Worst-Case Modeling with SPAYN
Presentation Outline

Motivation

- Requirements for Accurate Worst-Case Modeling
- Traditional Approach to Worst-Case Modeling
- PCA or PFA Approach
- Worst-Case Design Techniques Employing PCA or PFA
- Worst-Case Analysis Example
Random statistical variablilities in any IC manufacturing process (sometimes unavoidable) lead to variations in device model parameters and thus also in circuit performance.
Motivation – Process Fluctuations

- Process Fluctuations Can:
  - Reduce circuit yield
  - Reduce circuit reliability
  - Cause expensive re-design cycles
  - Increase product time-to-market
  - Make circuit design difficult
Motivation – Aim

- To generate realistic and accurate worst-case model parameter sets using independent process-related components/factors so that circuit performance variability's can be predicted prior to circuit fabrication.
Motivation – Specific Aim

- Predict statistical circuit performance spreads
- Isolate the critical or “core” process variability's responsible
- Utilize this information to improve circuit reliability/yield
- Create a link between Process and Design functions
- Initiate Design For Manufacturability (DFM) projects
Motivation

Requirements for Accurate Worst-Case Modeling

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Requirements for Accurate Worst-Case Modeling

- Existing “Stable” Process
  - Automatic prober
  - Adequate electrical test (E-test) data
  - Accurate and ideally physical circuit simulator models
  - Accurate and fast parameter extraction software
  - Measured device/circuit performance data for verification of worst-case models
  - Split lots if possible
Requirements for Accurate Worst-Case Modeling

- Process Under Development
  - Accurate and calibrated process and device simulators
  - Integrated process and device simulation
  - Split lot (DOE, Monte Carlo) generation software
  - Split lot submission software
  - Integrated parameter extraction software
  - Integrated circuit simulation software
  - Split lots in silicon
Requirements for Accurate Worst-Case Modeling

- Additional
  - Statistical data analysis software
  - Accurate worst-case model generation software
  - Other statistical circuit design approaches allowed
  - Automatic link to circuit simulation
  - Dialog between Process, CAD, and Design personnel
  - Acceptance of worst-case methodologies by IC designers during circuit design stage
Requirements for Accurate Worst-Case Modeling

- Extracted Model Parameters (UTMOST)
- Process_Device Simulation Data (VWF)
- Electrical-Test Data
- Other sources of process and/or device data
- Circuit Test Data

SPAYN and/or VWF

Worst-Case Model Parameter Sets

Minimized Set of E-test Parameters

Minimized Set of SPICE Model Parameters

Relationships Between Process and CAD Parameters

Etc.

\[ P_i = a_1x_1 + a_2x_2 + \ldots + a_6x_6 \]
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Traditional Approach to Worst-Case Modeling

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Traditional Approaches to Worst-Case Modeling

- Measurements From Split Lots
  - Slow
  - Expensive
  - Process equipment concerns
  - Limited statistical information
  - May not reflect the true statistical process character
  - Over-optimistic or over-pessimistic predictions
  - Not enough information about model parameter variations and correlation's
Traditional Approaches to Worst-Case Modeling

- Educated Guesses
  - Deviate model parameters about their nominal values by +/- ?% so as to maximize or minimize device drive current
  - May not be so “educated”
  - Will not reflect true parameter variability's
  - Parameter correlation's ignored
  - Very limited statistical information
  - Usually over-conservative
  - Random
Traditional Approaches to Worst-Case Modeling

- Measured High Current and Low Current Wafer Die
  - Not enough statistical information
  - Unreliable
  - Bias dependent
  - High or low current may not be the issue
  - Parameter correlation's will not be accurately reflected
  - Predicted limits only, no probability information
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SPAYN Approach

- Collect Data
  - E-test
  - Parameter extraction
  - Circuit Test
  - Simulation
  - etc.

- Read data into SPAYN
  - Use SPAYN merge/append facilities where appropriate
PCA or PFA Approach

- Measure (or simulate) many sets of model parameters
- Remove outliers, calculate parameter statistics and correlation matrix
- Derive reduced set of independent components/factors that explain a predefined amount of variability (i.e. 80%) of the original correlated model parameters (PCA or PFA)
- Interpret results if possible
- Replace components/factors by their “dominant” parameters
- Generate equations relating original parameters to dominant pars
- Employ dominant parameters in worst-case approaches
- Utilize dominant parameters as useful process control quantities
Worst-Case Modeling with SPAYN

PCA or PFA Approach

Principal Factor Analysis (PFA) or Principal Component Analysis (PCA)

\[ P_i = a_{i1}X_1 + a_{i2}X_2 + \ldots + a_{im}X_m \]

- \( n \) correlated device and/or process monitor and/or circuit parameters
- \((n-1) \times (n-1)\) correlations of various magnitudes
- \( m \) \((m < n)\) uncorrelated process-related factors \((X's)\).

