Campbell Millar, Gold Standard Simulations Limited.

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VARIABILITY-AWARE SPICE MODELLING AND CIRCUIT SIMULATION IN SUPERTHEME

Conference Sponsors:

OUTLINE

1. Introduction
2. SPICE Model Extraction
3. Combined Global and Local Simulation
4. Process Variation and Local Variation
5. Conclusion

INTRODUCTION

- Design at advanced technology nodes REQUIRES accurate SPICE Models.
  - Reduces design cost and time to market
  - Design Right first time
- Systematic/Global variability and local mismatch can no longer be treated in isolation.
  - Complex and correlated
- Need a holistic approach to modelling Global and Local variability and reliability effects
- Design Technology Co-Optimisation (DTCO)
- Software and modelling methdologies which accurately capture the interplay between global and local variability and reliability.

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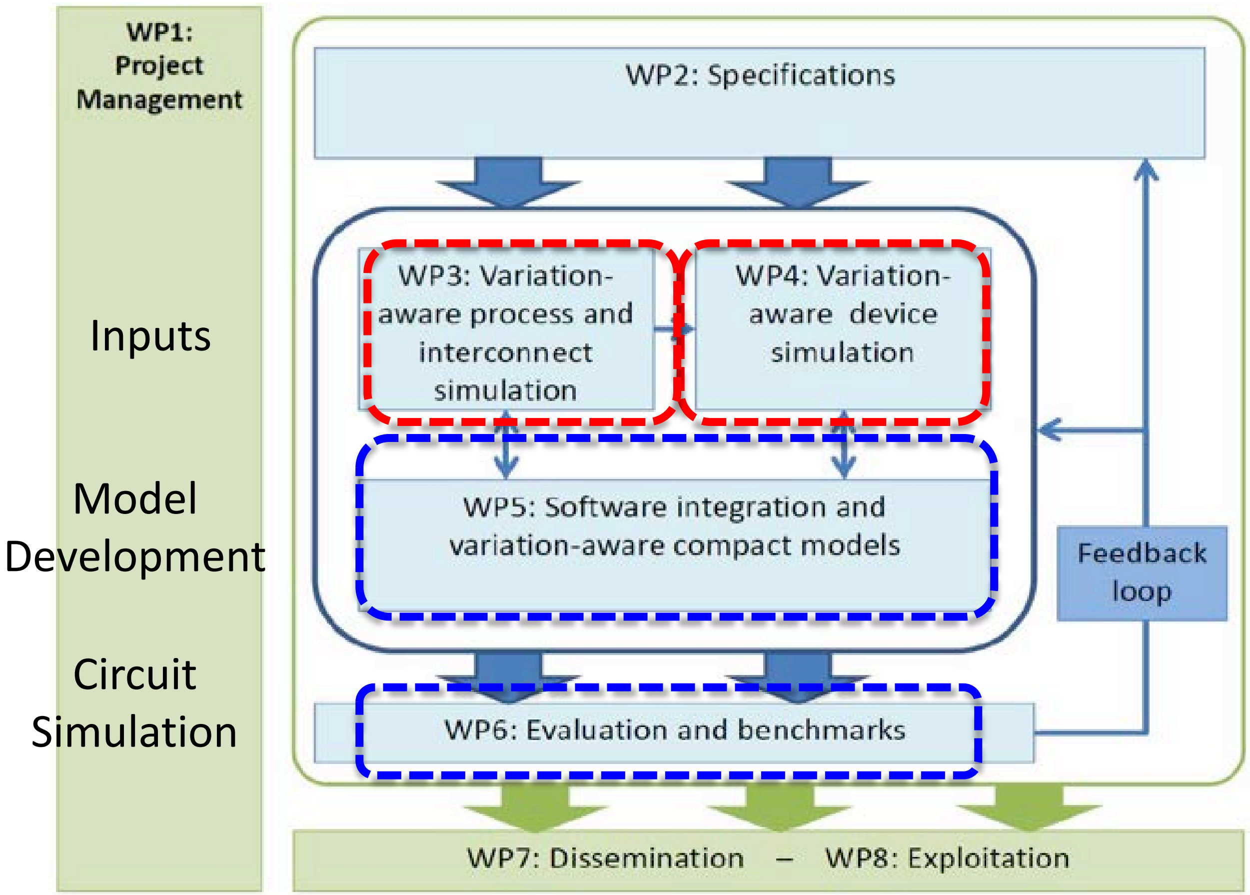
INTRODUCTION - CONTEXT



Collaborators

GSS

ams

Fraunhofer IISB

Fraunhofer IIS

University of Glasgow

SUPERTHEME

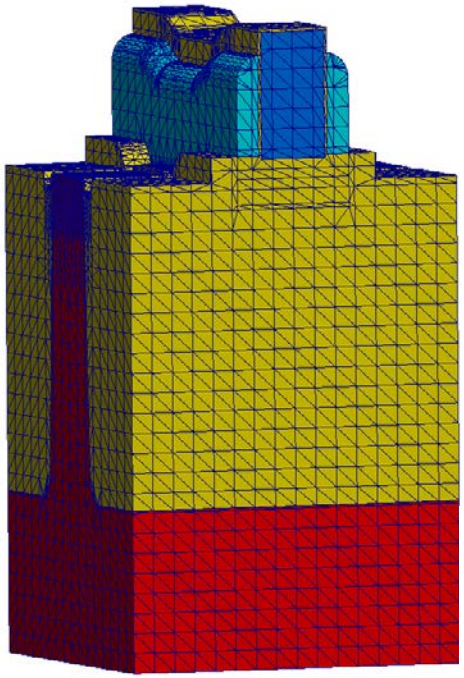
GSS

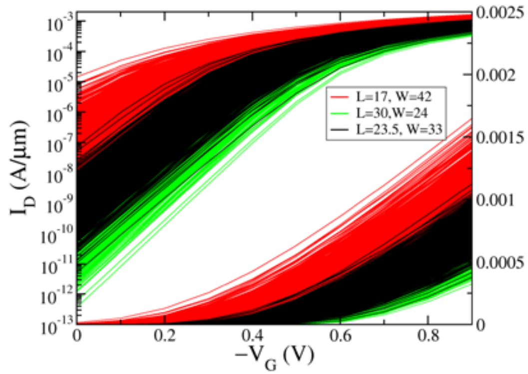
INTRODUCTION - TOOLCHAIN

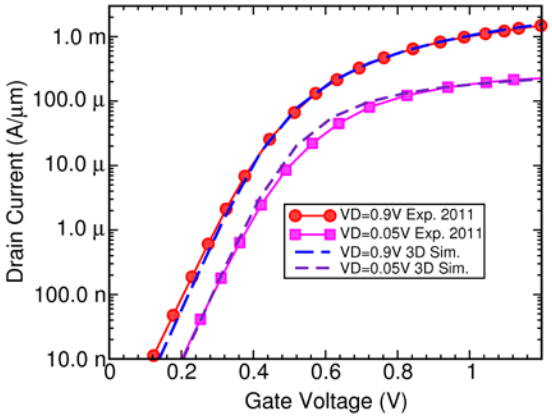
Full simulation tool chain

- Structure Manipulation/Translation
  - Monolith
- Device Simulation GARAND
  - DD, 3D Full Band MC , 1D Multi-sub-band MC
- Statistical SPICE Modelling
  - Mystic –SPICE Model extraction
  - ModelGEN – Advanced process and statistical aware SPICE Model generation technology
- Circuit Simulation
  - RandomSPICE – Statistical Circuit Simulation Engine
- Toolchain integration
  - Enigma – Automation and Integration framework

SUPERTHEME 20NM MOSFET







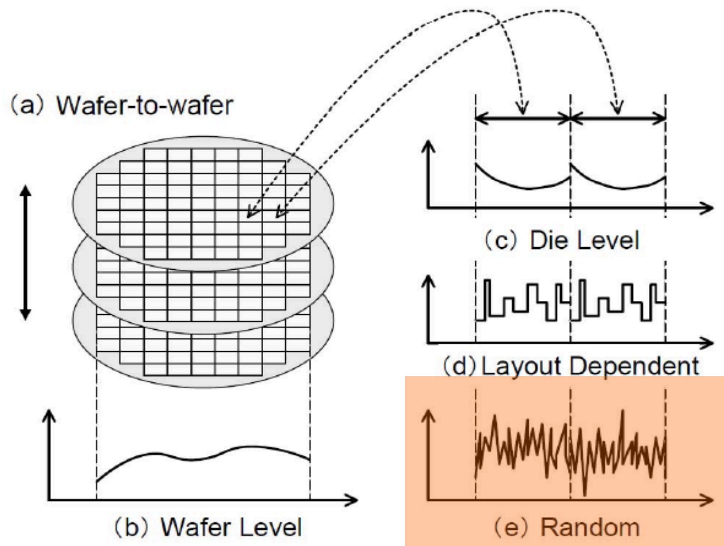
Process simulation (Sentaurus Process/ Dr Litho)

