

# Bip AK München 2016

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A. Steinmair

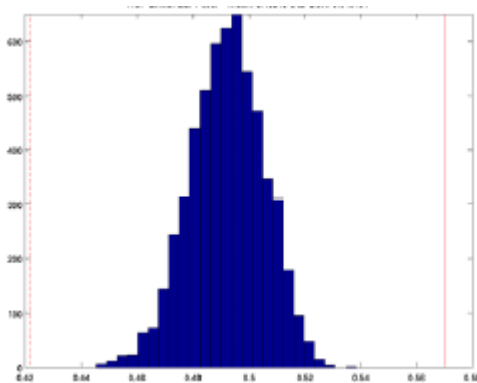
2016-11-25

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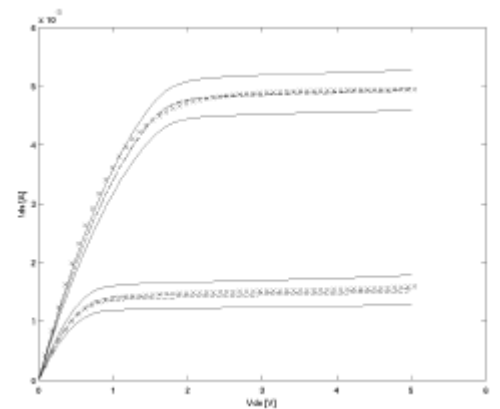
# Simulation of Process Variability Introduction

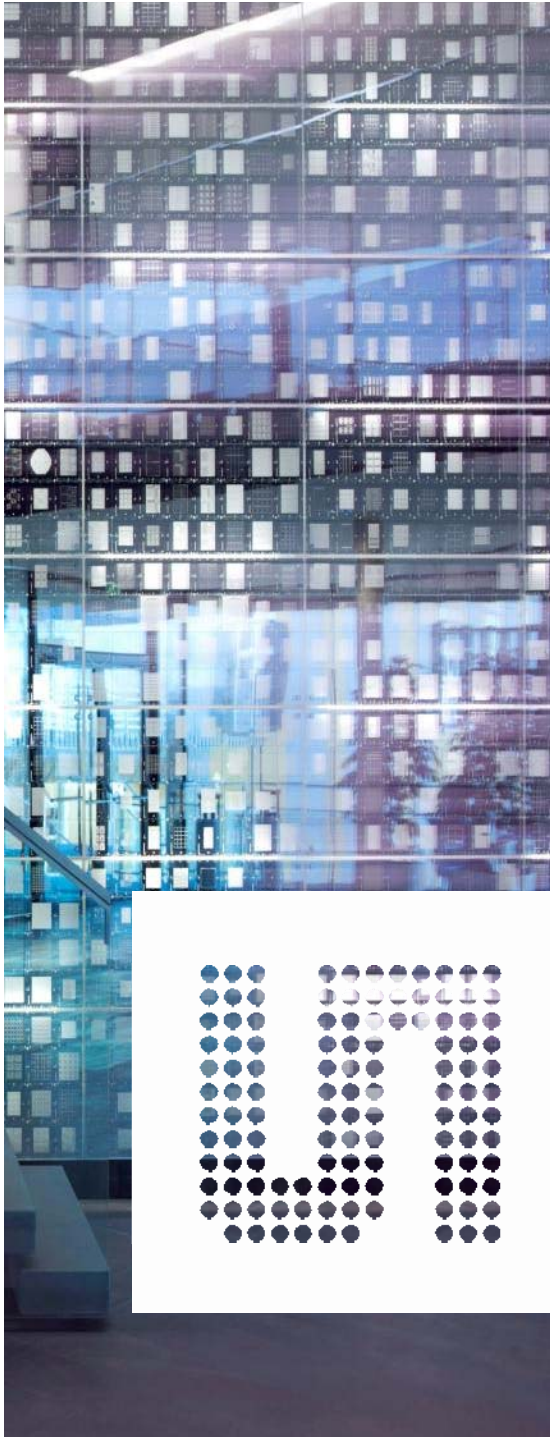
- ❑ Unavoidable statistical fluctuation in the silicon process
- ❑ Design of products needs to take the variability into account.
- ❑ IC design is extensively dependent on the simulation and models
- ❑ Implementation of variability in Compact models.
- ❑ Corner models support during process/device development