Can be used for isolating “core” process variables, relating device and circuit parameters to these “core” process variables, and for statistical circuit design.
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Worst-Case Design Techniques Employing PCA or PFA

- Worst-Case Analysis Example
Worst-Case Design Using PCA or PFA

SPAYN Options

User-defined Worst-case

- $2^n$ Corners (upper and lower factors/component limits)
- $3^n$ (upper limit, lower limit and nominal value)
  - Monte Carlo

SmartSpice Options

- View Parameter
- View Current

Internal SPICE equation solver

$P_i = a_1X_1 + a_2X_2 + \ldots + a_mX_m$

$Z =$ device or circuit characteristics

Worst-Case Modeling with SPAYN
Worst-Case Design Using PCA or PFA

- **User-Defined Corners**
  - Set each of the independent dominant parameters to +/- $N\sigma$ value
  - Calculate an associated correlated “corner” model parameter set
  - Simulate the device/circuit performance characteristic for which the worst-case parameters are required
  - Repeat with other user-defined corners
  - Select worst-case parameter set
Worst-Case Design Using PCA or PFA

- All Corners
  - Select upper and lower limits for the dominant parameters
  - Compose all combination of independent components (2 for upper and lower limits only, 3 if nominal values are included where n is the number of dominant parameters)
  - Calculate all “corner” model parameter sets
  - Simulate the device/circuit performance characteristic for which the worst-case parameters are required
  - Select worst-case performances
  - Identify worst-case model parameter sets
Worst-Case Design Using PCA or PFA

- Correlated Monte Carlo
  - Select number of parameter sets required for analysis
  - Use a random number generator (gaussian) to derive the required number of dominant parameter sets
  - Calculate associated model parameter sets
  - Simulate the device/circuit performance characteristic for which the worst-case parameters are required
  - Create predicted circuit performance histogram
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Worst-Case Analysis Example
Worst-Case Analysis Example

- Collect Data, (E-test, Parameter extraction, Circuit Test, Simulation, etc.)
- Read data into SPAYN. (use SPAYN merge/append facilities where appropriate)
- Remove outliers, calculate parameter statistics and correlation matrix, prepare histograms, scatter plots, PM or SPC charts, investigate parameter relationships, etc.
- Derive a reduced set of independent factors that explain a predefined amount of the variability (i.e. 80%) of the original correlated model parameters (i.e. PCA or PFA).
Worst-Case Analysis Example

- Interpret. Replace factors by their associated “independent”
- Dominant parameters
- Formulate equations relating the original parameters to these
- Dominant parameters
- Generate “process corner”, worst-case, or Monte Carlo parameter sets. Dominant parameters can also be utilized as very useful process control quantities
- Activate circuit simulations using SmartSpice or Third-party circuit simulators. Derive device characteristics using SPAYN’s internal SPICE model equations. Analyze results
Worst-Case Analysis Example

Import data, filter data, transform data if necessary, and prepare parameter statistics.
Worst-Case Analysis Example

Example: N-channel low-field mobility parameter (SPICE Level 3). Gaussian distribution as shown by histogram and cumulative plots.
Worst-Case Analysis Example

Example: N-channel static feedback parameter (SPICE Level 3). Log normal distribution as shown by histogram plots.
Worst-Case Analysis Example

Two correlated parameter pairs. One linear and one reciprocal.
Worst-Case Analysis Example

Typical correlation matrix (NMOS and PMOS parameters). Typical PCA setup conditions.
Worst-Case Analysis Example

Parameter groupings resulting from the PCA analysis. Dominant parameters selected by SPAYN used to generate a system of linear (default) equations for non-dominant parameters.
Worst-Case Analysis Example

Investigate/monitor trends using PM or SPC charts
Worst-Case Analysis Example

Investigate parameter/device characteristic relationships -> perform simulations
Dominant parameters can be changed. Typical SPAYN simulation interface display.
Worst-Case Analysis Example

Compare measured characteristics to worst-case simulations.
Worst-Case Analysis Example

Compare measured characteristics to worst-case simulations
Worst-Case Analysis Example

Circuit examples using process corner models (6 factors)
Presentation Outline

- Motivation
- Worst-Case Modeling Environment
- Traditional Approaches to Worst-Case Modeling
- SPAYN’s Approach
- Worst-Case Modeling Example

Conclusions/References
Conclusions

- Worst-case model parameters set generation using measured data is possible with Simucad’s SPAYN statistical analysis software package
- The combination of SPAYN and Virtual Wafer Fab (VWF) will enable worst-case model generation for a process under development
- SPAYN can be directly interfaced with commercial circuit simulators
- The methodology is both simple and accurate
References