Mesh Conversion/Transfer (GSS Monolith)

Device simulation (GSS Garand)

SUPERTHEME GSS

VARIABILITY DECOMPOSITION



(Takeuchi, Nishida, Hiramoto, SISPAD 2009)

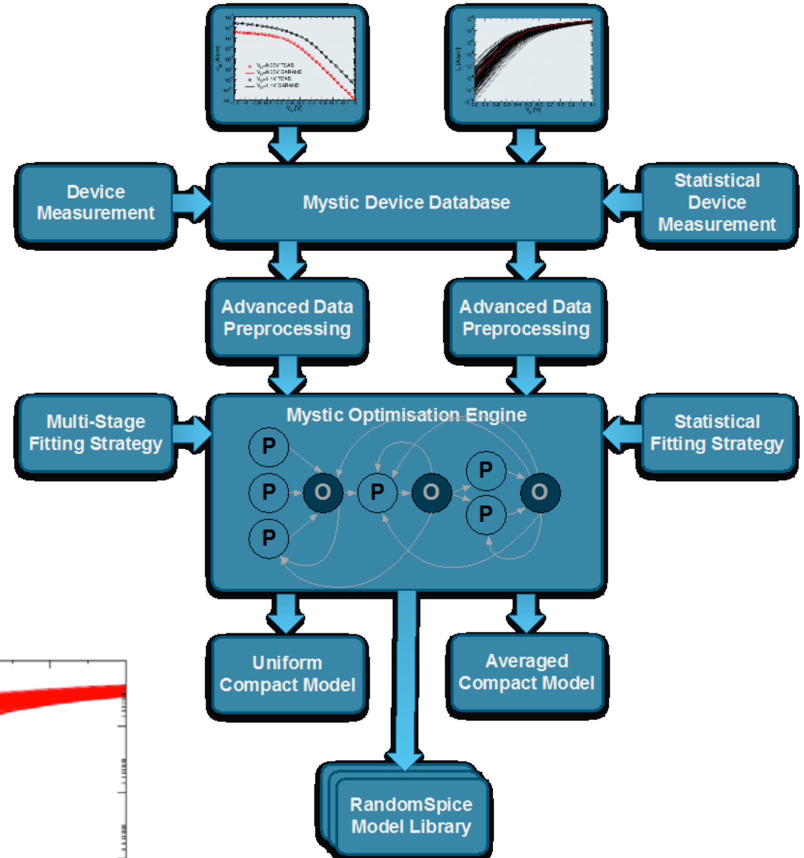
	Process	Environment	Temporal
Global	<L_g> and <W>, <layer thicknesses>, <R>'s, <doping>, <t_{ox}>, <V_{body}>	Operating temperature range, V_{DD} range	<NBTI> and Hot electron shifts
Local	**Line Edge Roughness (LER), Discrete doping, Discrete oxide thickness,** R and V_{body} distributions	Self-heating, IR drops	**Distribution of NBTI,** Voltage noise, SOI V_{body} history effects, Oxide breakdown currents
Across-chip	Line Width, due to pattern density effects	Thermal hot spots due to nonuniform power dissipation	Computational load dependent hot spots

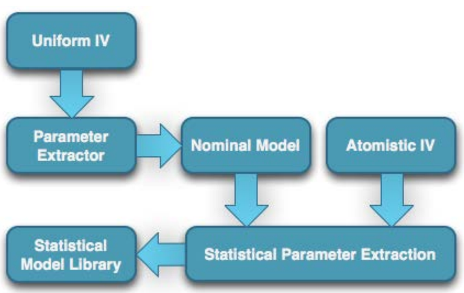
(D. Frank, IBM)

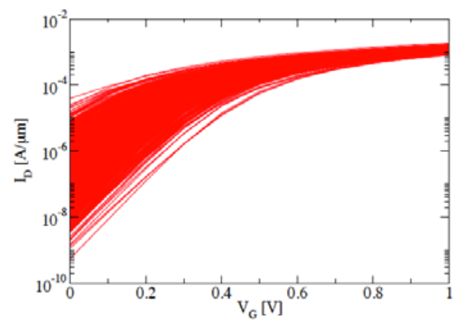
- In general, variability can be decomposed into global process variation and local random variability.
- Global Variability: systematic, spatially correlated, long-range.
- Local Variability: random, no (weak) correlation, short-range.

COMPACT MODEL EXTRACTION WITH MYSTIC

- Extraction of nominal and statistical compact models
- Flexible extraction based on state machine workflow.
- Supports PCA and ModelGEN
- ModelGEN preserves correlations between non-normal parameter distributions
- Unprecedented statistical accuracy

