Different Strategies for Statistical Compact Modeling

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Overview

- **Process Manufacturing – Q&A**
- **Strategies for Statistical Compact Modeling**
- **Examples of Modeling process variations**

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Abstract

Statistical circuit simulations require model parameters that accurately represent not only the standard deviation of process control monitors (PCMs), but also the correlation structure between them. Usually the standard deviations of PCMs are chosen from specification limits of the technology, where are correlations between PCMs can be measured from sample wafers. The difficult task is then, to find the correlation structure of model parameters, which are widely used as independent and normally distributed random sources, so that correct PCM correlations are achieved by Monte-Carlo simulations. From our view, the correlation structure of model parameters can be combined into 5 different groups: uncorrelated, fully correlated, correlated within the same device type, correlated between different device types or by arbitrary correlation structure. In this presentation we review different strategies for selection of correlation structures of model parameters based on their physical meanings.

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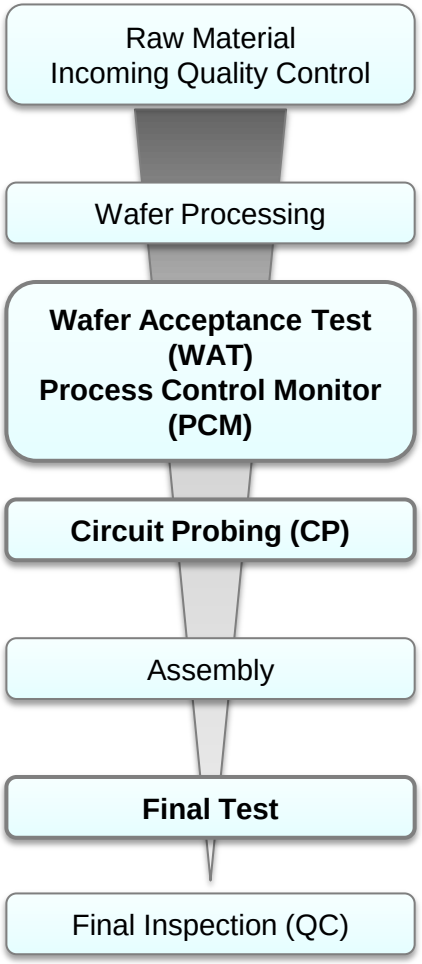
Process Variation – Manufacturing QA



Monitor environment, layer thickness, …
Daily, bi-weekly or monthly

Electrical & Visual, every wafer, 5 points per wafer

Electrical, every circuit, measuring specs

Electrical, every circuit, measuring specs

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Process Variation – Wafer Acceptance Test – Process Control Monitor

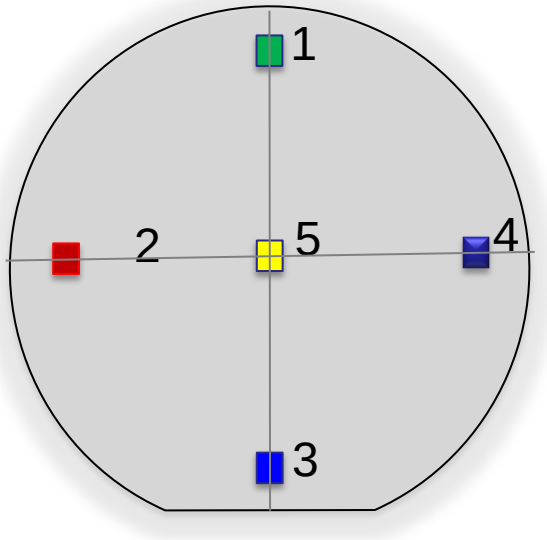
Usual:

- Measuring 5 data points per wafer
  - Pass/fail parameters: Used for wafer selection (WAT) – Process Control Monitor (PCM)
  - Information parameters: do not lead to wafer reject in case of failure
- Wafer accepted if pass/fail parameters are inside limits for at least 4 points

Example:

DISPOSITIONAL PASS/FAIL PARAMETERS					
Parameter	**Symbol**	**Min**	**Typ**	**Max**	**Unit**
NWELL sheet resistance	RSHN	54	60	66	Ω/□
PWELL sheet resistance	RSHP	76	90	104	Ω/□

Wafer map with 5 data points:



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Process Variation – Wafer Acceptance Test – Process Control Monitor (2)

Issues

- Only few parameters are measured. WAT/PCM does not contain all parameters that are necessary for correct MOS operation in analog circuits.
- Wafers with few WAT /PCM violations still get accepted.

Example:

Only digital DC metrics. No gm, rds, Cgs, …

DISPOSITIONAL PASS/FAIL PARAMETERS					
Parameter	**Symbol**	**Min**	**Typ**	**Max**	**Unit**
VTH(tri) long channel	VTLINL	540	600	660	mV
VTH (sat), long channel	VTSATL	560	640	720	mV
IDSAT short channel	IDSATS	340	360	380	uA/um
Drain-Source Breakdown short channel	VBDSS	4.1	>4.2	-	V

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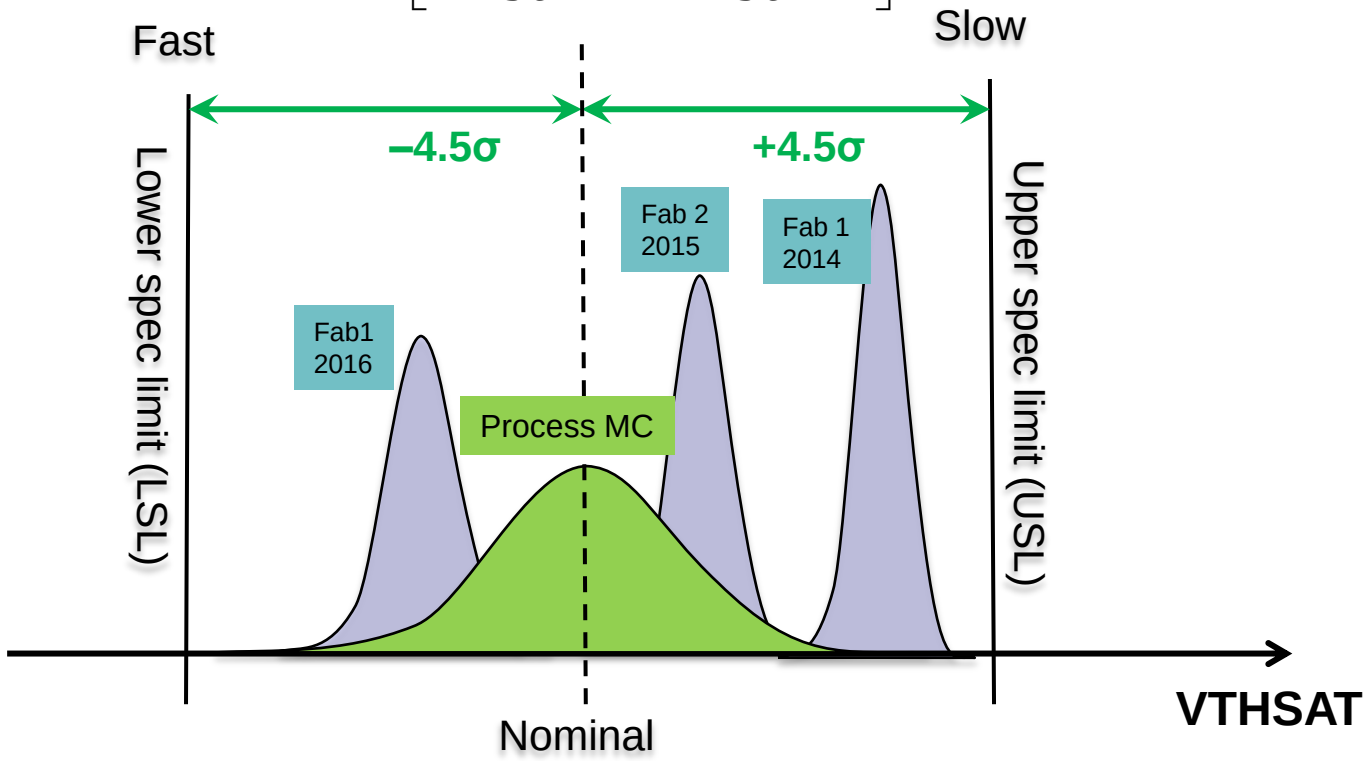
Process Monte-Carlo Analysis of Process Control Monitors (PCM)