Definition of parameter Spec based on statistical data



Generation of Corner Models





# Correlated Statistical SPICE Models for High-Voltage LDMOS Transistors based on TCAD

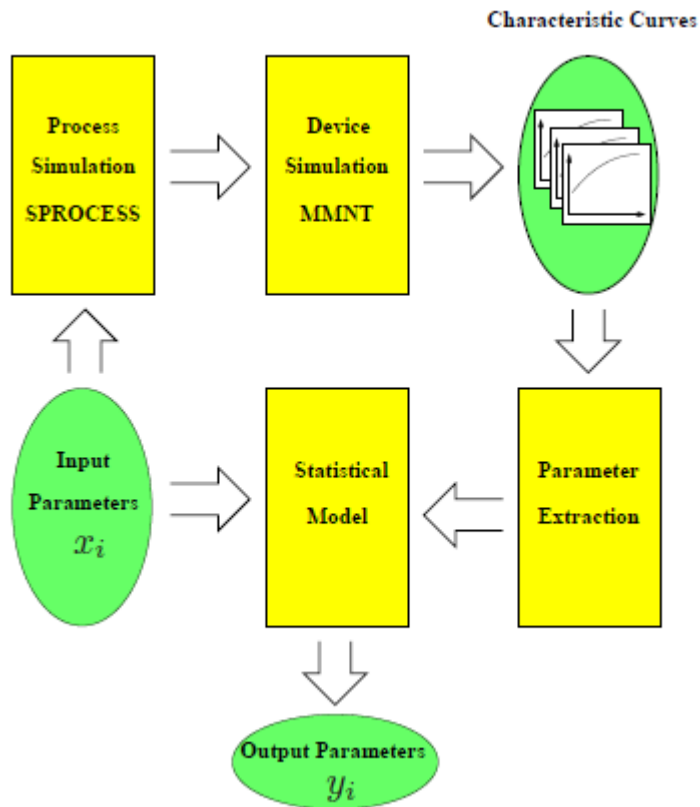
## Cooperation ams and TUW



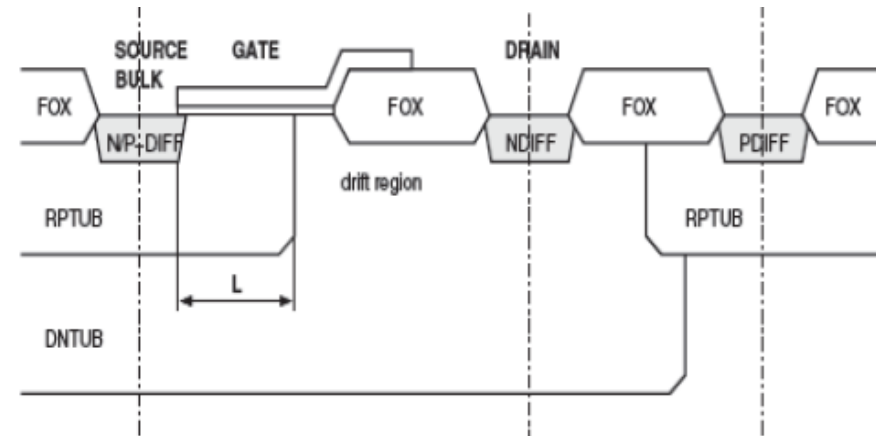
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November 22, 2016

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# TCAD Simulations of Statistical Process Variations for High-Voltage LDMOS Transistors



## Parameter Variability for: RON, VT, IDSAT, Gamma



# Input and Output parameter

7- 8 critical process variables as input parameter

Responsible for the variability of the electrical parameters

## Input Parameter

|               |   |
|---------------|---|
| SX.....       | Substrate resistivity                       |
| DN_DOSE....   | DN Dotierung                                |
| DPOVERLAY.... | DP variation under active                   |
| SNOVERLAY.... | SN variation under active                   |
| PADOX_VTH.... | Screening oxide thickness during VT implant |
| VT_Imp.....   | VT implant dose                             |
| TOX.....      | OXIDE thickness for thin oxide              |



## Output Parameter:

VTlarg  
 VTshort,  
 RON,  
 IDSAT,  
 Gamma



# PROCESS VARIATION AWARE TCAD SIMULATION

•time consuming method of  $3^8=6561$  full factorial combinations

→Central Composite Face - centered (CCF) design was chosen

- For n parameters this method consists of  $2n$  full factorial simulations of the min/max combinations,
- $2n$  axial points of the screening analysis, and one simulation for the center point.

In sum this leads to 273 (143) variations in 8 (7) parameters for each, minimum and long channel length device.



## Input Parameters (N & PLDMOS)

|                          |           |           |           |
|--------------------------|-----------|-----------|-----------|
| SX                       | 18        | 20        | 22        |
| DN_DOSE                  | 4.05E+012 | 4.10E+012 | 4.15E+012 |
| DPOverlay<br>(SPOverlay) | -0.1      | 0         | 0.1       |
| SNOverlay                | -0.1      | 0         | 0.1       |
| PADOX_VthM               | 0.1       | 10.05     | 20        |
| Vt_2p7e12                | 2.65E+012 | 2.70E+012 | 2.75E+012 |
| TOXTH                    | -2        | 0         | 2         |

- 143 (7 PV for HV-PMOS) and
- 272 (8 PV for HV-NMOS)
- Full Process and Device Simulations

|               |   |
|---------------|---|
| SX.....       | Substrate resistivity                       |
| DN_DOSE....   | DN Dotierung                                |
| DPOVERLAY.... | DP variation under active                   |
| SNOVERLAY.... | SN variation under active                   |
| PADOX_VTH.... | Screening oxide thickness during VT implant |
| VT_Imp.....   | VT implant dose                             |
| TOX.....      | OXIDE thickness for thin oxide              |





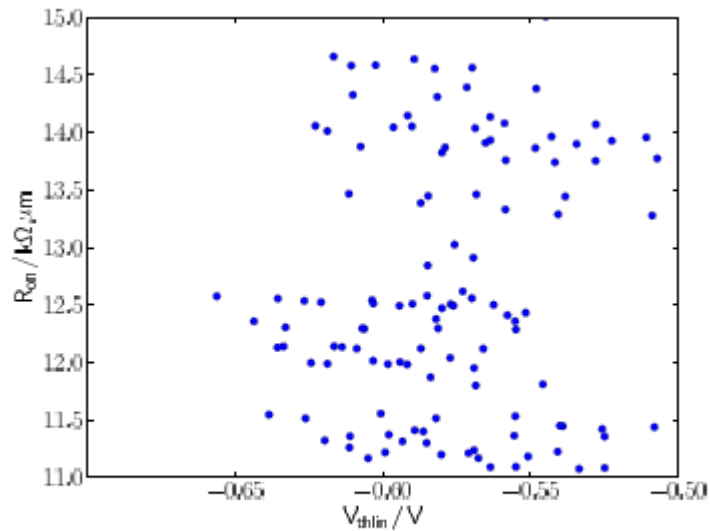
# Extracted Data based on process and device simulation

