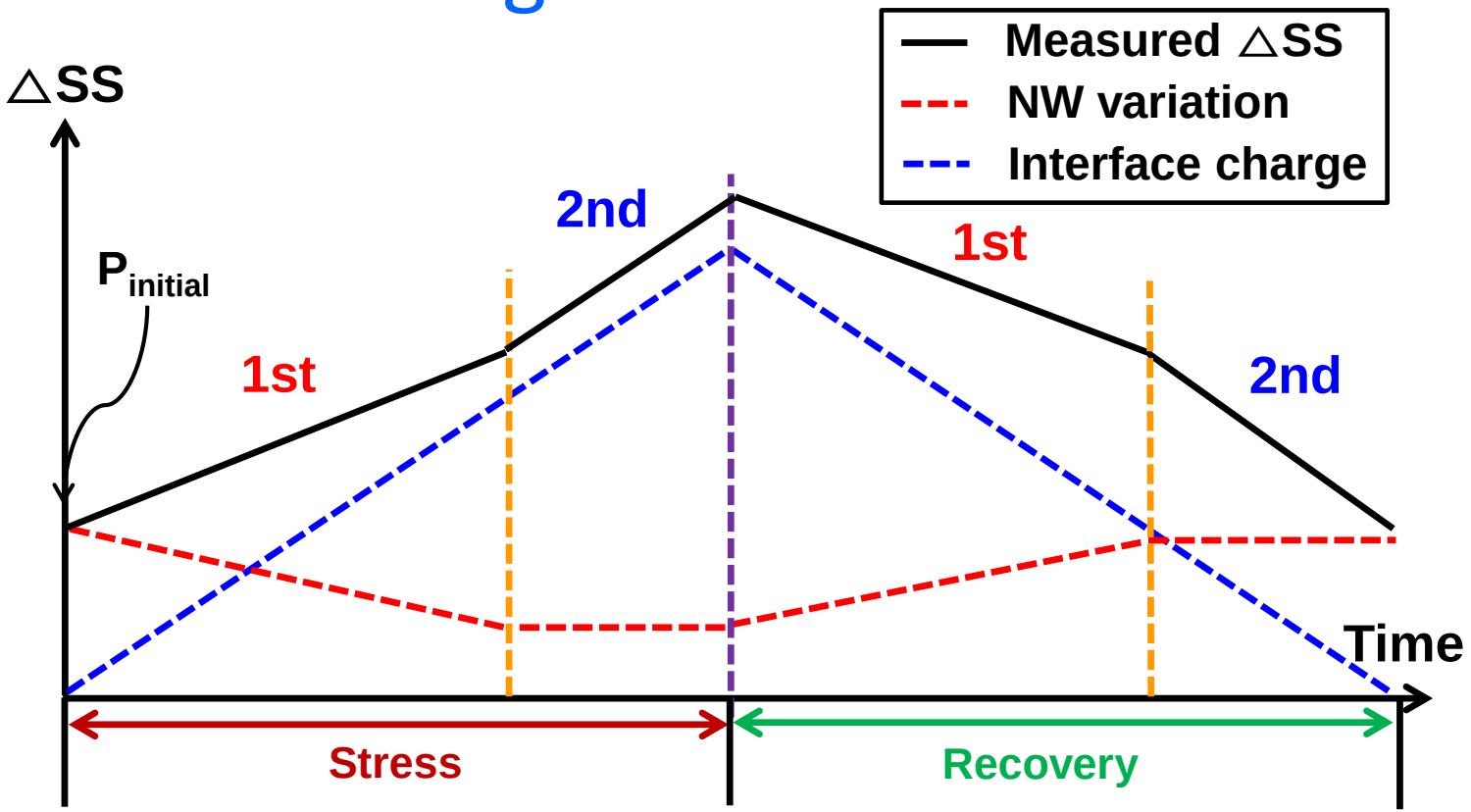
HCI dominated by trapping, PBTI by donor trap generation