$$CPK = \min\left[\frac{USL - \hat{\mu}}{3\sigma}, \frac{\hat{\mu} - LSL}{3\sigma}\right] = 1.5$$



- Process MC include variation, drift, difference between Fabs
- Good for design centering
- Does not enable “yield estimation”.

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Process Monte-Carlo model parameters' generation

- **Process MC is used to estimate variability of analog performances**

- **Advantage of process MC over process corners (ff,ss,…):**
  - Correct correlations between devices and parameters in devices
    (Corners usually correlate regular MOS, moscaps, I/O, …
    to achieve worst-case speed or power of digital logic)
  - More efficient when many device types are used (MOS, RES, CAP, …).
    (number of corners grows exponentially with device types)
  - Can be used for design centering (measuring safety distances of specs).
    (Corners: only pass/fail information)

- **Disadvantage to process corners:**
  - Does not prove correct function at process limits.
    Process drift may cause low yield although process MC shows high yield.

→ **Use both corners and process MC for analog sign-off**

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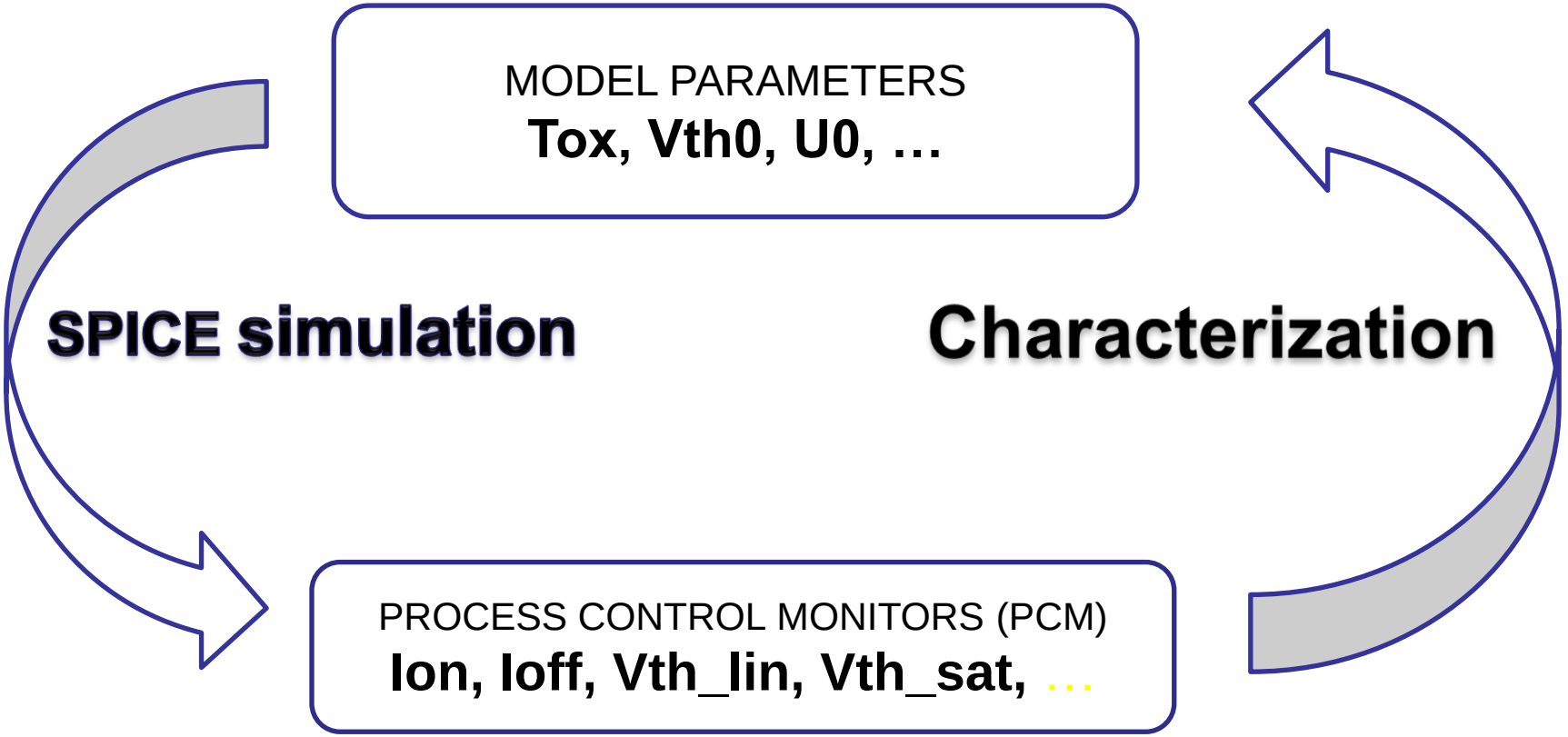
Relation between model parameters and PCM – Process Control Monitors



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MunEDA Statistical Fit Project Node

- **Purpose: Create Statistical Models that reproduce long-term process variation**
- **Inputs**
  - Netlist or schematic to simulate PCM testbenches with model files
  - Target PCM sigmas
  - Samples of PCMs for correlations/ Correlation file of PCMs
- **Results**
  - Set of model parameter sigmas (global MC parameters) and correlations between them if necessary
- **Benefit: More realistic sigmas / correlations of global MC parameters for analog design and verification**
  - Safer verification
  - Less pessimism in design → better utilization of process technology

Ultimate goal of statistical compact modeling is to reproduce electrical performances variations by simulations