Resulting Input and Output Parameter (142 PMOS, 272 NMOS)

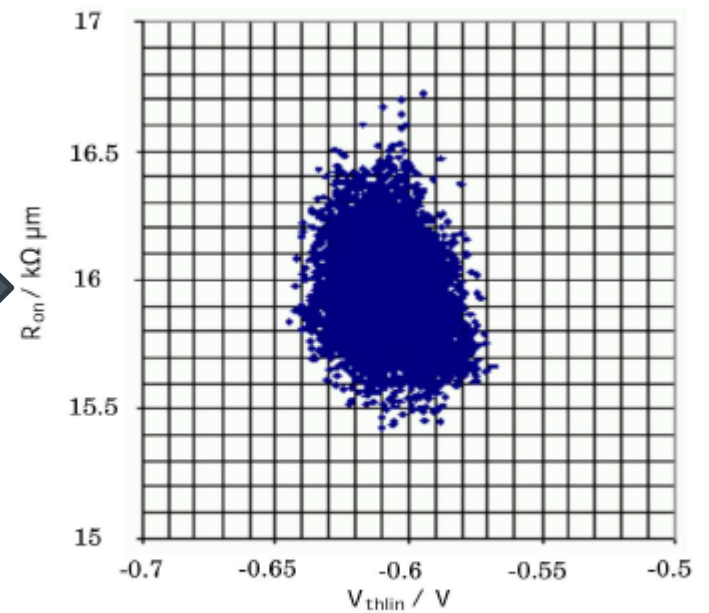
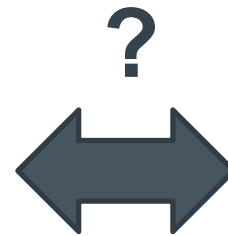
| Experiment | SX | DN_DOSE   | DPOverlay | SNOOverlay | PADOX_VthM | Vt_2p7e12 | TOXTH | Vth_sat      | Ron            | Sleak         | Gamma        | Vth_lin       | alpha1       |
|------------|----|-----------|-----------|------------|------------|-----------|-------|--------------|----------------|---------------|--------------|---------------|--------------|
| 1 n785     | 20 | 4.10E+012 | 0         | 0          | 10.05      | 2.70E+012 | -2    | 0.4418389961 | -12.4108273522 | 4.6859879685  | 0.5423365316 | -0.5577937672 | 0.6156625542 |
| 2 n786     | 20 | 4.10E+012 | 0         | 0          | 10.05      | 2.70E+012 | -2    | 0.4602886729 | -12.5072147868 | 3.1225007814  | 0.5388226045 | -0.5769522122 | 0.6195464646 |
| 3 n787     | 20 | 4.10E+012 | 0         | 0          | 10.05      | 2.70E+012 | 2     | 0.4683726609 | -12.5804197039 | 2.8517789478  | 0.5365587374 | -0.58496324   | 0.6148850785 |
| 4 n788     | 20 | 4.10E+012 | 0         | 0          | 10.05      | 2.65E+012 | 0     | 0.4744379463 | -12.5101207659 | 2.5805565115  | 0.5272041217 | -0.5899195998 | 0.6267222883 |
| 5 n789     | 20 | 4.10E+012 | 0         | 0          | 10.05      | 2.75E+012 | 0     | 0.445164127  | -12.5018939588 | 4.4669351227  | 0.5490772146 | -0.5624501016 | 0.6117389456 |
| 6 n790     | 20 | 4.10E+012 | 0         | 0          | 0.1        | 2.70E+012 | 0     | 0.4335202708 | -12.4328948488 | 6.4209033331  | 0.556062035  | -0.5516030764 | 0.610602673  |
| 7 n791     | 20 | 4.10E+012 | 0         | 0          | 20         | 2.70E+012 | 0     | 0.4898875652 | -12.5424790247 | 2.2370144398  | 0.5160682191 | -0.6035310431 | 0.641221596  |
| 8 n792     | 20 | 4.10E+012 | 0         | -0.1       | 10.05      | 2.70E+012 | 0     | 0.4642360194 | -13.0246494878 | 2.8260358903  | 0.5463227897 | -0.5756626942 | 0.569953534  |
| 9 n793     | 20 | 4.10E+012 | 0         | 0.1        | 10.05      | 2.70E+012 | 0     | 0.4369470711 | -12.1197159606 | 5.9920471343  | 0.533641826  | -0.5659602304 | 0.6698419167 |
| 10 n794    | 20 | 4.10E+012 | -0.1      | 0          | 10.05      | 2.70E+012 | 0     | 0.4590493509 | -14.0378154885 | 3.5221770033  | 0.5383912192 | -0.5686837414 | 0.6462426306 |
| 11 n795    | 20 | 4.10E+012 | 0.1       | 0          | 10.05      | 2.70E+012 | 0     | 0.432571597  | -11.8000308712 | 5.4886131214  | 0.5575221921 | -0.5684836969 | 0.6242860798 |
| 12 n796    | 20 | 4.05E+012 | 0         | 0          | 10.05      | 2.70E+012 | 0     | 0.4632900827 | -12.8433151386 | 3.5129901574  | 0.5372342823 | -0.5847523526 | 0.651636429  |
| 13 n797    | 20 | 4.15E+012 | 0         | 0          | 10.05      | 2.70E+012 | 0     | 0.4540051456 | -12.5588375259 | 3.6693590395  | 0.5374016228 | -0.5697960769 | 0.6170017315 |
| 14 n798    | 18 | 4.10E+012 | 0         | 0          | 10.05      | 2.70E+012 | 0     | 0.4549768458 | -12.9110716565 | 3.5979748537  | 0.5364611355 | -0.5693054502 | 0.6316684158 |
| 15 n799    | 18 | 4.05E+012 | -0.1      | -0.1       | 0.1        | 2.65E+012 | -2    | 0.4449956529 | -14.3931081538 | 4.0072610488  | 0.5593832897 | -0.5715088193 | 0.595919401  |
| 16 n800    | 18 | 4.05E+012 | -0.1      | -0.1       | 0.1        | 2.65E+012 | -2    | 0.4775020453 | -14.5849403811 | 2.7718958897  | 0.5513596748 | -0.6023441778 | 0.6013351223 |
| 17 n801    | 18 | 4.05E+012 | -0.1      | -0.1       | 0.1        | 2.75E+012 | -2    | 0.4123633378 | -14.3812962843 | 7.2351746343  | 0.5838005433 | -0.5480147365 | 0.5824273421 |
| 18 n802    | 18 | 4.05E+012 | -0.1      | -0.1       | 0.1        | 2.75E+012 | -2    | 0.4393799347 | -14.5637331427 | 5.1521965534  | 0.5746753792 | -0.5696760526 | 0.5836232195 |