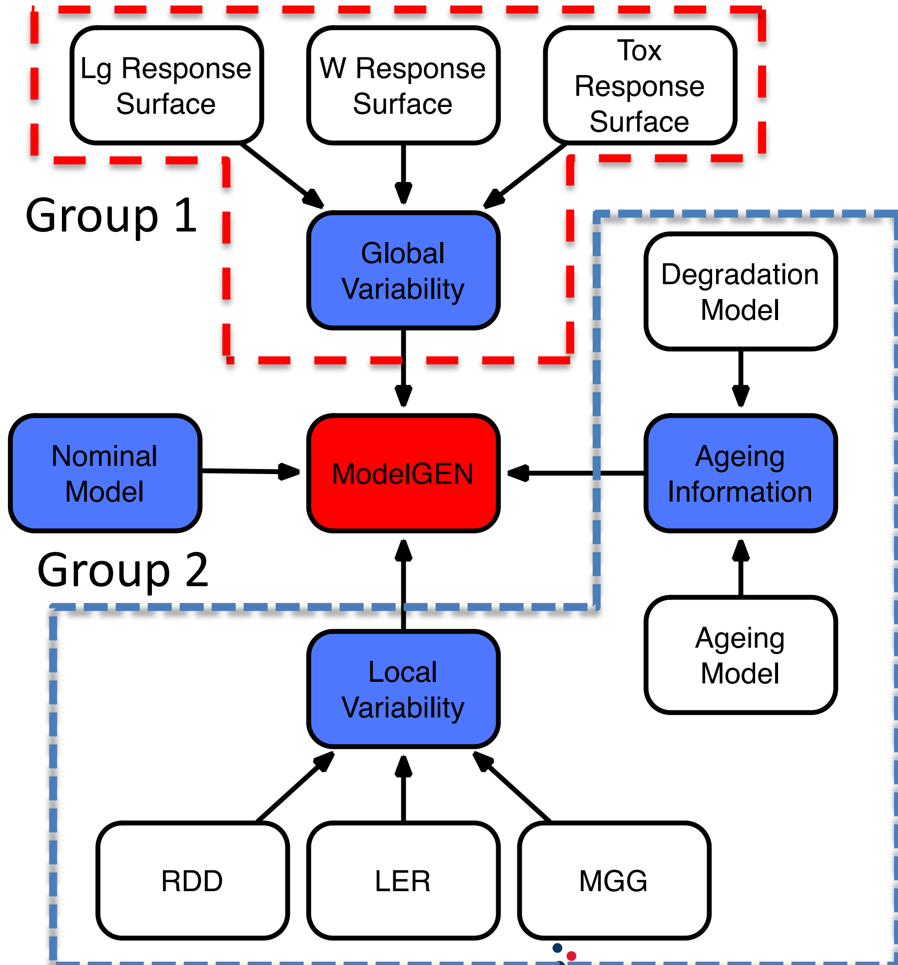






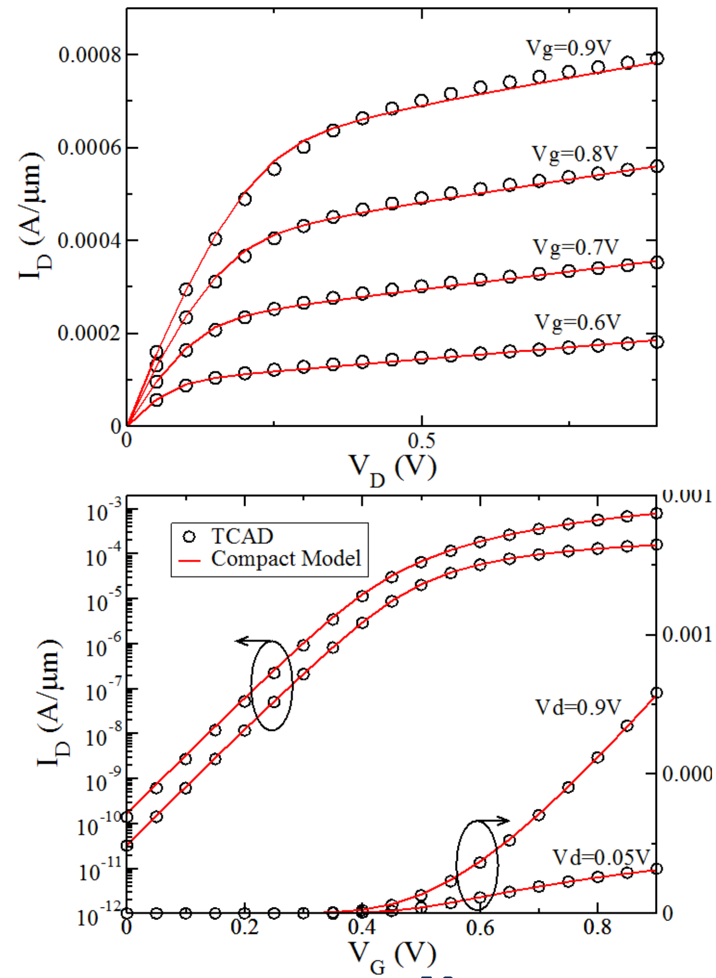
HIERARCHICAL MODELLING METHODOLOGY

- Multi-stage extraction process
- Nominal Base Model
  - Standard SPICE Model Extraction
- GV Process Aware Model
  - Identify Group 1 Model Parameters
  - Define DoE Space
  - Fit to TCAD process splits or Si
- LV Statistical SPICE Model
  - Identify Group 2 Model parameters
  - Simulate variability under appropriate GV conditions



NOMINAL MODEL EXTRACTION

- Extract Base Model from TCAD using Mystic
- Full model extraction
- Uniform Doping
- Basis for variability model extraction
- Typically Target <2-3% error
  - Needs to cover range of W and L
  - Range of Temperatures

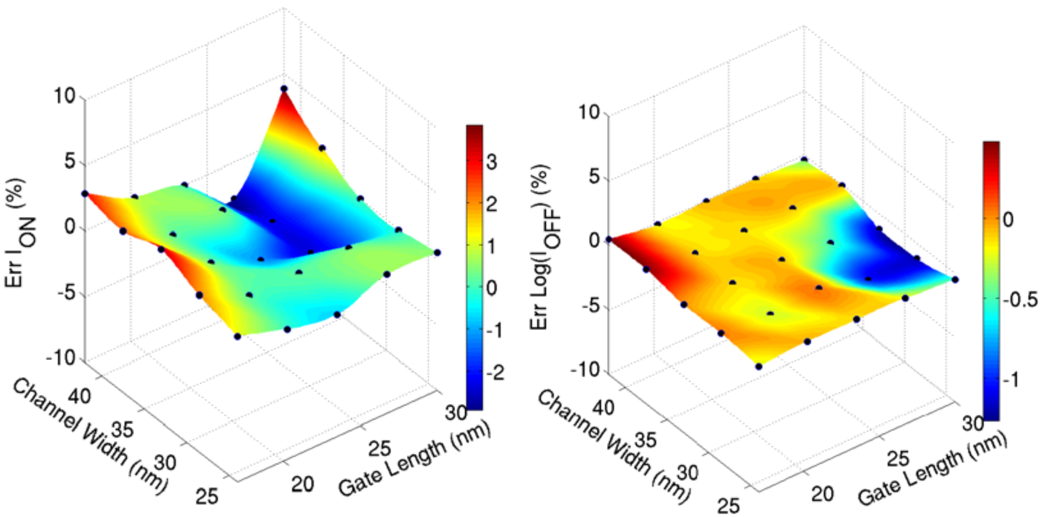


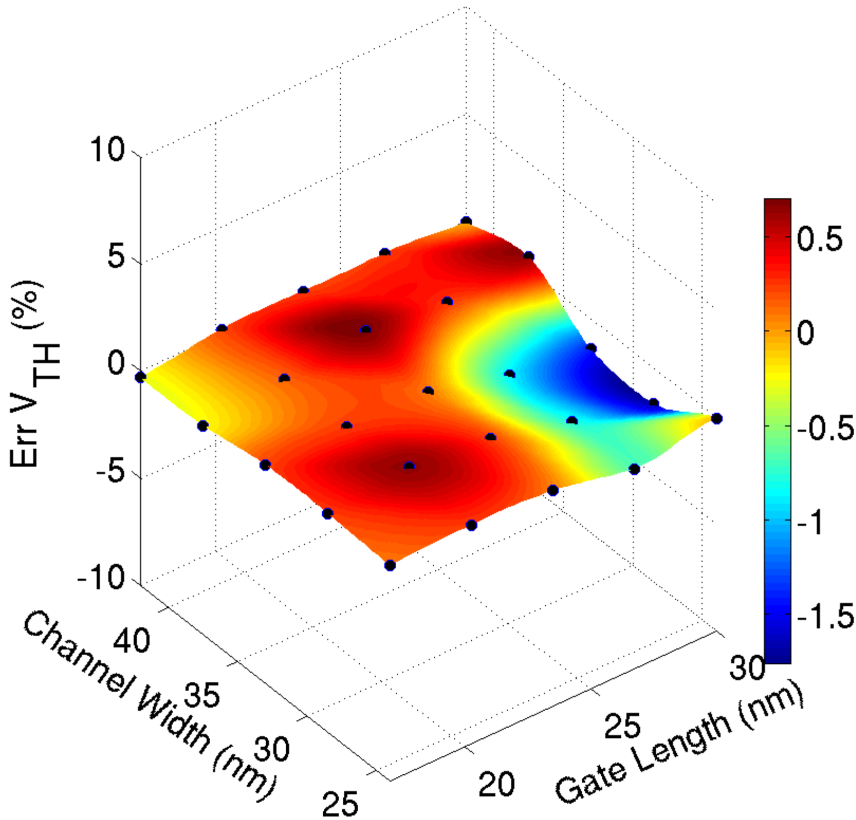
EXTENDED UNIFORM MODEL – GROUP 1

Group 1 Parameters - Subset of model parameters capture process/geometry variation