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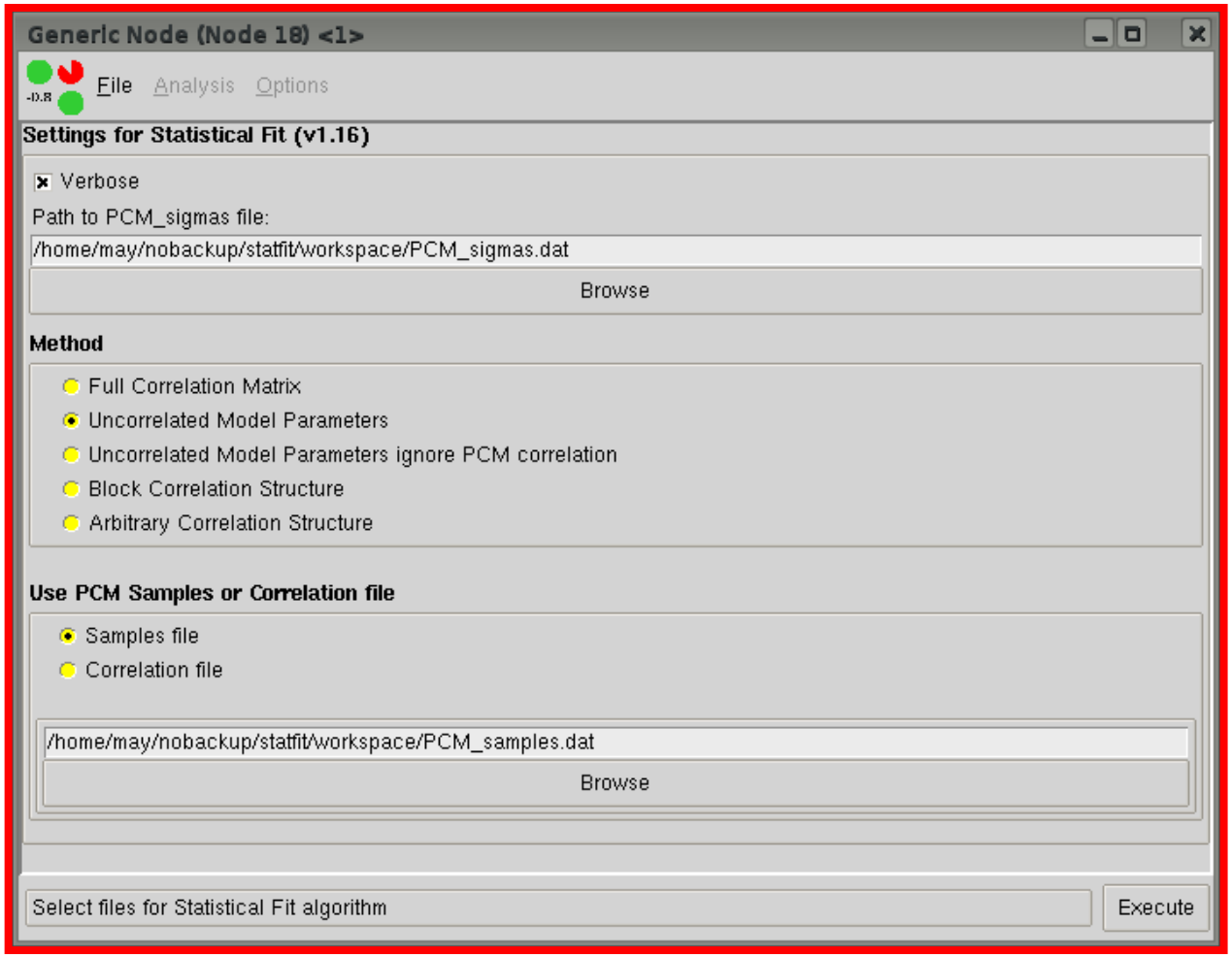
Screenshot of the Statistical Fit Project Node

Statistical Fit Project Node

Selection of target sigmas

Selection of strategy

Selection of Samples file or Correlation file



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Linear dependence of PCM variation on Model parameter variations

- **Assumption of linear dependence of PCM variation from model parameter variation:**

$$\Delta P = S \cdot \Delta M$$

- **ΔP – variation of PCM**
- **S – sensitivity of PCMs w.r.t. model parameters M (by simulation)**
- **ΔM – variation of model parameters**

- **Sample PCMs are not linear; transform them to alternative:**
  - COX – measurements of capacitance ⇒ TOX – oxide thickness
  - RON – measurements of on-resisitance ⇒ GON – on-conductance
  - ILEAK – leakage current ⇒ log(ILEAK) – logarithm of ILEAK
- **In order to include second order nonlinearities into the dependence of PCMs on parameter variation, consider, "quadratic BPV" ***

* I. Stevanovic, C.C.McAndrew, „Quadratic Backward Propagation of Variance for Nonlinear Statistical Circuit Modeling", IEEE on CAD, V.28,No.9, 2009

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Linear dependence of PCM variation on Model parameter variations

- **The variances of target PCMs are defined by specification:**
  - **σ(P) are defined from technology , e.g. (USL-LSL)/9**
- **The correlation of PCMs are measured from the FAB:**
  - **corr(P) are calculated from wafer**
- **Covariance matrix of PCM are constructed from variances and correlations of PCMs:**

$$cov(P) = \sigma(P) \cdot corr(P) \cdot \sigma(P)$$

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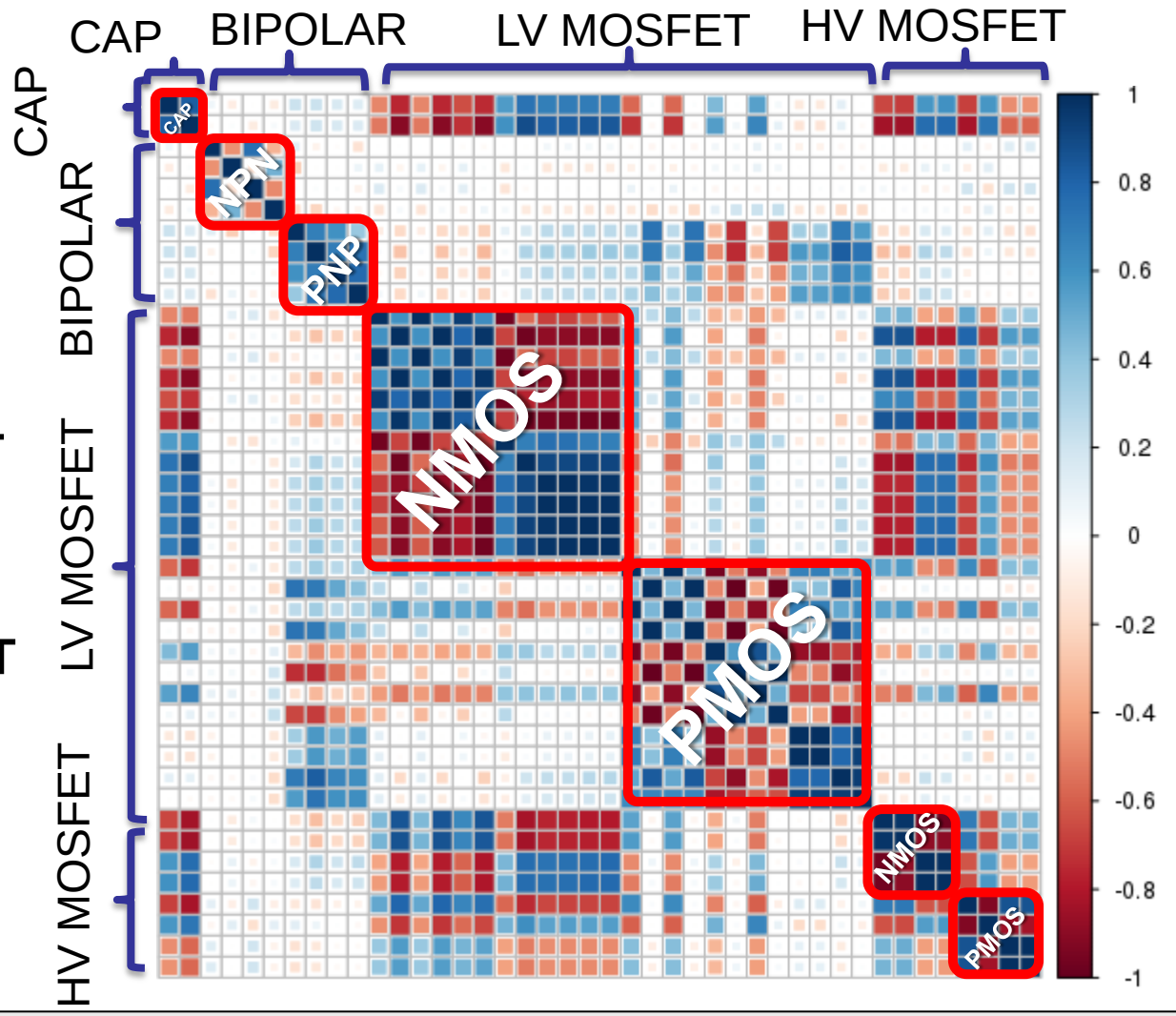
Sample structure of correlation matrix of PCMs (Measurement)