| 19 n803    | 18 | 4.05E+012 | -0.1      | -0.1       | 20         | 2.65E+012 | -2    | 0.4950741667 | -14.5815764508 | 1.7571754132  | 0.5217500559 | -0.6105929237 | 0.6201752265 |
| 20 n804    | 18 | 4.05E+012 | -0.1      | -0.1       | 20         | 2.65E+012 | -2    | 0.5106363237 | -14.659803787  | 1.2258344986  | 0.5081660988 | -0.6165805936 | 0.6038043282 |
| 21 n805    | 18 | 4.05E+012 | -0.1      | -0.1       | 20         | 2.75E+012 | -2    | 0.4626939103 | -14.5545905943 | 2.8334431763  | 0.5445241294 | -0.5823585212 | 0.6028930571 |
| 22 n806    | 18 | 4.05E+012 | -0.1      | -0.1       | 20         | 2.75E+012 | -2    | 0.4832332173 | -14.6375421441 | 2.1842807434  | 0.5290107896 | -0.5893039894 | 0.5906334375 |
| 23 n807    | 18 | 4.05E+012 | -0.1      | 0.1        | 0.1        | 2.65E+012 | -2    | 0.4170966218 | -13.288013412  | 9.081437868   | 0.5488223298 | -0.5406273617 | 0.6843583582 |
| 24 n808    | 18 | 4.05E+012 | -0.1      | 0.1        | 0.1        | 2.65E+012 | -2    | 0.4438372914 | -13.4610584971 | 5.8786223976  | 0.5377936321 | -0.5683030339 | 0.690237953  |
| 25 n809    | 18 | 4.05E+012 | -0.1      | 0.1        | 0.1        | 2.75E+012 | -2    | 0.3840666699 | -13.2782627125 | 15.0845992593 | 0.5709341008 | -0.5087702864 | 0.6659691494 |
| 26 n810    | 18 | 4.05E+012 | -0.1      | 0.1        | 0.1        | 2.75E+012 | -2    | 0.4126441761 | -13.4430776001 | 10.3850814712 | 0.5594072999 | -0.5382100551 | 0.6730844191 |
| 27 n811    | 18 | 4.05E+012 | -0.1      | 0.1        | 20         | 2.65E+012 | -2    | 0.4671125257 | -13.3865616043 | 3.4167649668  | 0.5131811007 | -0.5871053047 | 0.7133460284 |
| 28 n812    | 18 | 4.05E+012 | -0.1      | 0.1        | 20         | 2.65E+012 | -2    | 0.4894992788 | -13.4666551949 | 2.8224303517  | 0.4946479537 | -0.6114052771 | 0.7001755939 |
| 29 n813    | 18 | 4.05E+012 | -0.1      | 0.1        | 20         | 2.75E+012 | -2    | 0.4390509924 | -13.3301534697 | 6.2150015594  | 0.5321455876 | -0.5584720188 | 0.6899781843 |
| 30 n814    | 18 | 4.05E+012 | -0.1      | 0.1        | 20         | 2.75E+012 | -2    | 0.4607523073 | -13.4483336203 | 4.8378531811  | 0.5163932992 | -0.5846012016 | 0.6854563173 |
| 31 n815    | 18 | 4.05E+012 | 0.1       | -0.1       | 0.1        | 2.65E+012 | -2    | 0.444136006  | -11.8713547113 | 4.687988329   | 0.558061498  | -0.5837573282 | 0.5675913522 |
| 32 n816    | 18 | 4.05E+012 | 0.1       | -0.1       | 0.1        | 2.65E+012 | -2    | 0.4708634868 | -12.0044047522 | 3.015288591   | 0.5439775439 | -0.5941042159 | 0.5578486935 |
| 33 n817    | 18 | 4.05E+012 | 0.1       | -0.1       | 0.1        | 2.75E+012 | -2    | 0.4145117994 | -11.8115666053 | 7.6255135335  | 0.5758242308 | -0.545796978  | 0.544628763  |
| 34 n818    | 18 | 4.05E+012 | 0.1       | -0.1       | 0.1        | 2.75E+012 | -2    | 0.4375555995 | -12.040657713  | 5.4752007276  | 0.5704622414 | -0.5771183551 | 0.5529039803 |
| 35 n819    | 18 | 4.05E+012 | 0.1       | -0.1       | 20         | 2.65E+012 | -2    | 0.5019246069 | -11.9893224533 | 1.6135908547  | 0.5126558424 | -0.6186469928 | 0.5878295793 |
| 36 n820    | 18 | 4.05E+012 | 0.1       | -0.1       | 20         | 2.65E+012 | -2    | 0.521306122  | -12.1308780048 | 1.2344111     | 0.5004409783 | -0.6355801065 | 0.5809422143 |
| 37 n821    | 18 | 4.05E+012 | 0.1       | -0.1       | 20         | 2.75E+012 | -2    | 0.4725931804 | -11.9829492937 | 2.9483422691  | 0.5351008282 | -0.5916939477 | 0.574897651  |
| 38 n822    | 18 | 4.05E+012 | 0.1       | -0.1       | 20         | 2.75E+012 | -2    | 0.4930672693 | -12.1206559667 | 1.9708808967  | 0.5210728232 | -0.6087511712 | 0.5674039238 |