- 5 × 5 DoE space
- L_G=17, 20.25, 23.5, 26.75, 30
- W=24, 28.5, 33, 37.5, 42

Typical extraction <3% Fitting Error

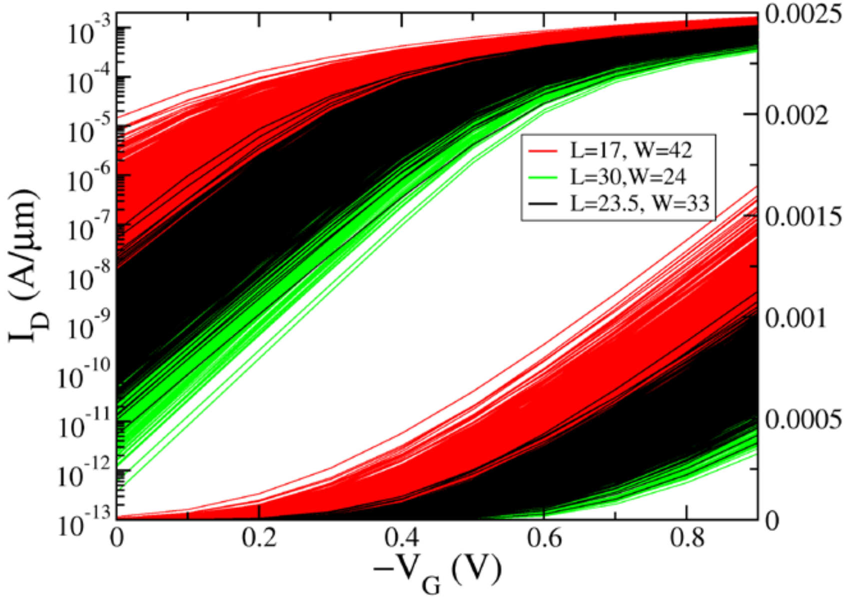


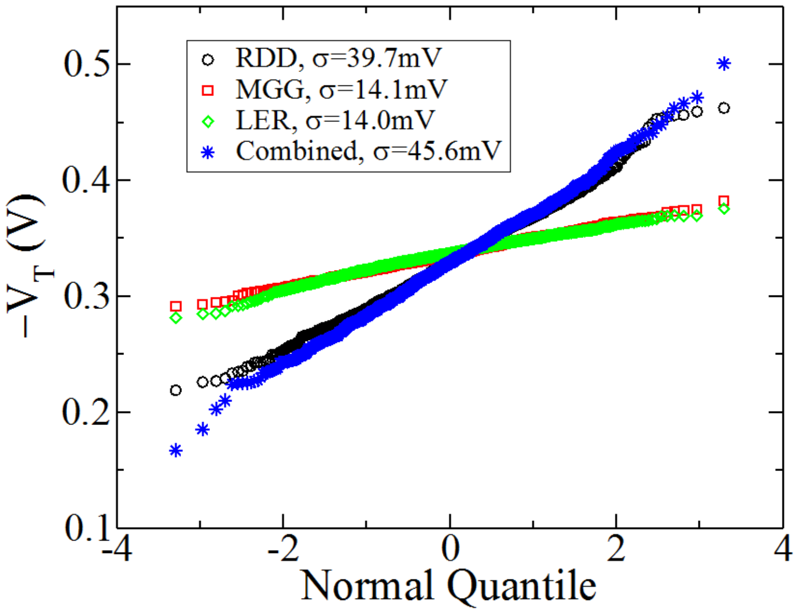


STATISTICAL MODELS - GROUP 2

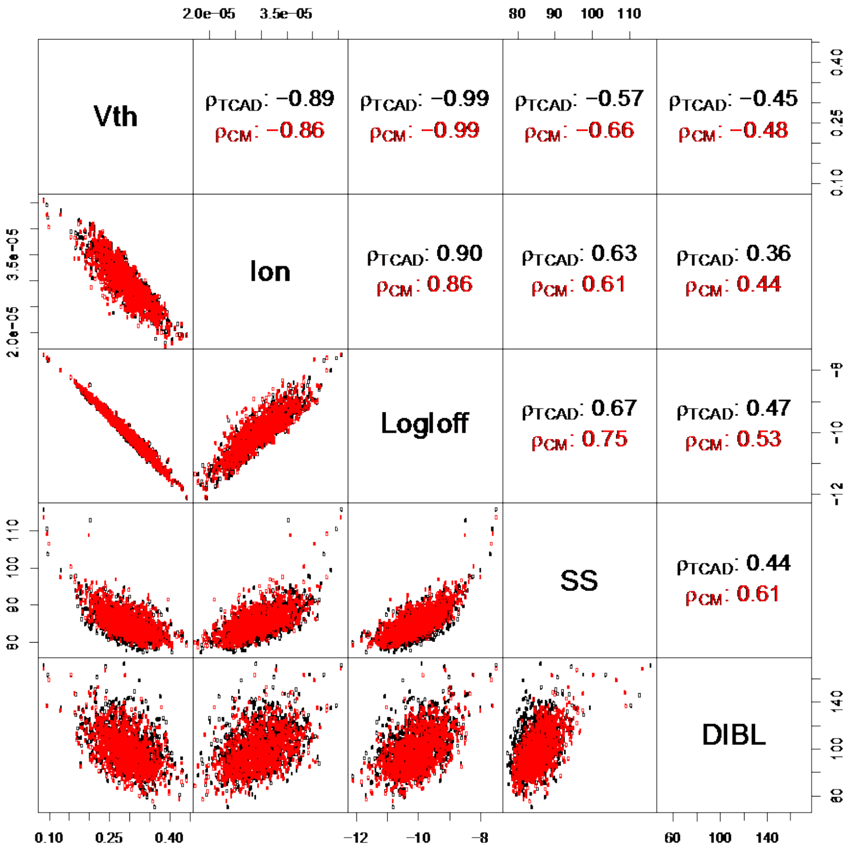
Group 2 Parameters - Subset of model parameters capture local variations and reliability

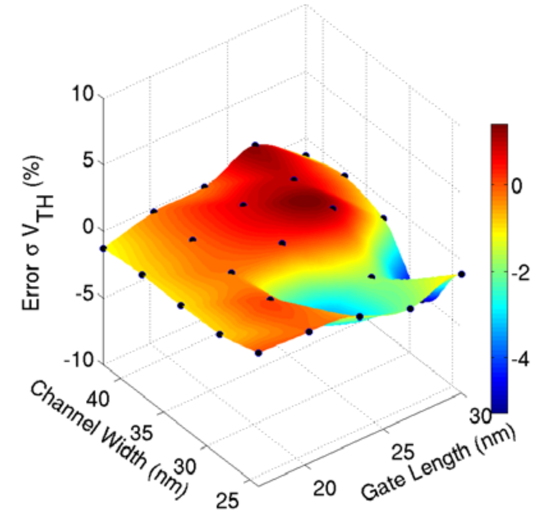
- 5×5 DoE space
- RDD, LER, MGG
- L_G=17, 20.25, 23.5, 26.75, 30
- W=24, 28.5, 33, 37.5, 42

