Spayn

Statistical Parameter and Yield Analysis

Spayn is a statistical modeling tool for analyzing variances from model parameter extraction sequences, electrical test routines, and circuit test measurements. Spayn helps to identify the relationship between device or circuit performance variations and the process fluctuations.

- **Automatic generation of worst-case and corner SPICE models**
- **Advanced principal factor / component analysis**
- **Identification of inter-relationship among groups of parameters**
- **Statistical process control, process monitor, and yield analysis**
- **Advanced Wafer Map displaying wafer-to-wafer and die-to-die variances**
- **Seamless integration with fast SmartSpice API for statistical circuit design**
- **Flexible data input, output, append, merge, and split options with histogram, 2D & 3D scatter plot, and response surface model display options**
- **Silvaco's strong encryption is available to protect valuable customer and third party intellectual property**

SILVACO

Spayn is a statistical analysis software package tailored for the semiconductor industry.

It is applied for two main fields:

- Characterization
- Process Control/Analysis

Spread in performance of analog or digital circuits is largely due to inherent fluctuation in the manufacturing process. Achieving statistical control is fundamental to product quality.

Spayn is the ideal statistical modeling tool for analyzing variances from model parameter extraction sequences, electrical test routines, and circuit test measurements.

Spayn performs statistical analysis on parametric data, and helps determine the complex relationships between circuit design and process fabrication parameters.

$$Pi = ai1*X1 + ai2*X2 + \ldots ai6*X6$$
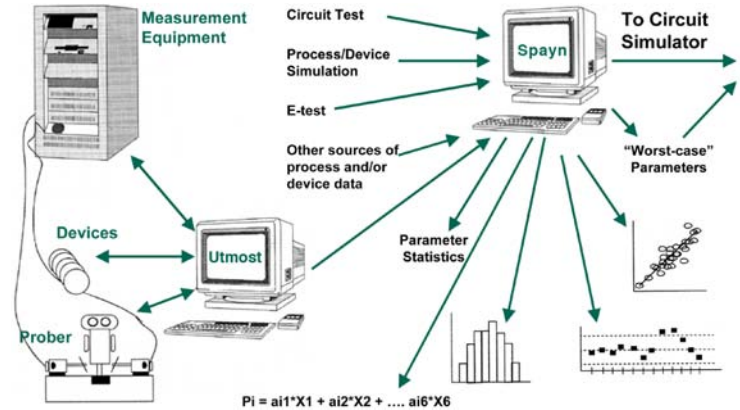
Spayn Users:

- Parameter Extraction and Circuit Simulator Support Personnel
- Device Modeling Engineers
- Circuit Designers
- Process Development / Integration Engineers

Spayn Applications

Used standalone, or linked to a circuit simulator, Spayn is a user-friendly tool requiring little detailed knowledge of statistics and no user-created programs.

Usage ranges from SPICE parameter extraction, process development and integration, over product and yield engineering, to circuit designing.

Spayn is a simple, powerful, and affordable tool for statistical modeling and process control.

Spreadsheet data format is used to view combined data from various sources.