# Measurements v. TCAD

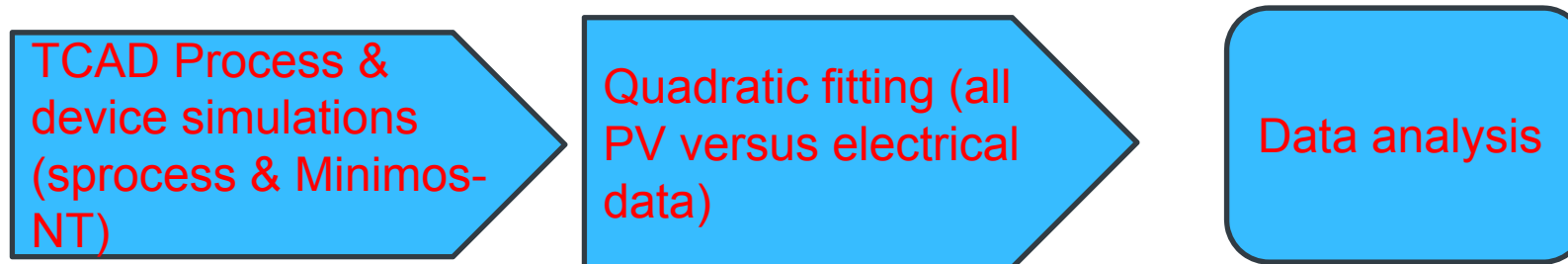


Dependency of  $R_{on}$  versus  $V_{thlin}$  for the simulated devices.



Measured view of  $R_{on}$  versus  $V_{thlin}$  for produced transistors.

## Data Generation



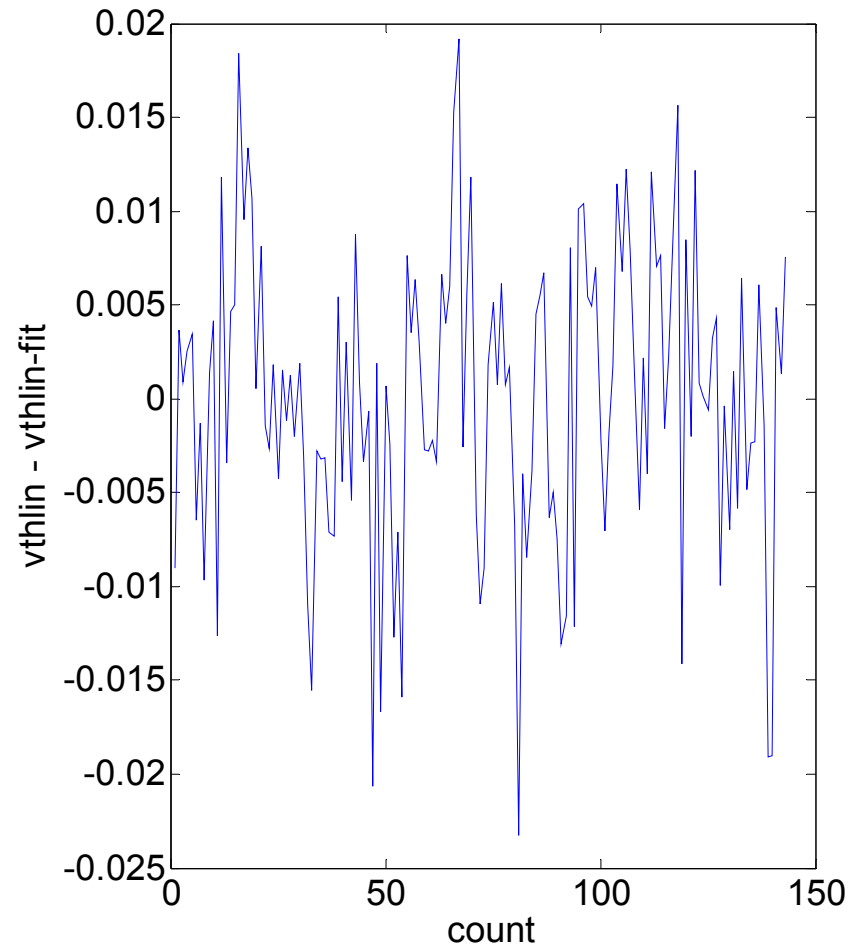
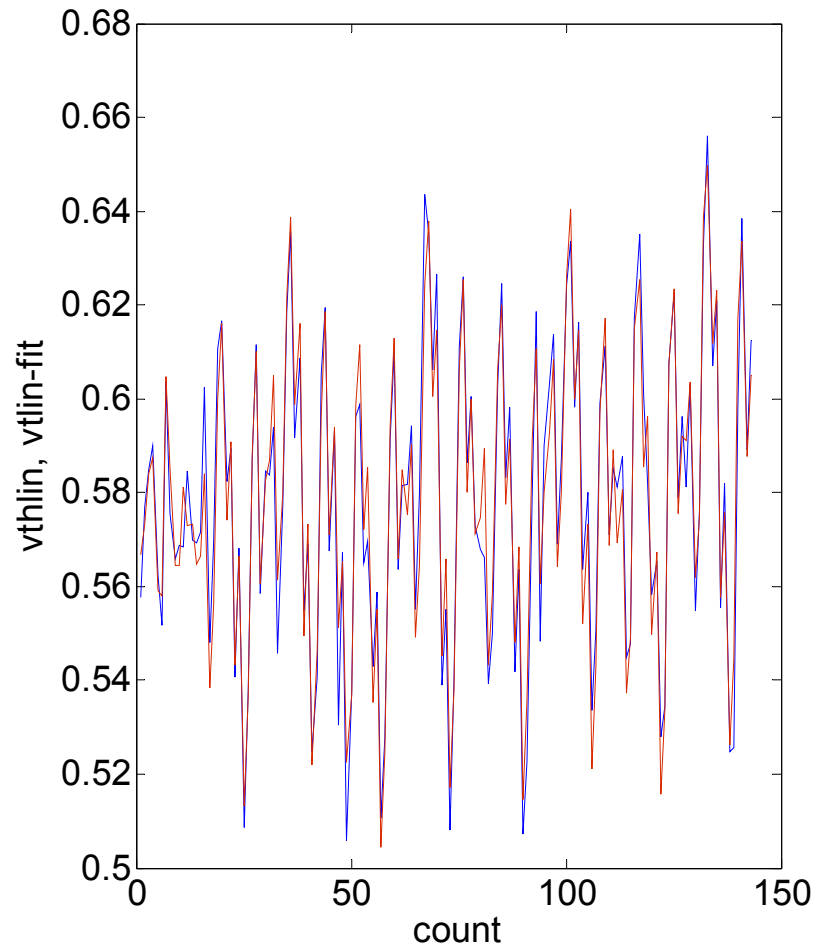
- Random 10000 PV-set generation by considering inline PV distributions
- Electrical parameter calculation from the quadratic formula