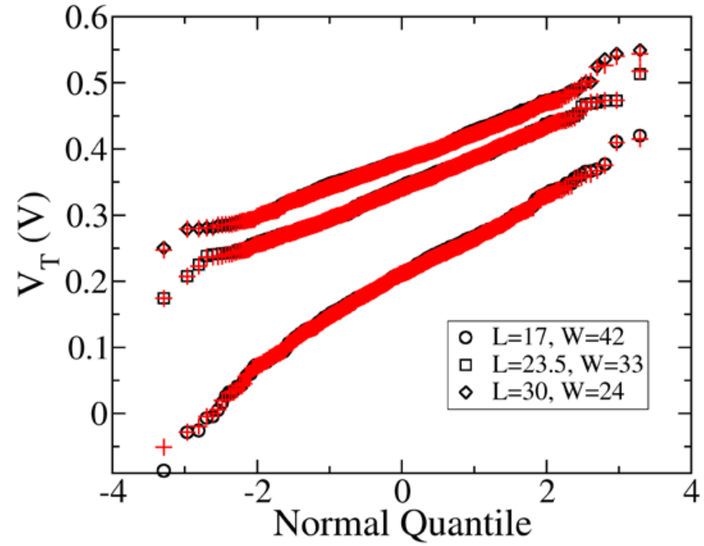




STATISTICAL MODELS

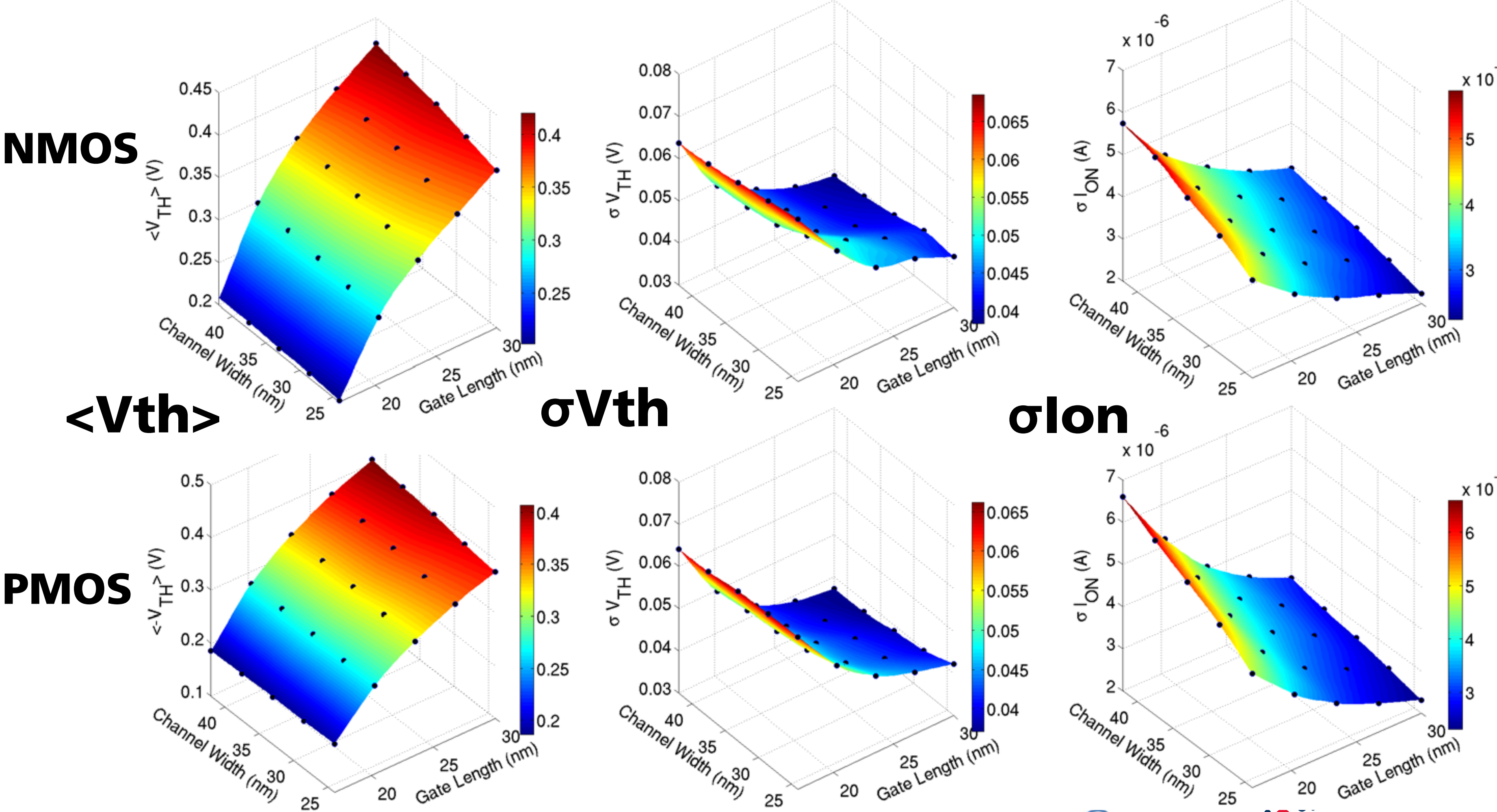






Accurately capture device variation including variations in SS and DIBL

LOCAL VARIATION RESPONSE SURFACES



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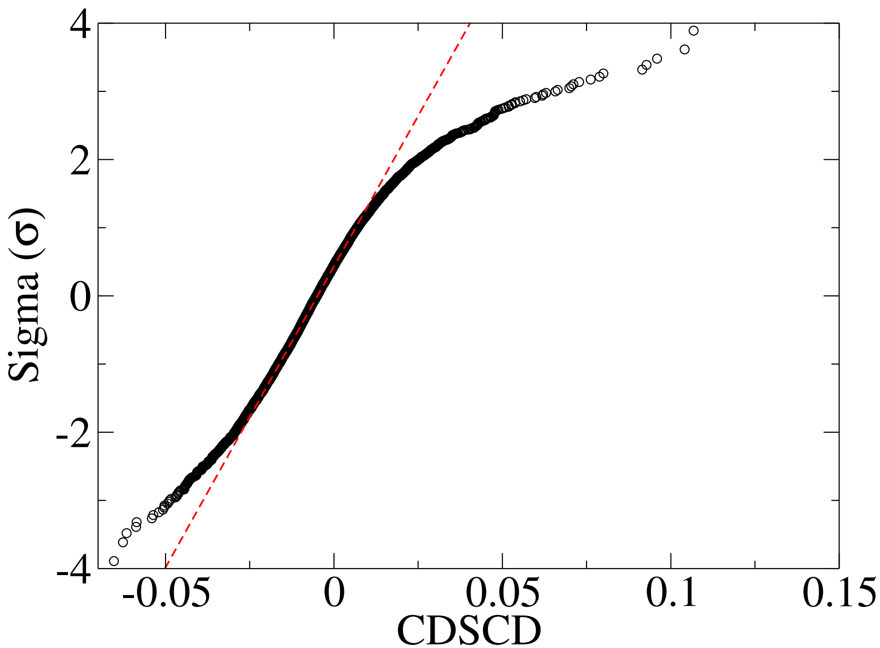
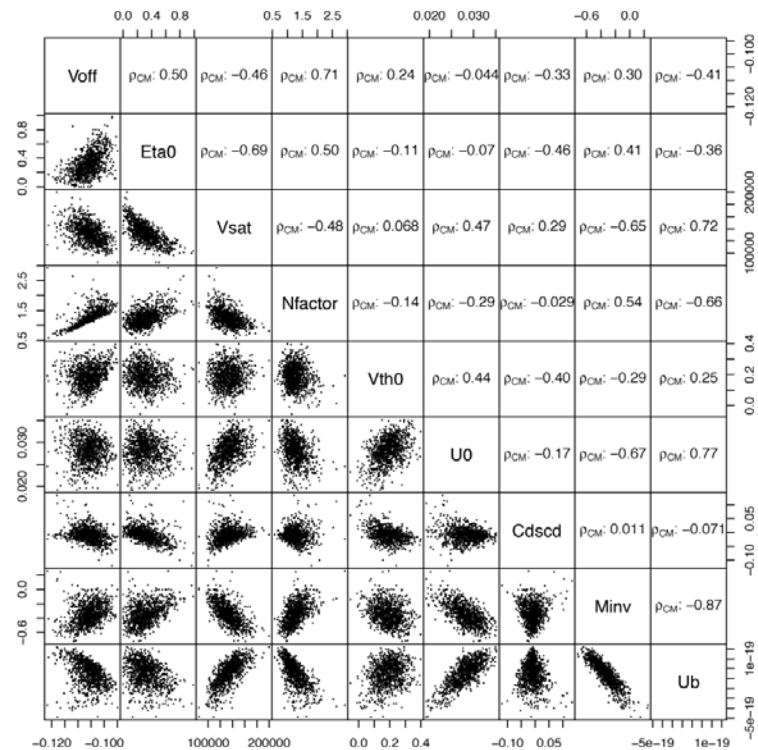
GROUP 2 PARAMETER DISTRIBUTIONS



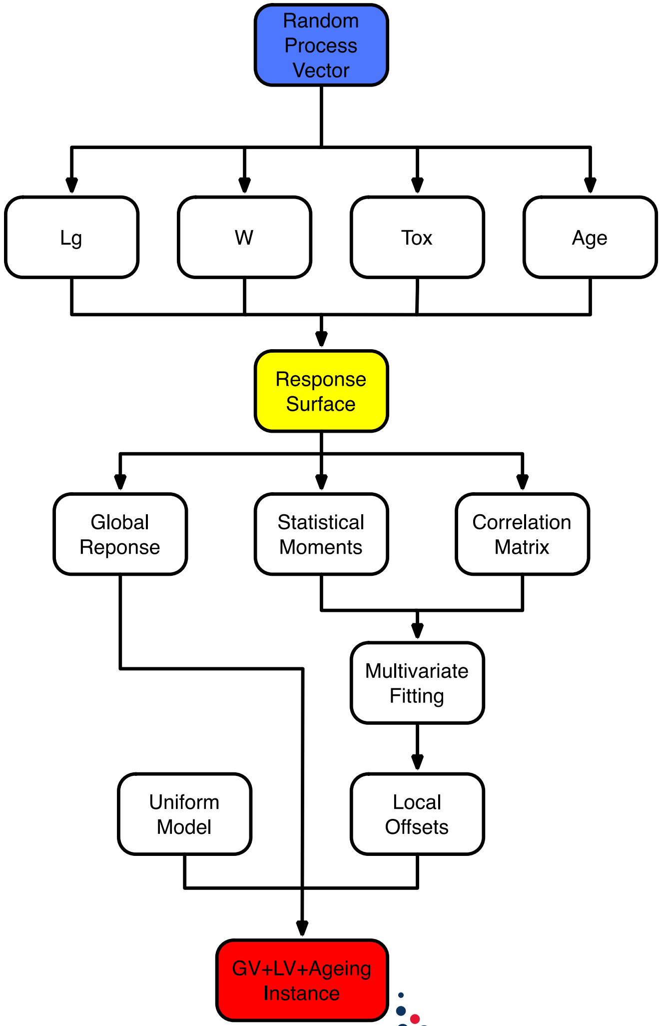


Distributions of SPICE model parameters for Group 2 are non-Gaussian and have complex correlations.