|	WAFER NUM.	DIE NUMBER	GROUP NUMB	DEVICE	TOX_N	U0_N	LD_N	WD_N	PHI_N	RI
2	WAFER1	DIE9	group	device	1.816e–08	5.912e+02	1.789e–07	2.262e–07	7.000e–01	
3	WAFER1	DIE10	group	device	1.816e–08	5.888e+02	1.687e–07	1.767e–07	7.000e–01	
4	WAFER1	DIE13	group	device	1.816e–08	5.841e+02	1.717e–07	1.877e–07	7.000e–01	
5	WAFER1	DIE14	group	device	1.816e–08	5.917e+02	1.770e–07	2.014e–07	7.000e–01	
6	WAFER1	DIE15	group	device	1.816e–08	5.881e+02	1.792e–07	1.733e–07	7.000e–01	
7	WAFER1	DIE20	group	device	1.816e–08	5.942e+02	1.741e–07	1.848e–07	7.000e–01	
8	WAFER1	DIE21	group	device	1.816e–08	5.982e+02	1.740e–07	2.751e–07	7.000e–01	
9	WAFER1	DIE22	group	device	1.816e–08	5.982e+02	1.646e–07	1.928e–07	7.000e–01	
10	WAFER1	DIE25	group	device	1.816e–08	5.996e+02	1.632e–07	2.540e–07	7.000e–01	
11	WAFER1	DIE26	group	device	1.816e–08	6.064e+02	1.719e–07	2.248e–07	7.000e–01	
12	WAFER1	DIE27	group	device	1.816e–08	5.920e+02	1.728e–07	1.499e–07	7.000e–01	
13	WAFER1	DIE30	group	device	1.816e–08	5.988e+02	1.723e–07	1.521e–07	7.000e–01	
14	WAFER1	DIE31	group	device	1.816e–08	6.027e+02	1.656e–07	1.705e–07	7.000e–01	
15	WAFER1	DIE32	group	device	1.816e–08	6.010e+02	1.667e–07	1.312e–07	7.000e–01	
16	WAFER1	DIE34	group	device	1.816e–08	6.069e+02	1.618e–07	2.430e–07	7.000e–01	
17	WAFER1	DIE35	group	device	1.816e–08	5.913e+02	1.724e–07	2.221e–07	7.000e–01	
18	WAFER1	DIE36	group	device	1.816e–08	6.034e+02	1.684e–07	2.095e–07	7.000e–01	
19	WAFER1	DIE38	group	device	1.816e–08	5.939e+02	1.695e–07	2.109e–07	7.000e–01	
20	WAFER1	DIE39	group	device	1.816e–08	5.858e+02	1.741e–07	5.289e–08	7.000e–01	
21	WAFER1	DIE40	group	device	1.816e–08	6.081e+02	1.645e–07	8.686e–08	7.000e–01	

SPAYN 2.0.2.C © Simucad 2007

Data Filtering

Spayn is capable og managing a large number of Attributes, Parameters and Samples, limited only by workstation memory and processor performance. To deal with large data sets, Spayn provides a powerful filtering concept allowing selection of samples to reduce the number of data sets used. "Filter by Attributes" allows definition offilters based on data set attributes. "Filter by Parameters" can be used to further reduce the number of data sets by specifying limits on the parameter values.

Even with a spreadsheet table, it can be tedious and numbing to work with all data. To address this, Spayn provides filters to precisely select samples and reduce the number of data sets in use. Filtering can be done at the Attributes or Parameters level. First, "Filter by Attributes" defines database identification selection key. Second, "Filter by Parameters" defines value limits to reduce the number of sets that satisfy criteria.
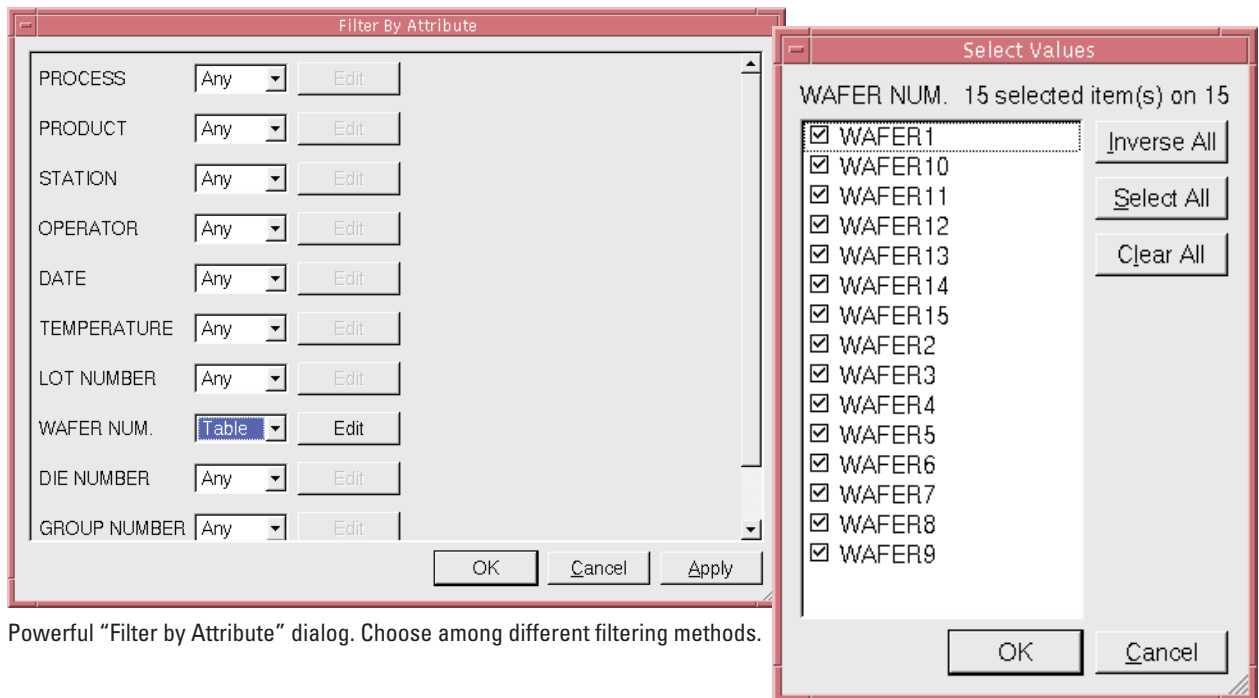
Powerful "Filter by Attribute" dialog. Choose among different filtering methods.