$$\hat{y} = \mathbf{x}^T \mathbf{A} \mathbf{x} + \mathbf{b}^T \mathbf{x} + c$$

$$\sum_i ||y_i - \mathbf{x}_i^T \mathbf{A} \mathbf{x}_i + \mathbf{b}^T \mathbf{x}_i + c|| \rightarrow \min$$

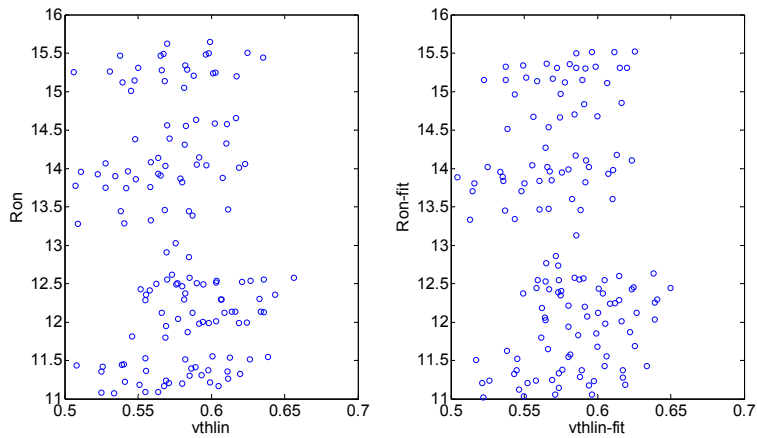
model each electrical output parameter  $y$  as a quadratic model function of the based input parameters  $x$  by a least square fit of  $A$ ,  $b$ , and  $c$  for all design points  $i$  of their simulated output parameters  $y_i$ .