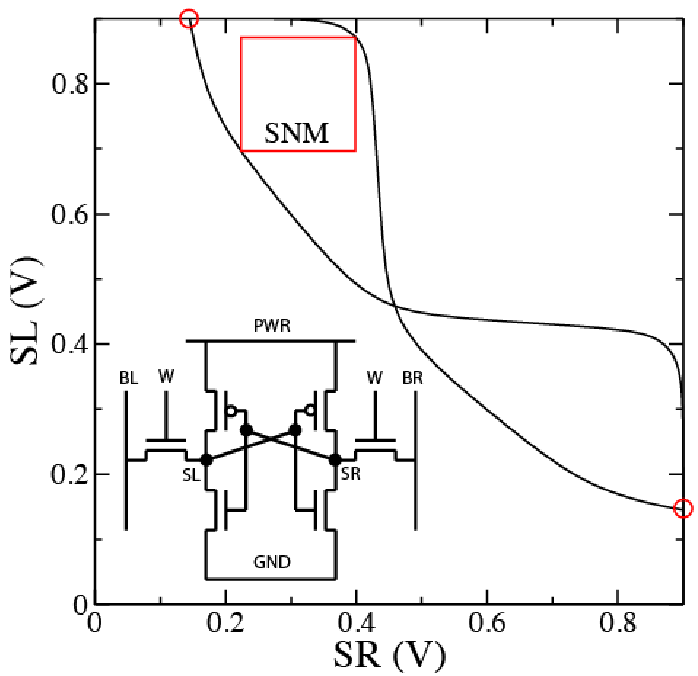
SUPERTHEME GSS

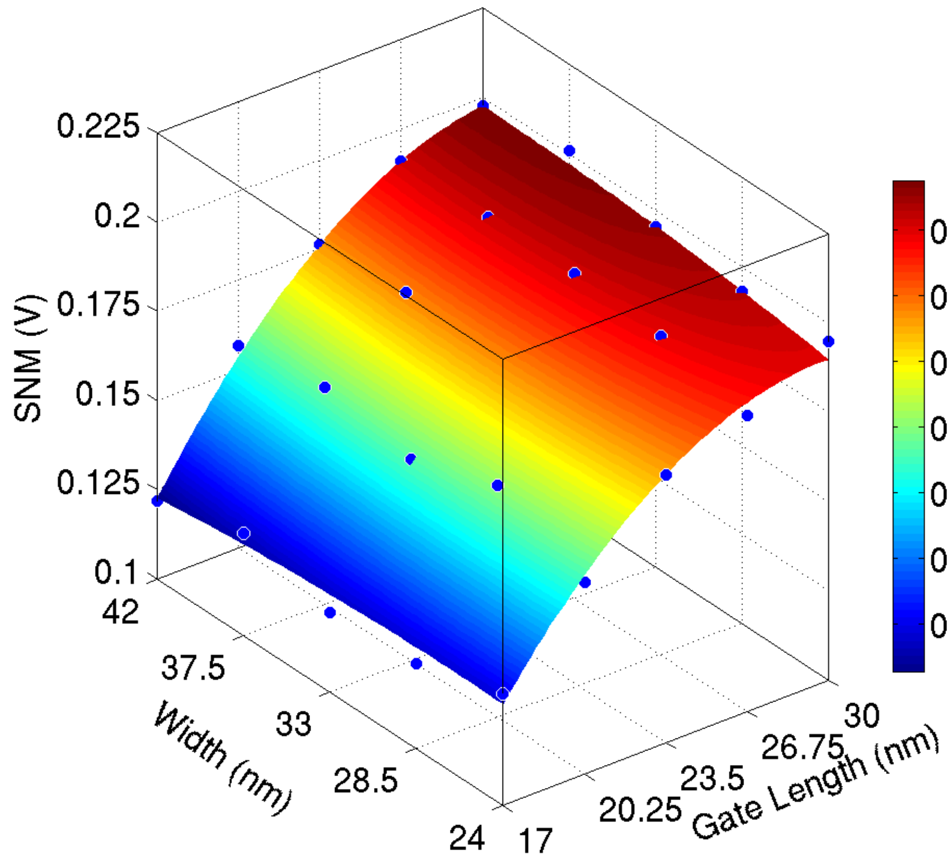
MODELGEN

- Highly accurate Compact Model Generation
  - Captures non-Gaussian distributions
  - Parameter correlations
- Models combined impact of
  - Global Variation
  - Local variation
  - Reliability and ageing
- Uses response surface models for GV
- Model interpolators used for
  - BTI-induced ageing response.
  - Local statistical variability information.
- GSS RandomSPICE Statistical Circuit Simulation Engine



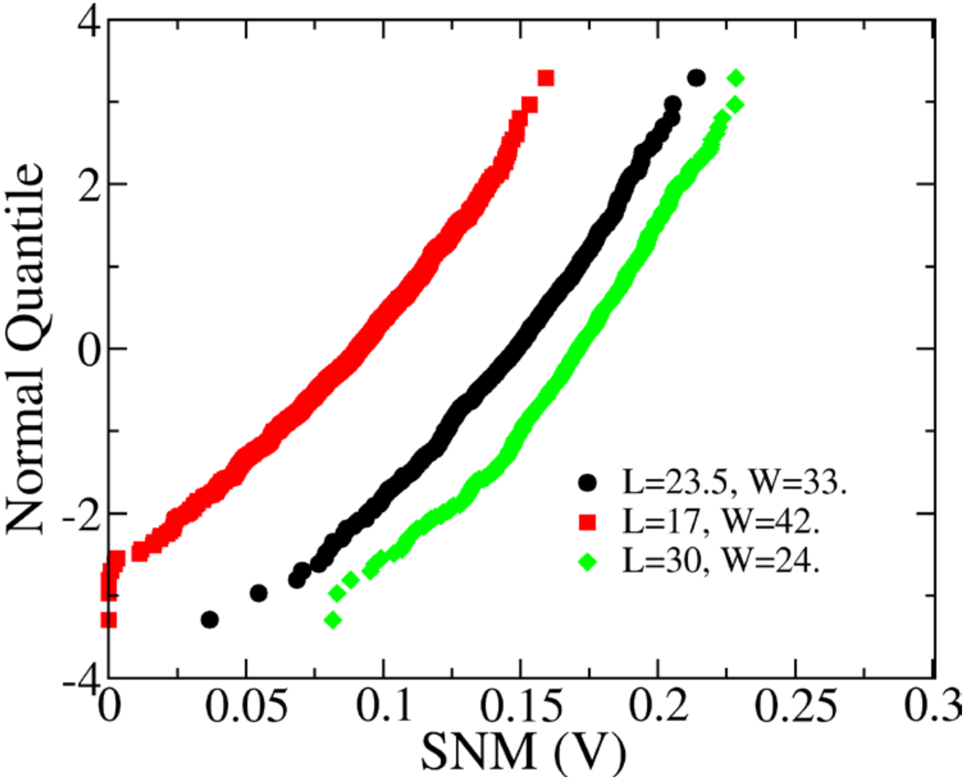
EXAMPLE: SRAM

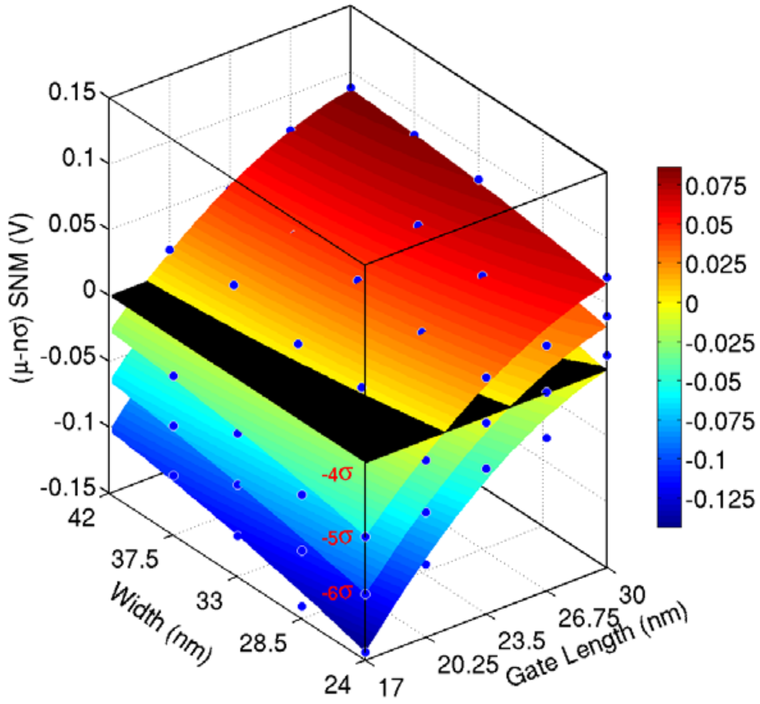




- 6T SRAM cell simulations
- ModelGEN response surface models
- Global PV has significant impact on SNM.