Typical correlation matrix of PCMs (Long-term data – 3 years of meas)

- **DEVICES**
- **CAPACITOR**
  - Different types
- **BIPOLAR**
  - NPN
  - PNP
- **Low Voltage MOSFET**
  - NMOS (diff geom)
  - PMOS (diff geom)
- **High Voltage MOSFET**
  - NMOS (diff geom)
  - PMOS (diff geom)



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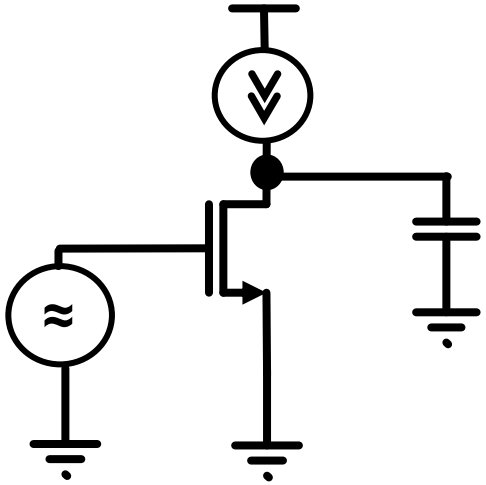
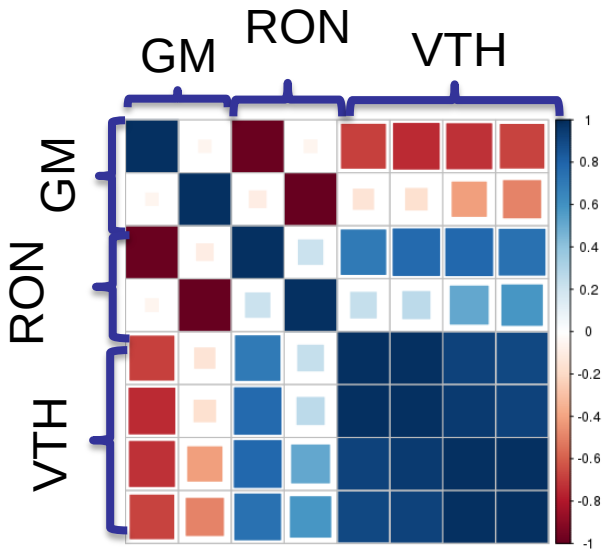
Why is the correlation between PCMs so important for analog design?

- **Common source single stage amplifier**



- **Low frequency gain: $A_v = g_m \cdot r_{on}$**
- **There is strong negative correlation between g_m and r_{on}:**



- **The MC model shall reproduce these correlation**

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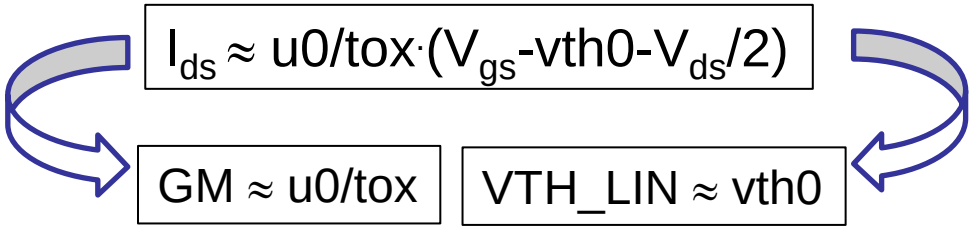
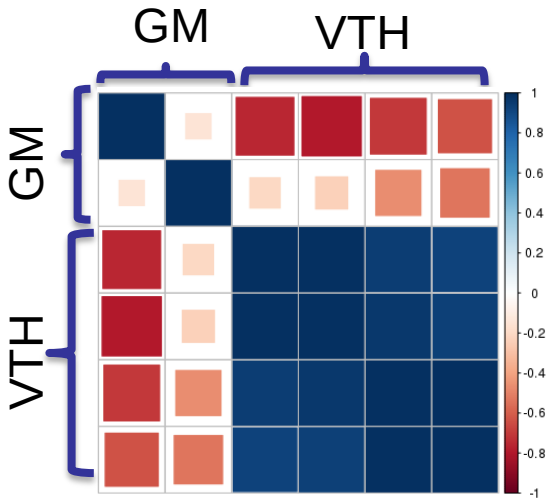
Typical problem with modeling of the correlation of PCMs

- **Three typical model parameters for process MC:**
  - tox – oxide thickness
  - u0 – mobility
  - vth0 – threshold voltage



- **Consider two PCMs from the same device:**
  - GM – maximum gm
  - VTH_LIN – extrapolated Vth
- **The variance of Gm:**
  - ≈ 60% dependence on u0
  - ≈ 40% dependence on tox
- **The variance of VTH_LIN:**
  - ≈ 100% dependence on vth0



If **tox**, **u0** and **vth0** are independent random source, then in simulations there is no correlation between GM and VTH_LIN, what is wrong!

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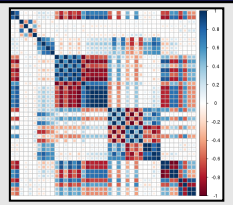
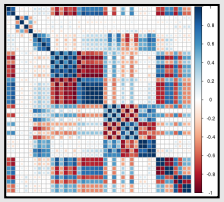
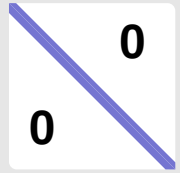
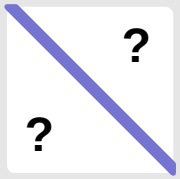
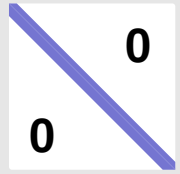
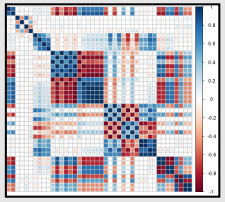
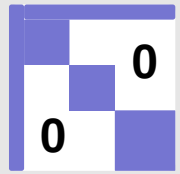
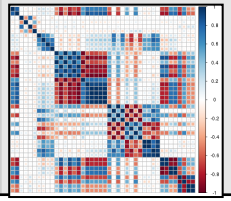
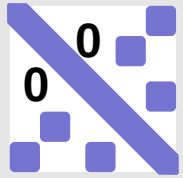
Strategies for Statistical Compact Modeling