# PLDMOS (20/0.6): $V_{thlin}$ and $V_{thlin-fit}$

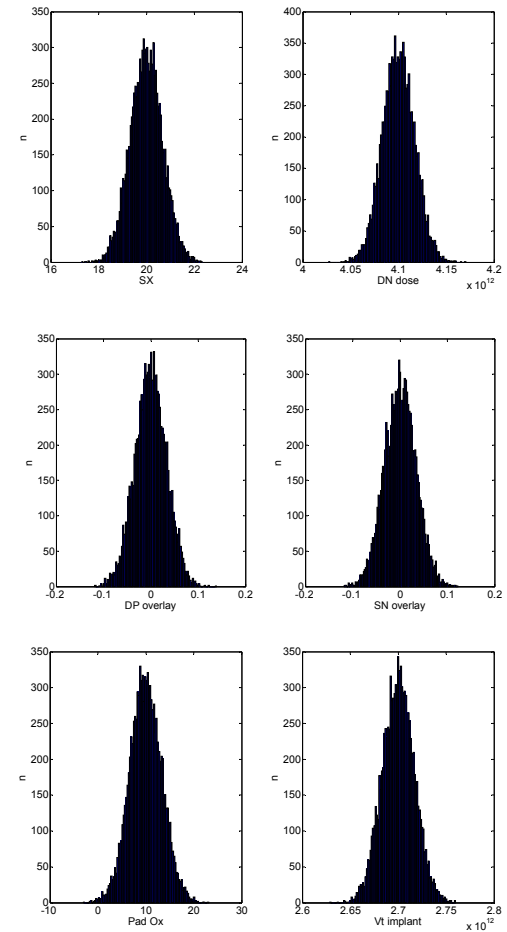


# PLDMOS (20/0.6): Ron and Vthlin correlation

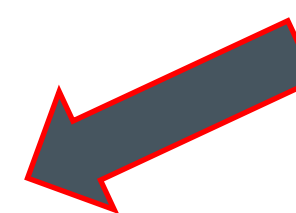
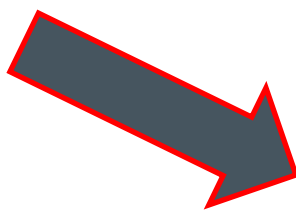
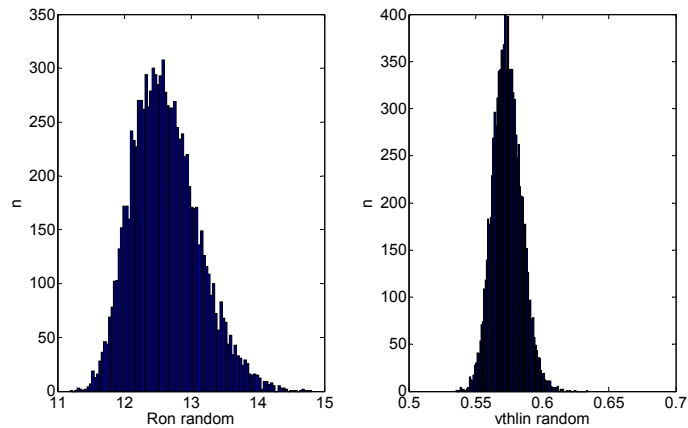
PLDMOS (20/0.6): Ron and Vthlin correlation



PLDMOS (20/0.6): 7 PV distributions (10000 random values)

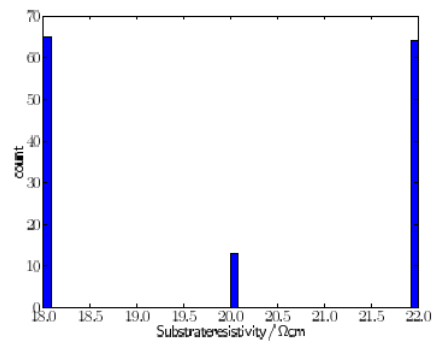


PLDMOS (20/0.6): Ron and Vthlin distribution

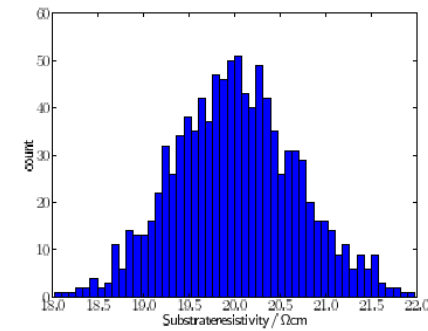
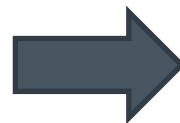


# Summary of PV TCAD Simulation

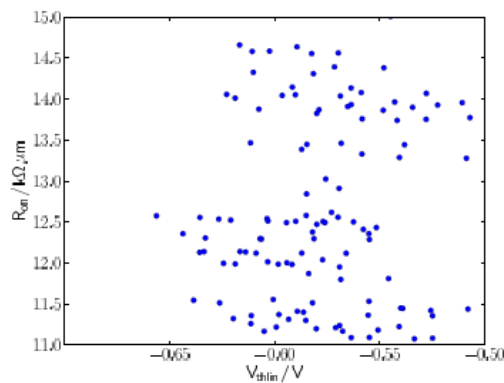
Simulation Flow with resulting PV and Correlation (Cij Covariance Matrix)



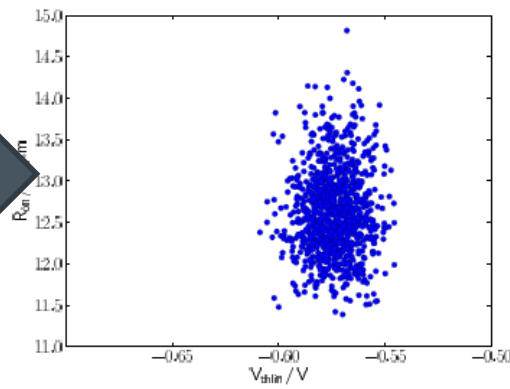
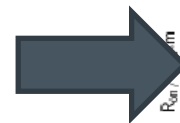
Originated input parameter distribution used in the CCF design for process simulation.



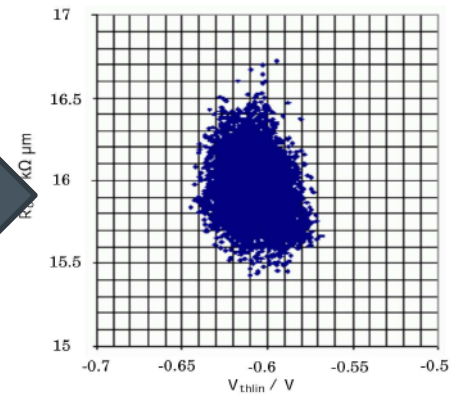
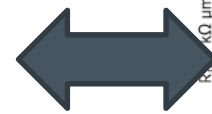
Randomly normally distributed input variation with mean value and standard deviation achieved from measurements.