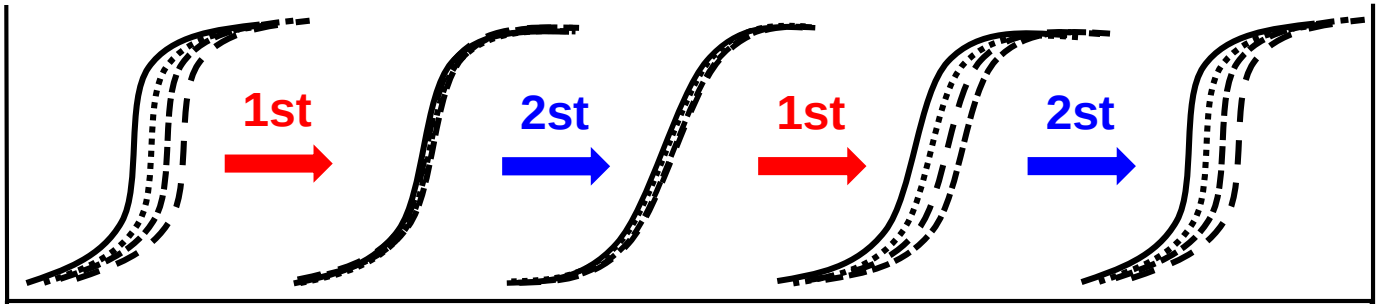
Variability-Reliability: Features of the Subthreshold Slope





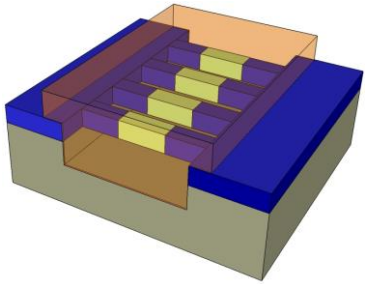
Multi-stage PBTI



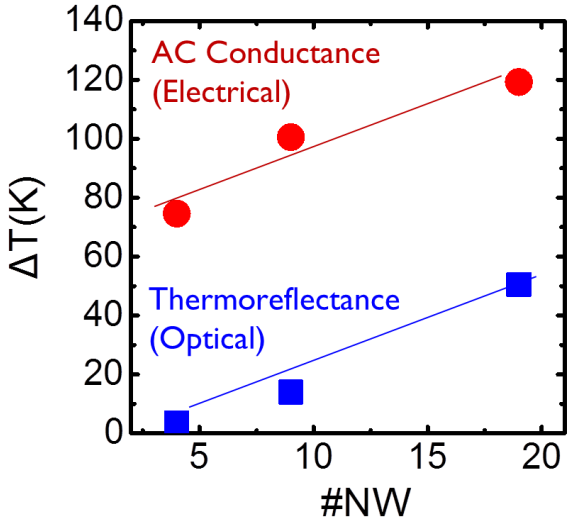


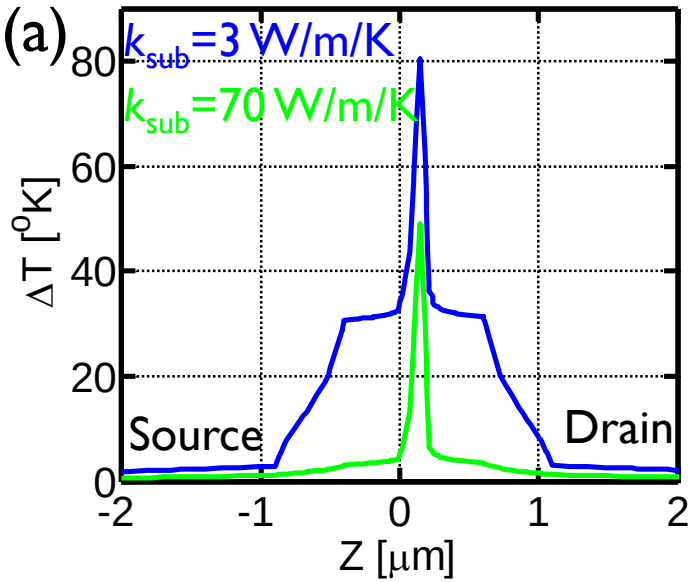
Time evolution of variation of transfer characteristic of NWs in a transistor