Method	Purpose	Matrix of PCMs		Matrix of Model Parameters	
Full Correlation Matrix	Mathematical approach without physical distinguishes of model parameters	Full Covariance		Full Covariance	
Uncorrelated Model Parameters	Pay attention on correlation of PCMs, but produce uncorrelated model parameters matrix	Full Covariance		Only diagonal elements	
Uncorrelated Model Parameters ignore PCM correlation	Unknown correlation between PCMs, preliminary estimation of model parameters' sigmas	Only diagonal elements		Only diagonal elements	
Block Correlation Structure	Known correlation structure of model parameters, take into account correlation between PCMs	Full Covariance		Block-wise model parameters	
Arbitrary Correlation Structure	Know correlation structure of model parameters, but not block wise	Full Covariance		Arbitrary structure	

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(1) Method: Full Correlation Matrix (*)

- Assuming special type of covariance matrix of PCMs – positive semi definite
- Produces full matrix of model parameters
- Advantage: it reproduces correctly correlations of PCMs
- Drawback: correlations between model parameters are not physically explainable

(1) $\Delta P = S \cdot \Delta M \quad (N_{pcm} \geq N_M)$

(2) $Cov(P) = S \cdot cov(M) \cdot S^T$

(3) $Cov(P) = Q \cdot \lambda \cdot Q^T$

(4) $G = Q \cdot sqrt(\lambda) \Rightarrow Cov(P) = G \cdot G^T$

(5) $S \cdot H = G$

(6) $Cov(M) = H \cdot H^T$

* Klaus-Willi Pieper, Elmar Gondro „An effective method for solving the covariance equation for statistical modeling“, 2011, IEEE

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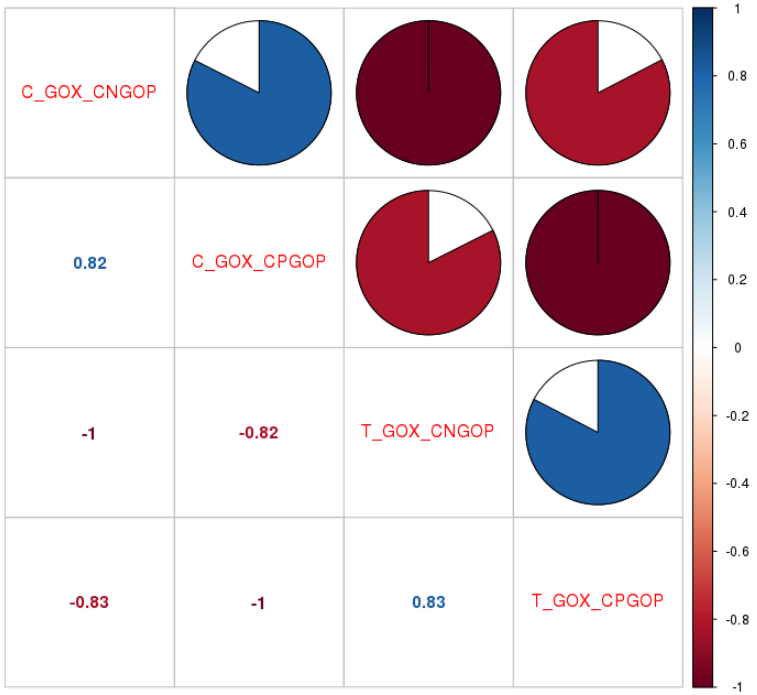
Example of Full Correlation Matrix Method

E.g. two different types of Capacitors:

- Modelled with two parameters and one correlation factor
  - TOXN
  - TOXP

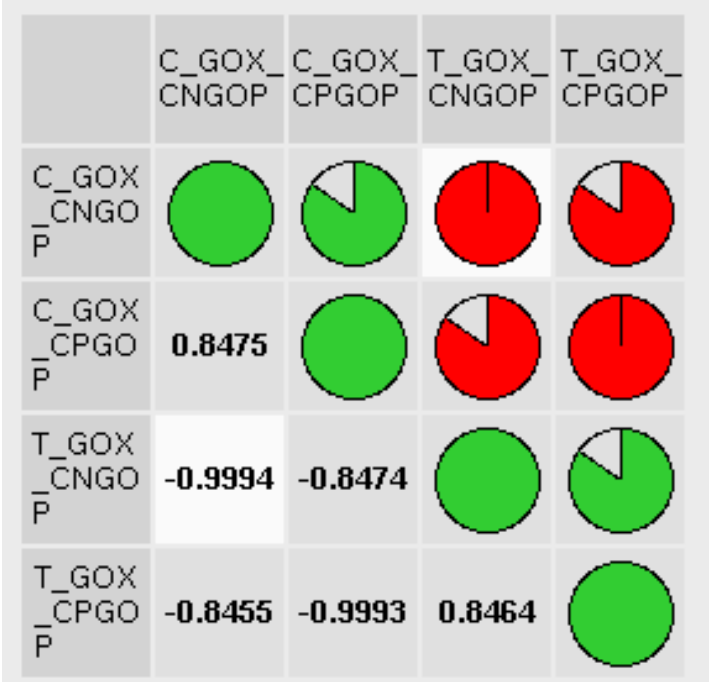
  } cc_TOXN_TOXP

Correlation matrix of measurements



cc(T_GOX_CPGOP,C_GOX_CNGOP)=-0.83

Simulation by Monte-Carlo



cc(T_GOX_CPGOP,C_GOX_CNGOP)=-0.85

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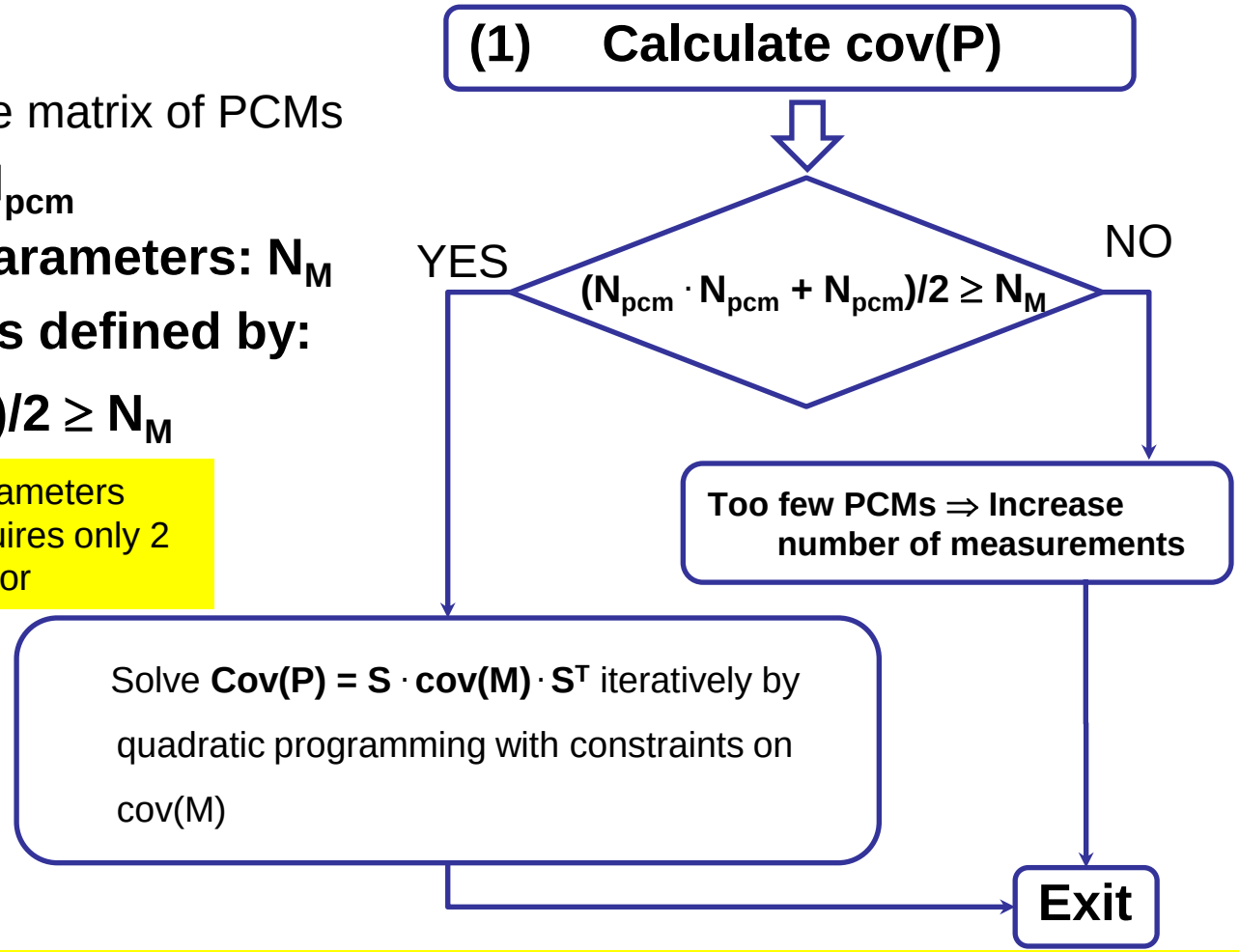
(2) Method: Uncorrelated Model Parameters *

- **Input is :**
  - cov(P) - covariance matrix of PCMs
- **Number of PCMs: N_{pcm}**
- **Number of model parameters: N_M**
- **Required min N_{pcm} is defined by:**

$$(N_{pcm} \cdot N_{pcm} + N_{pcm})/2 \geq N_M$$

As example for 3 model parameters estimation, this method requires only 2 PCMs and 1 correlation factor

- **Output:**
  - Sigmas of model parameters



* I. Stevanovic, X.Li, C.C.McAndrew, K.R.Green, G.Gildenblat „Statistical modeling of inter-device correlations with BPV“, Solid-State Electronics, 54, pp.796-800, 2010

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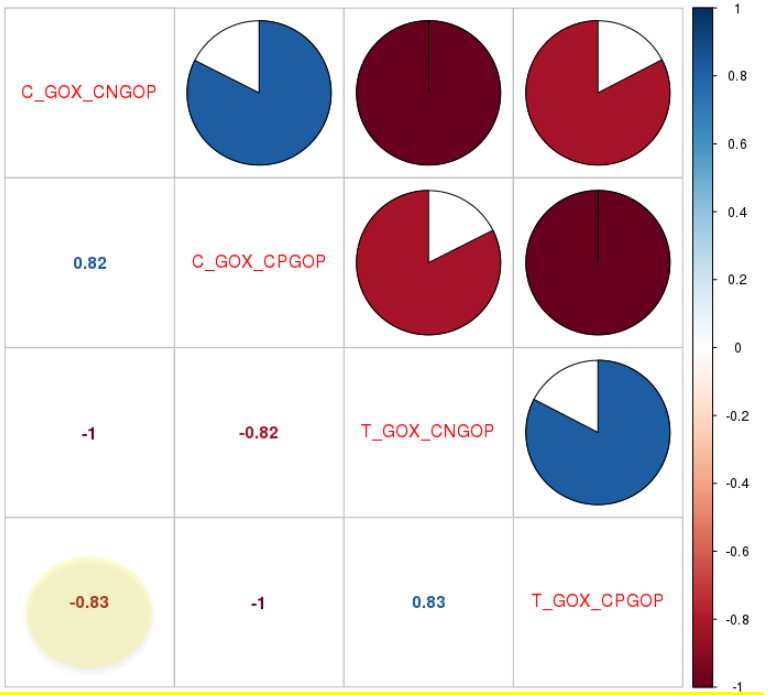
Example of Uncorrelated Model Parameters

E.g. two different types of Capacitors:

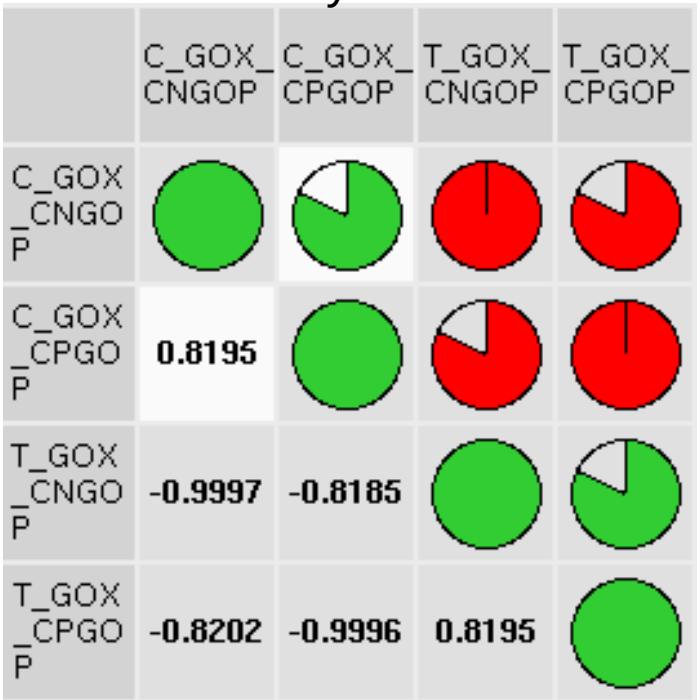
- Modeled with three model parameters
  - TOX
  - ΔTOXN
  - ΔTOXP