Dependency of  $R_{on}$  versus  $V_{thlin}$  for the simulated devices.



Dependency of the modelled parameters  $R_{on}$  versus  $V_{thlin}$  after applying normally distributed input parameters.



Measured view of  $R_{on}$  versus  $V_{thlin}$  for produced transistors.

# GENERATION OF STATISTICAL SPICE MODELS WITH MONTE CARLO

$$s_i = s_{i0} \cdot N(0, \sigma_i) + \sum (s_j \cdot C_{ij} \cdot N(0, \sigma_j) \cdot \underline{S})$$

|                                  |  |
|----------------------------------|--|
| $s_i$                            | SPICE parameter under investigation,   |
| $s_{i0}$                         | mean value,  |
| $N(0, \sigma_i), N(0, \sigma_j)$ | mean-free normal distributions,  |
| $s_j$                            | correlated parameters,   |
| $C_{ij}$                         | correlation coefficients   |
| $\underline{S}$                  | sensitivity matrix indicating the sensitivity of the underlying compact model equations. |



## Electrical (MAP) Parameter and corresponding SPICE Parameter

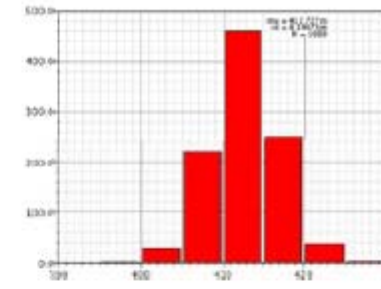
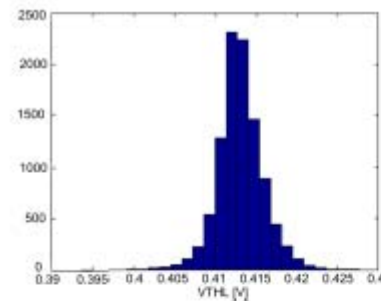
| Process variable   | HiSIM_HV parameter |
|--------------------|--------------------|
| Oxide Thickness    | TOX                |
| Large threshold    | VFBC, NSUBC        |
| Small threshold    | VFBC, NSUBP        |
| Body factor        | NSUBC              |
| Saturation current | MUEPH1, VMAX, RDVD |
| On-resistance      | RD, RDVD, RD23     |
| Leakage current    | VFBC               |



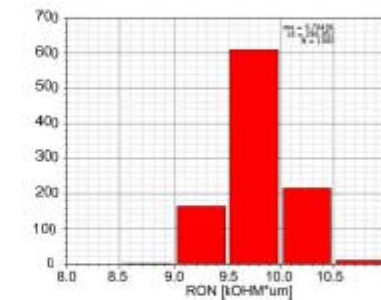
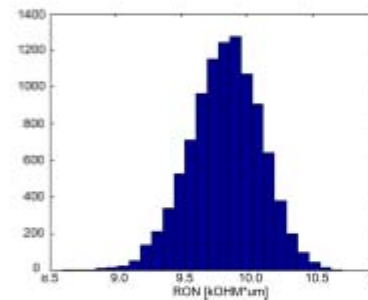
# Benchmark MC v. TCAD

|                                     | Target |       | MC Simulation |       |
|-------------------------------------|--------|-------|---------------|-------|
|                                     | Mean   | Sigma | Mean          | Sigma |
| VTH short [mV]                      | 412    | 3.73  | 413           | 4.19  |
| IDSAT [ $\mu\text{A}/\mu\text{m}$ ] | 327    | 9.0   | 324           | 10.0  |
| RON [ $\text{k}\Omega\mu\text{m}$ ] | 9.83   | 0.270 | 9.78          | 0.295 |

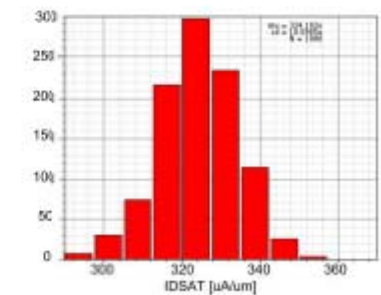
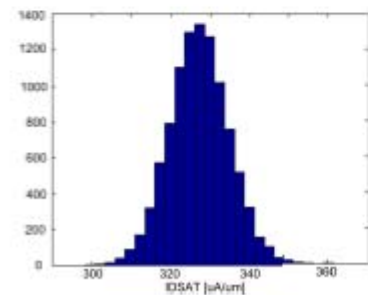
HV NMOS mean and sigma for TCAD vs. SPICE.



Histograms for VTHL HV NMOS, TCAD (blue, mean 412mV vs. SPICE Monte Carlo (red, mean 413mV)



Histograms for RON HV NMOS, TCAD (blue, mean 9.83 $\text{k}\Omega\mu\text{m}$ ) vs. SPICE Monte Carlo (red, mean 9.78 $\text{k}\Omega\mu\text{m}$ )



Histograms for IDSAT HV NMOS, TCAD (blue, mean 327  $\mu\text{A}/\mu\text{m}$ ) vs. SPICE Monte Carlo (red, mean 324  $\mu\text{A}/\mu\text{m}$ )



## Summary

- PV of N- and P- channel LDMOS transistors has been investigated by means of simulations
- Process and device simulations were performed by the SYNOPSIS tools and MINIMOS-NT
- Statistical data analysis with quadratic parameter optimization
- Benchmarked versus electrical process monitoring parameters from large silicon database
- TCAD based statistical SPICE models were successfully Implemented
- Deviations between TCAD and final simulation results (SPICE model) are in the few per cent range.



**Thank you**

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