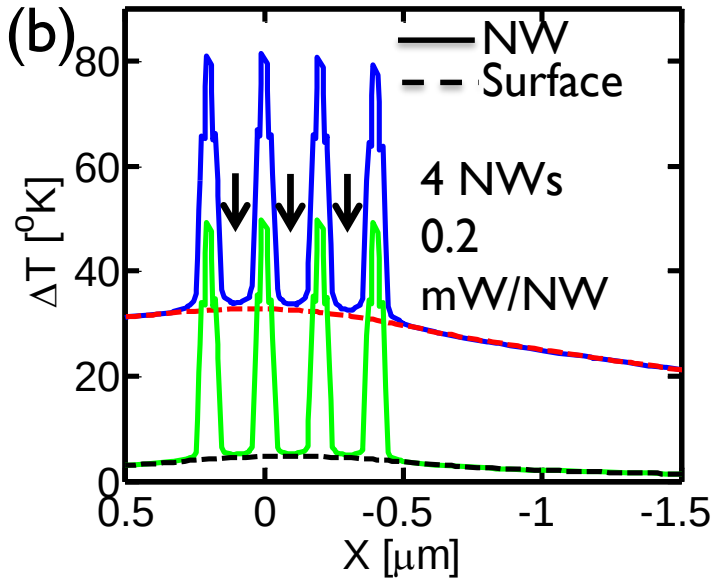
(3) TDDB: NW dictates self-heating



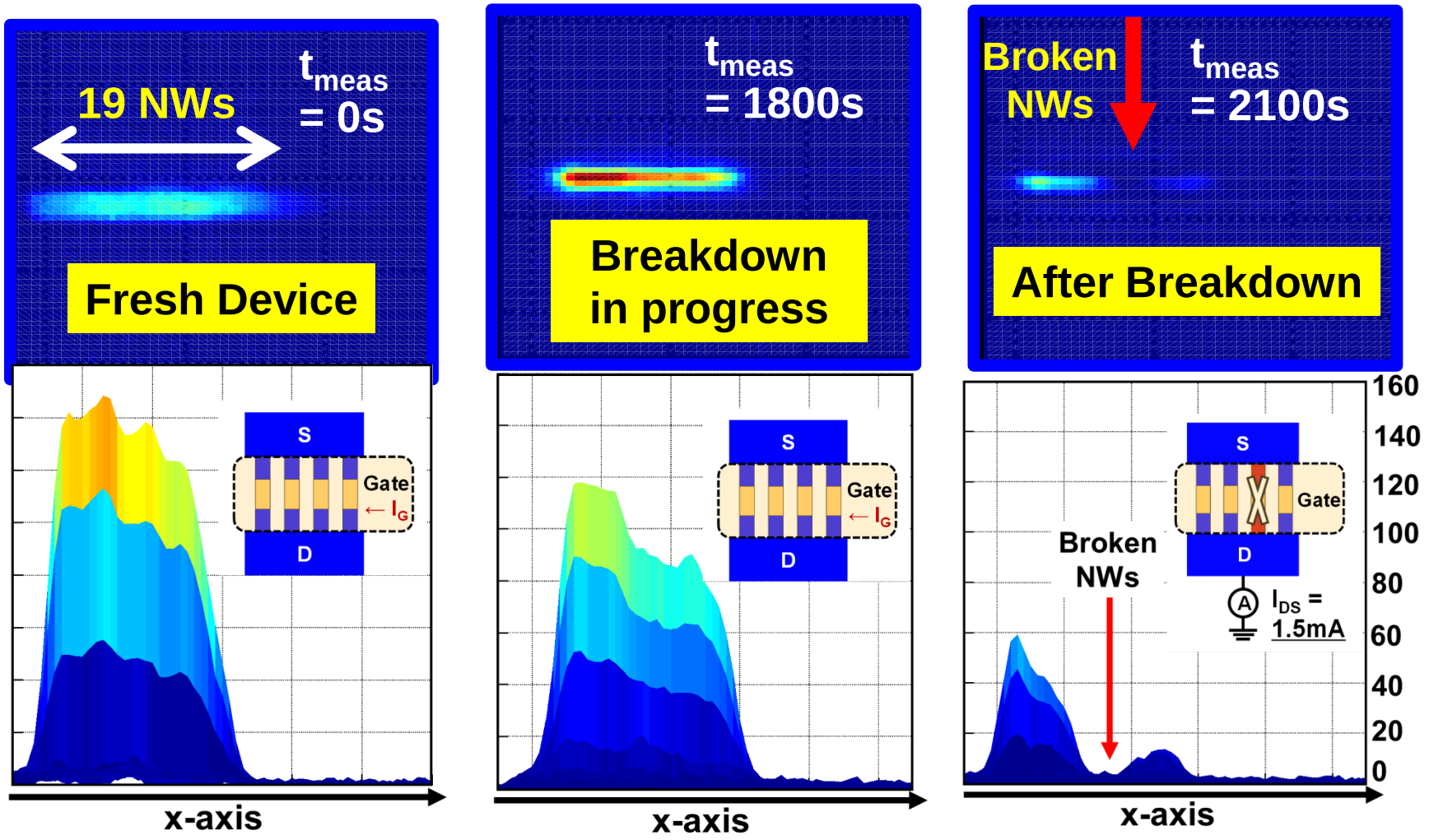
0.2 mW/NW







Correlated NW-dependent TDDB



TDDB depends on # of NW !

Conclusions

- Significant self-heating expected in surround gate technologies.
- This creates a new source of run-time variability, but also interesting correlation between process variability and reliability.
- Width dependence, TDDB and PBTI all require significant redefinition of design process.
- This is especially challenging for tail distribution.