Correlation matrix of measurements



cc(T_GOX_CPGOP,C_GOX_CNGOP)=-0.83

Simulation by Monte-Carlo



cc(T_GOX_CPGOP,C_GOX_CNGOP)=-0.82

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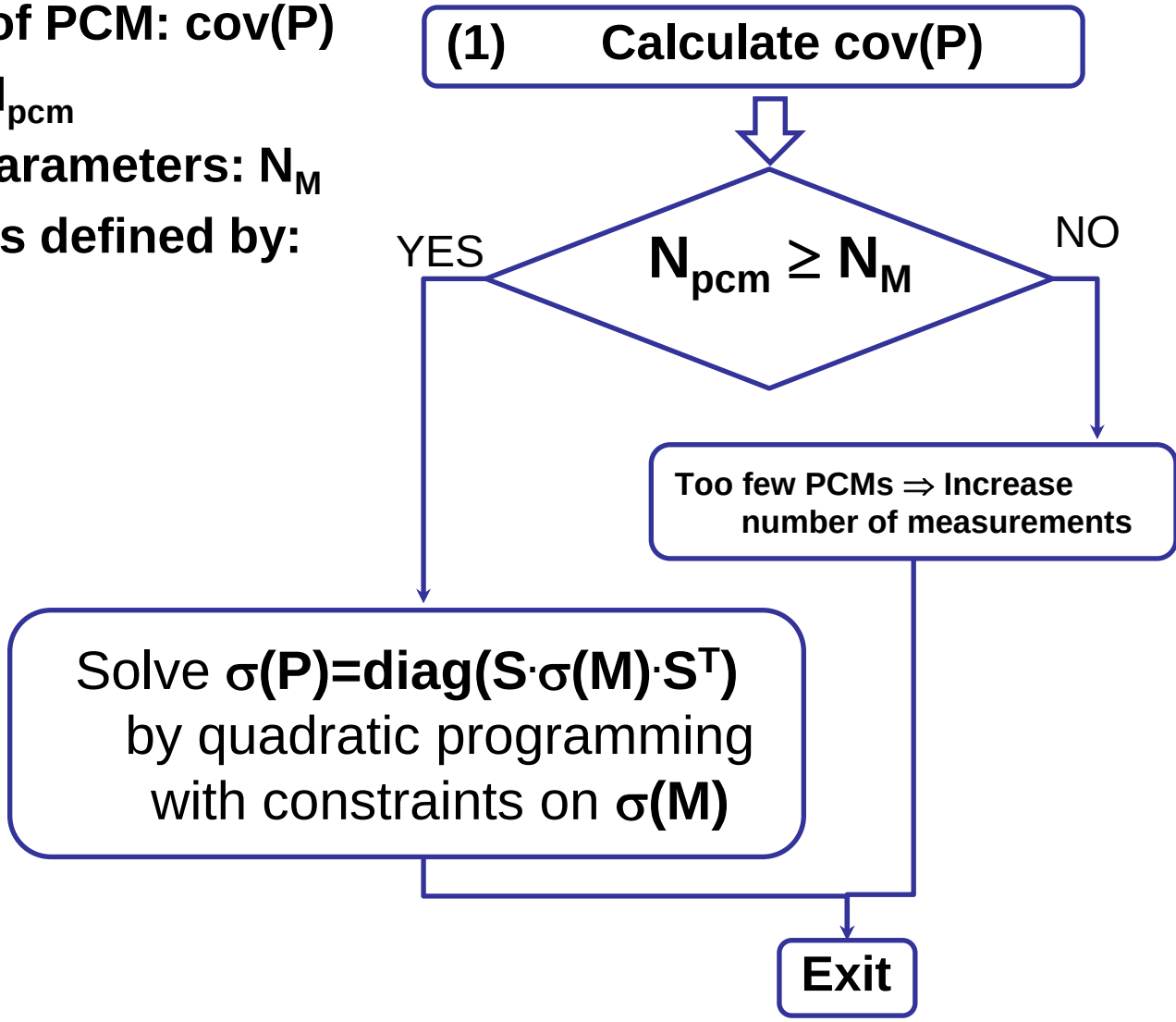
(3) Method: Uncorrelated Model Parameters ignore PCM correlation

- Covariance matrix of PCM: cov(P)
- Number of PCMs: N_{pcm}
- Number of model parameters: N_M
- Required min N_{pcm} is defined by:

$$N_{pcm} \geq N_M$$



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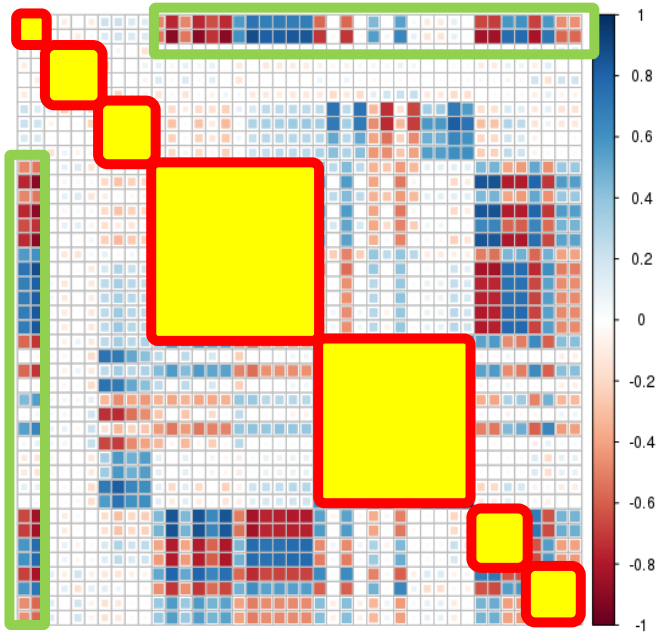
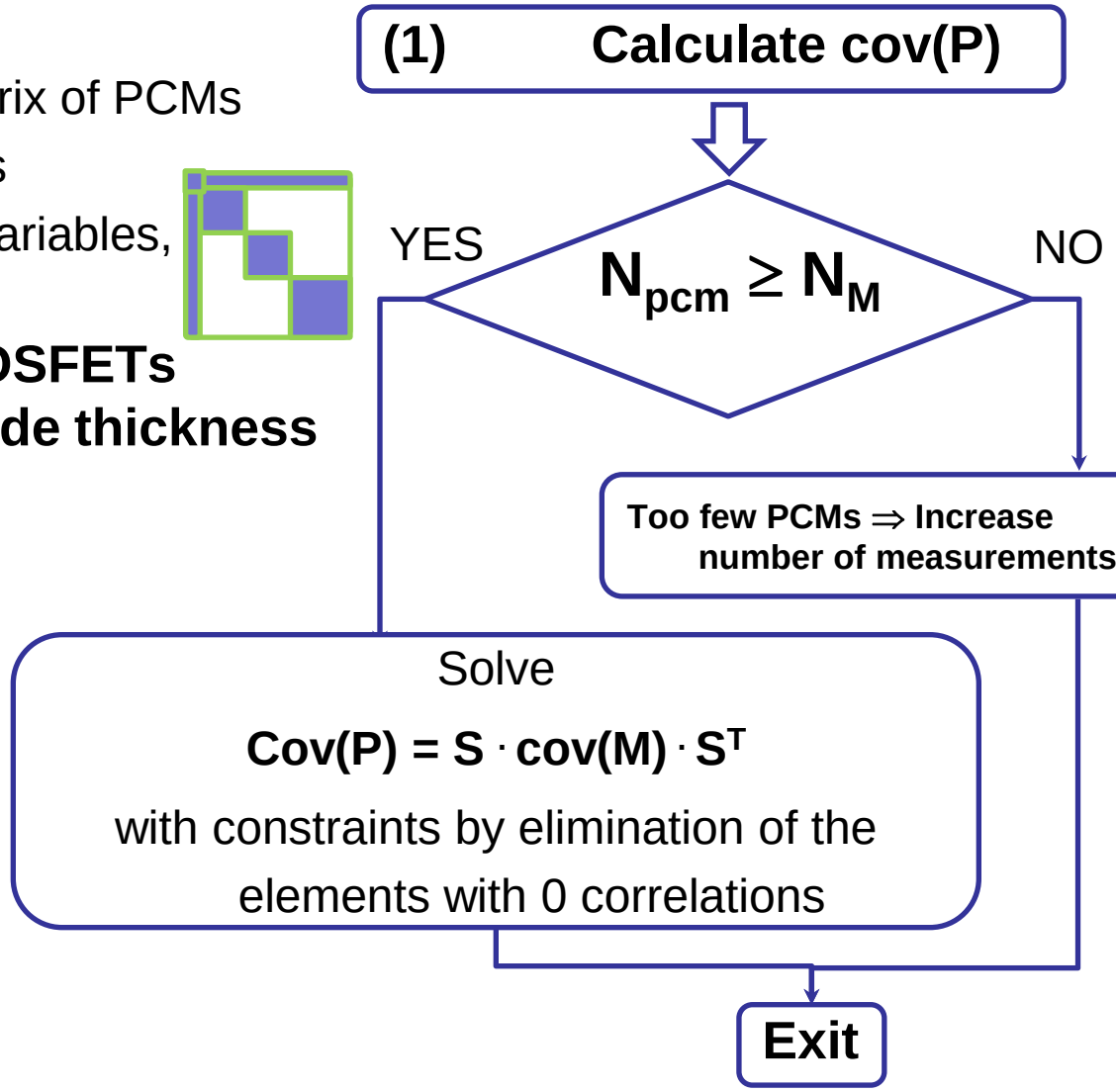
(4) Method: Block Correlation Structure

