MOVING VARIABILITY FROM DEVICES TO HIGHER LEVELS OF ABSTRACTION

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AGENDA

- Motivation & goals
- Preliminary discussions
- An approach for multivariate statistical modeling
- Extending BSIM4 towards statistical device modeling
- Abstracting variability using multivariate statistical modeling
- Summary & outlook
Motivation & Goals

- Fluctuations in semiconductor manufacturing
  - Global variations
    - lot-, wafer-, and reticle-based processing
  - Local variations in modern technology nodes
  - Discreteness of charge and matter

- Correlated variations in electrical characteristics

Bukhari et al., 2009.
Cheng et al., 2010.
Twaddle et al., 2009.
Motivation & Goals

- Statistical hierarchical model

- Anpassung
- Gleichrichtung
- Spannungsregelung

- Modulator
- Demodulator

- Transponder ASIC

- Overvoltage protection
- Takt-Erzeugung

- Digitalpart

- Sensor
- ADC
- EEPROM

Ch. Sohrmann, Fraunhofer EAS
Preliminary Discussions

- B. Cheng et. al.
  - 7 device parameters not necessarily Gaussian correlations

- U. Kovac et. al.
  - Multivariate Nonlinear Power Models (NPM)

- A. Lange et. al.
  - Generalized Lambda Distributions (GLD)
An Approach for Multivariate Statistical Modeling

- Description of marginal distributions: Generalized Lambda Distribution (GLD)

\[ x_i = F_{X_i}^{-1}(u) = \lambda_{i,1} + \left( \frac{y^{\lambda_{i,3}} - 1}{\lambda_{i,3}} - \frac{(1-y)^{\lambda_{i,4}} - 1}{\lambda_{i,4}} \right) / \lambda_{i,2} \]

- Multiple shapes, including Gaussian
- 4 parameters \( \rightarrow \) compact

- Correlations: rank correlation coefficients

\[ r_{X_i, X_j} = \text{corr} [\text{rk}(X_1), \text{rk}(X_2)] \]

- Application

   Training data \( \rightarrow \) Model fitting \( \rightarrow \) Random sampling
Extending BSIM4 towards Statistical Device Modeling

- (35x35)nm² NMOS and PMOS
- Device simulation of 200 microscopically different devices for each transistor type
- Mapping characteristics to BSIM4 device models
- 7 parameters capture variability

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Extending BSIM4 towards Statistical Device Modeling Marginal Distributions

- Usually non-Gaussian distributions
- Approximation using NPM and GLD feasible

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<tr>
<th>Model Parameter</th>
<th>Anderson-Darling test for normality</th>
<th>KS test</th>
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KS test: Kolmogorov-Smirnov test

NPM: Non-linear power model
Extending BSIM4 towards Statistical Device Modeling Correlations

Green: GLD; Red: NPM
Extending BSIM4 towards Statistical Device Modeling Application in SPICE Simulations

(a) inverter

(b) three-stage ring oscillator
Extending BSIM4 towards Statistical Device Modeling
Intermediate Results

- Origin: Industry-standard MOSFET compact model BSIM4
- Process variability leads to correlated non-Gaussian device model parameters
- GLD & rank correlation as a suitable method for modeling
- Application in circuit simulation shown

**Diagram:**
- Training data
- Model fitting
- Random sampling
Abstracting Variability Using Multivariate Statistical Modeling

- Focus on digital IC design
- Statistical extensions
  - Measurements → device model
  - Device model → logic gate model
  - …
Abstracting Variability Using Multivariate Statistical Modeling

- Example: Inverter chain
  - Up to 9 stages
  - Fixed input transition and output load

- Statistical gate-level analysis
  - Timing and energy

- Statistical inverter modeling
  - Delay, dynamic energy, leakage, …

- Characterization approaches
  - Direct extraction from SPICE reference simulation
  - Piecewise characterization
Abstracting Variability Using Multivariate Statistical Modeling

- Example: Inverter chain

- Direct extraction – 9 stages
Abstracting Variability Using Multivariate Statistical Modeling

- Example: Inverter chain

- Piecewise characterization – 8 stages
Abstracting Variability Using Multivariate Statistical Modeling

- Example: Inverter chain
- Analysis errors
Abstracting Variability Using Multivariate Statistical Modeling

- Example: Inverter chain

- Analysis effort

- Next steps
  - Application to industry-standard logic gate models: NLDM, CCS
  - Further research on characterization and analysis approaches
Summary & Outlook

- Global and local process variability
  - partially correlated device variability

- Modeling of variability
  - multivariate statistical modeling
    - Generalized Lambda Distribution (GLD)
    - Rank correlation coefficients

- Application examples
  - BSIM4 extension
  - Statistical logic gate models

- Outlook
  - Further abstraction of process variability