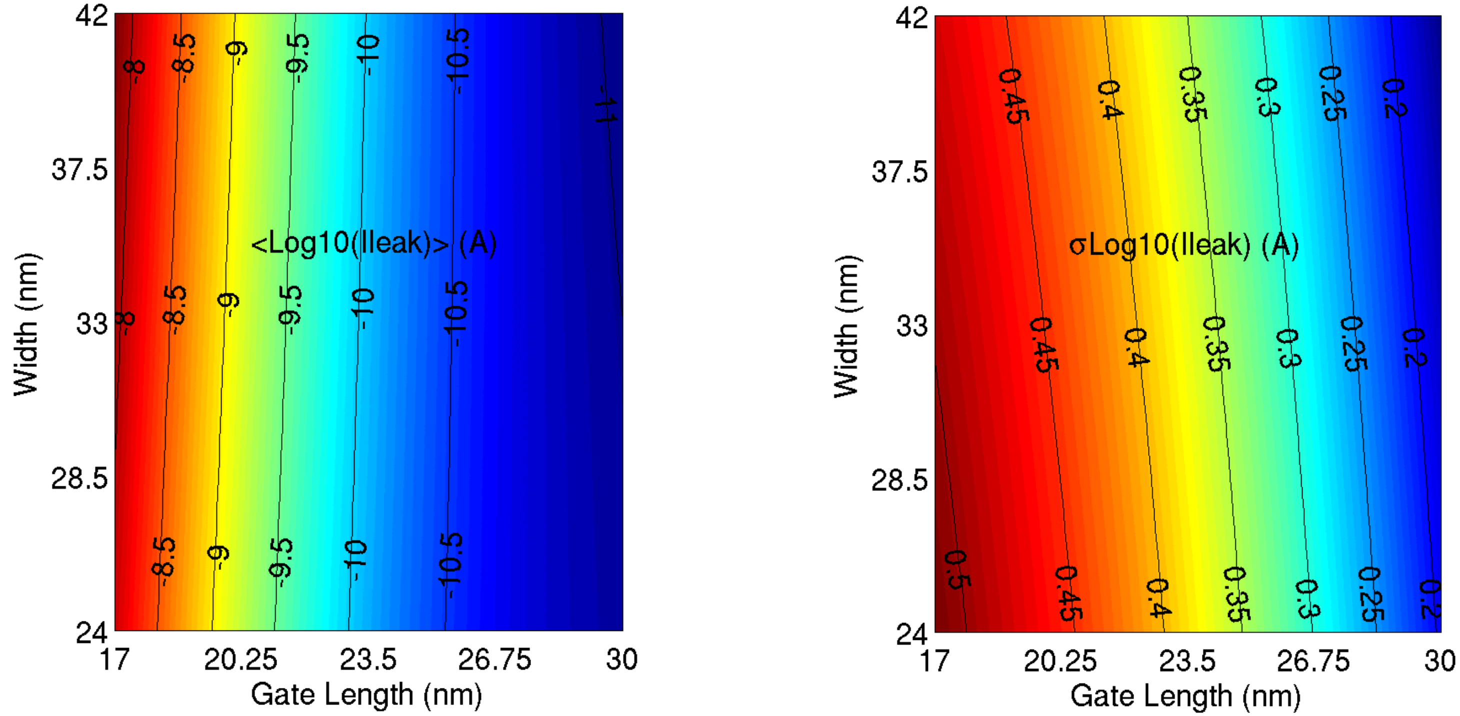
SRAM: SNM





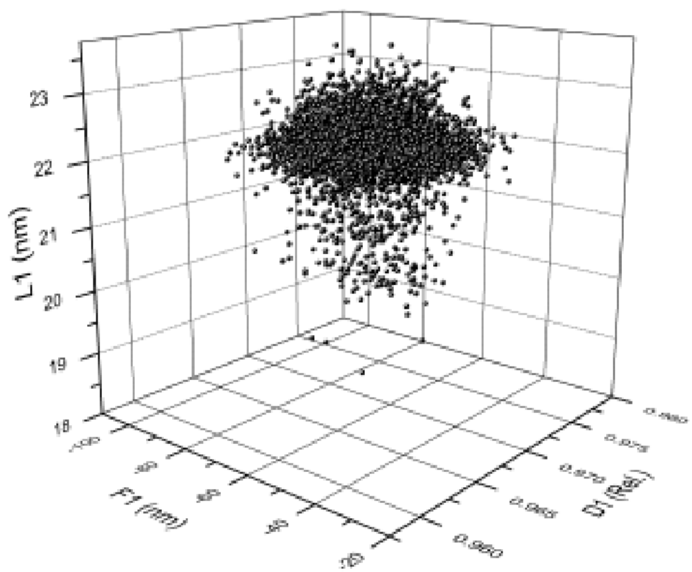
- Simulated SNM using RandomSPICE and ModelGEN Library
- Good control of PV is essential for yield.

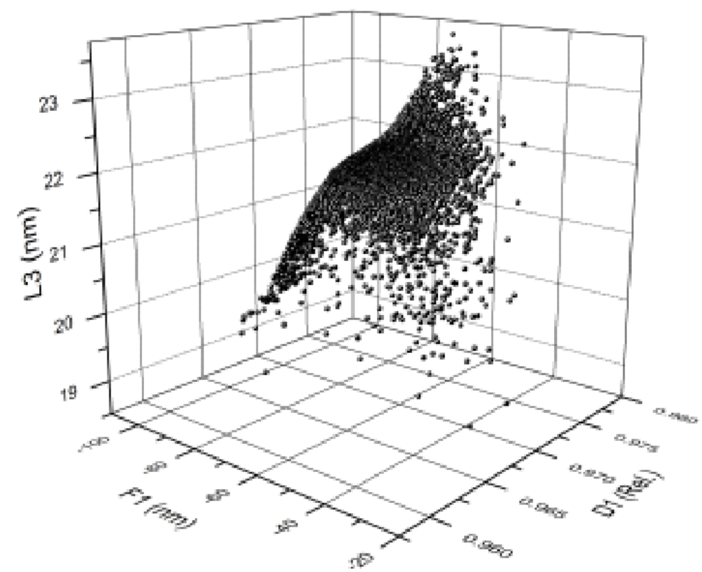
SRAM: CELL LEAKAGE

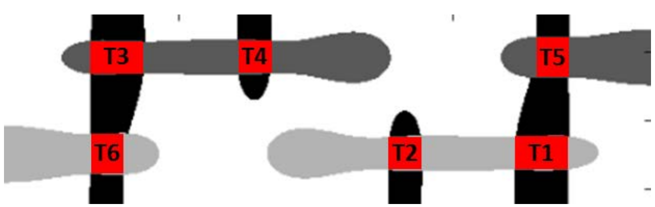


- SRAM Cell leakage critical for IOT applications
- In this case Lg variation dominates due to strong short channel effects
- σIoff changes due to Vt shift as well as L dependent σVt
- Variation span 3 orders of magnitude.