- **Inputs are**
  - Cov(P) – covariance matrix of PCMs
  - Blocks – indexes of blocs
  - First block is the global variables, correlate with all others

- **Strong correlation of MOSFETs through capacitance/oxide thickness**





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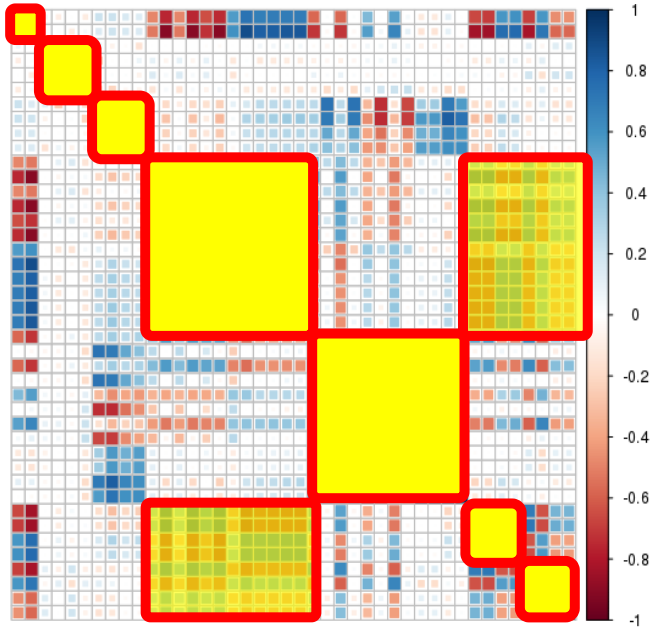
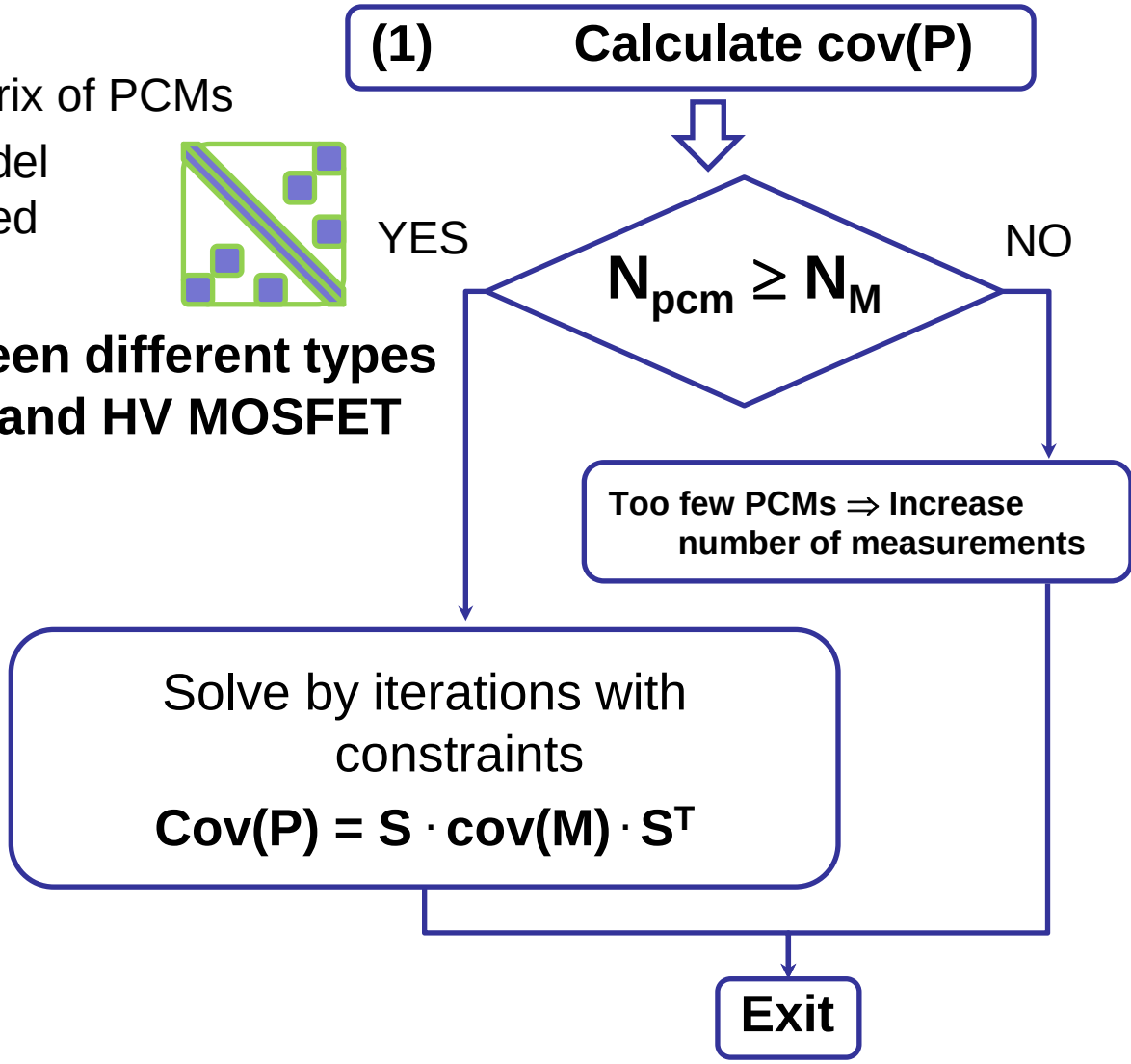
(5) Method: Arbitrary Correlation Structure

- **Inputs are**
  - Cov(P) – covariance matrix of PCMs
  - Indexes of blocks for model parametes to be correlated

- **Strong correlation between different types of devices: LV MOSFET and HV MOSFET**





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Conclusion

- Ultimate goal of statistical modeling to reproduce the correlations between measurements of PCMs can be achieved
- There are several strategies developed to obtain desired correlations of PCMs
- Mathematically rigorous method of transforming covariance matrix leads to unphysical correlation of model parameters, but gives the best fitting accuracy
- There are several physical meanings for selection of proper correlation of model parameters
- Based on the assumptions the complexity of model parameters' can be significantly reduced
- The Statistical Fit Project Node is developed for WiCkeD tools suite this can

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Thank You !

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