SUPERTHEME DEMONSTRATOR

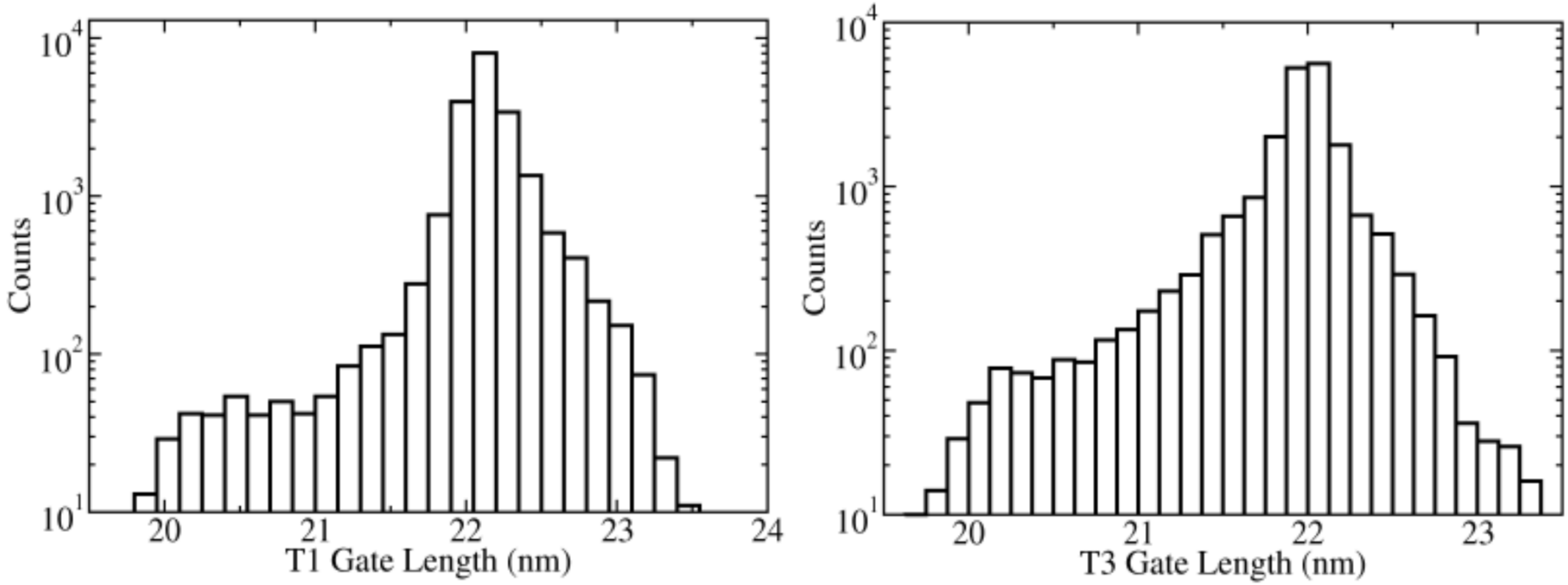






- Variation in SRAM cell DC variation due to Litho random variation in Focus (F1) and Dose (D1)
- Horizontal lines need to be structured with LFLE double patterning. Simulated with Dr Litho.

RANDOM CD VARIATION



- Probability distribution of lengths of transistor T1 and T3
- Provided as input distribution to ModelGEN
- Simulated using Dr Litho from Fraunhofer IISB

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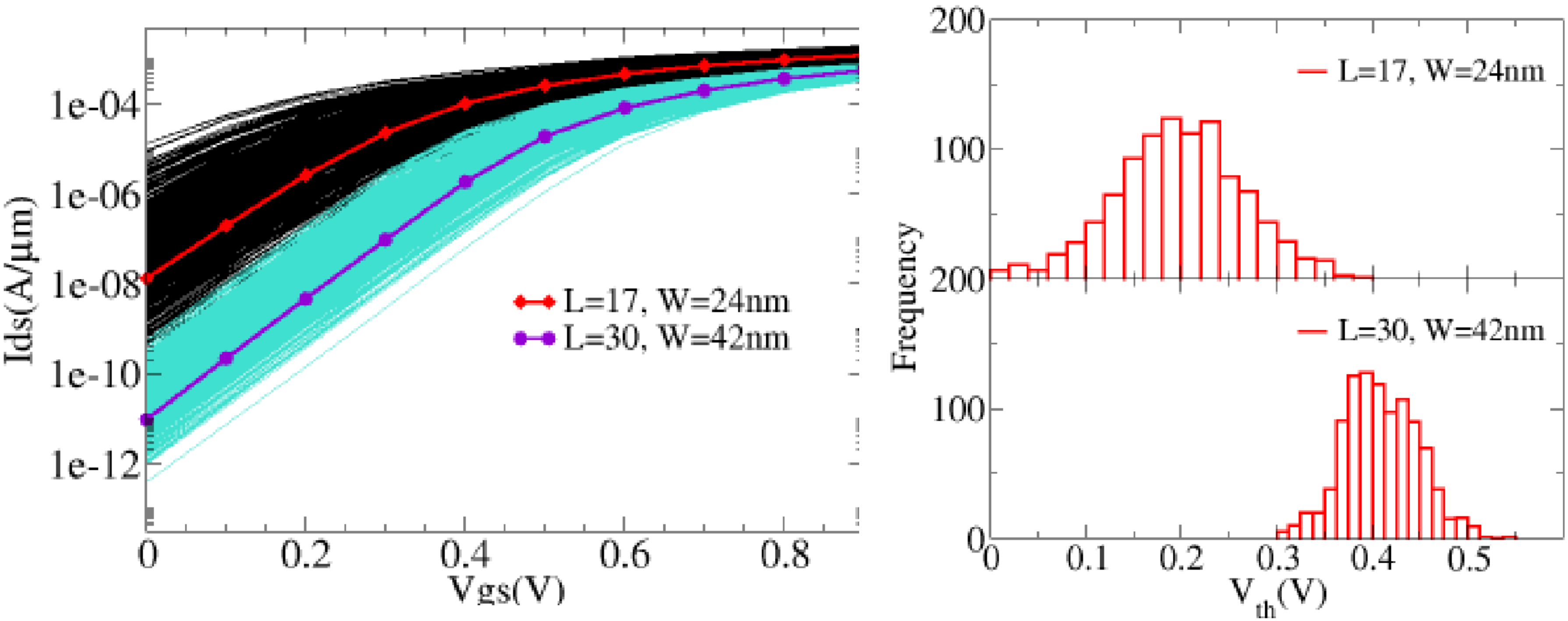
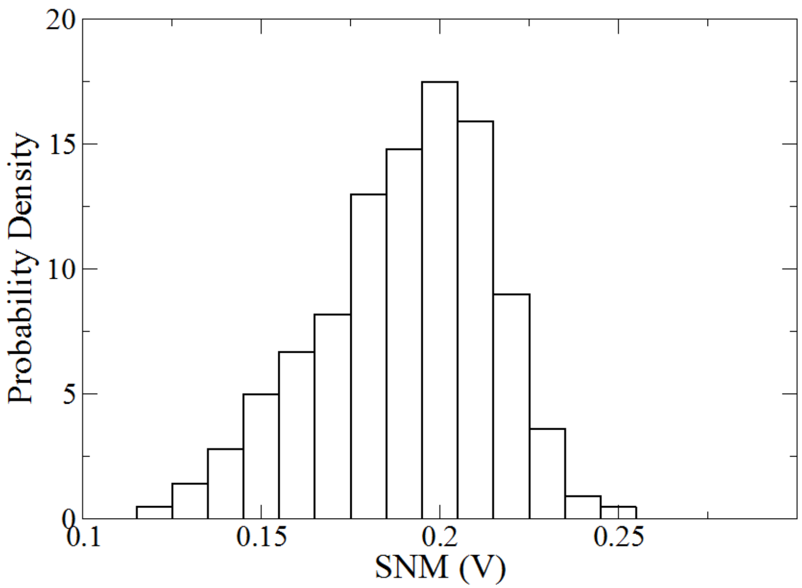
DEVICE CHARACTERISTICS

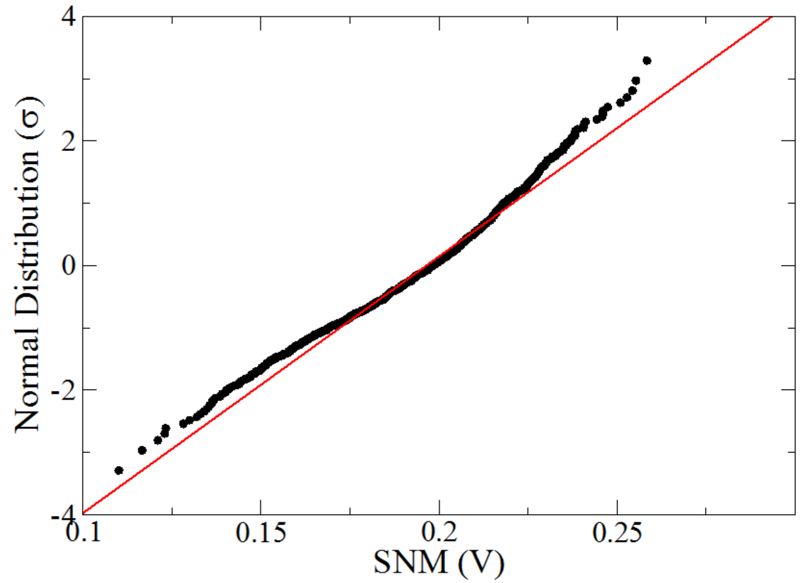


SPICE simulated IV-characteristics of 2 corner transistors due to GV in L and W resulting from combined lithography step and statistical variability due to RDD, LER and MGG.

SUPERTHEME GSS

SRAM SNM: COMBINED GV AND LV





- Example – SRAM SNM simulation in the presence of Combined Random GV and LV
- Produces multi-modal output distribution

CONCLUSIONS

- Performed comprehensive simulation of 20nm Planar Bulk MOSFETs
- At advanced technology nodes correlations between Global and Local variability require careful consideration
- Developed process and statistical variability aware compact modelling methodology and ModelGEN SPICE model generator to enable true TCAD DTCO flow.