Subset of dataset definition using powerful "Filter by Parameters." Some tools such as 'compute limits,' 'histogram plot,' Automatic Filter,' help build the Filter.
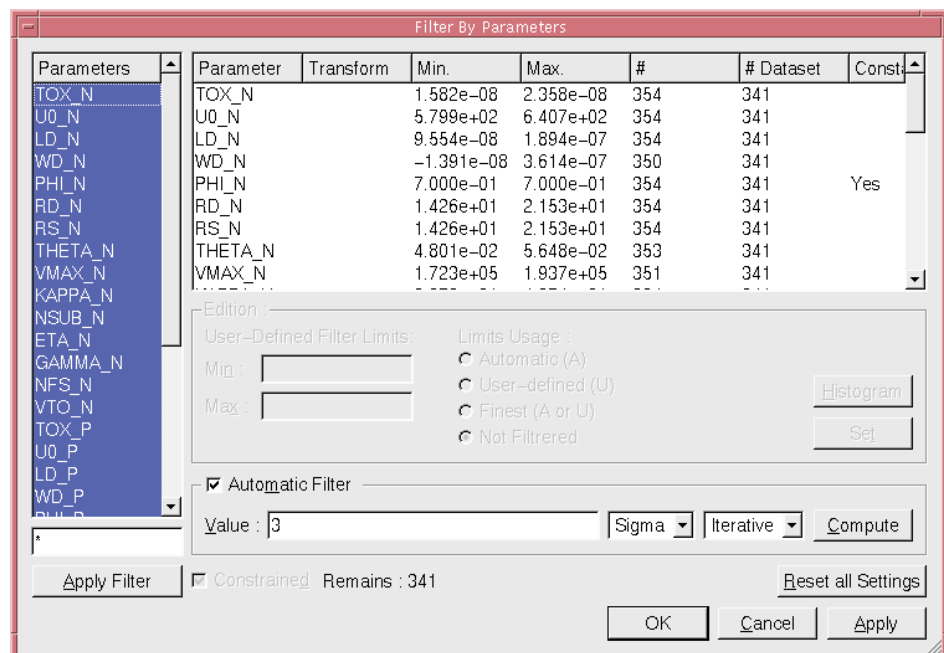
Statistical Analysis, Data Management and Visualization

Spayn accepts Utmost-generated SPICE model library formats, Virtual Wafer Fab format, and other industry formats (RS/1™, CSV, MS EXCEL™). Spayn offers unique and extremely fast search, merge, append, and split capabilities on data sets. Many built-in general purpose statistical analysis features aid in the examination of parametric data: Gaussian, exponential, log-normal, and Gamma distributions.

Scatter plots analyze the relationship between parameters using the least squares method to fit linear, logarithmic, parabolic, reciprocal, hyperbolic, exponential, power, root, or 3rd order polynomial. The resulting error residuals, ANOVA information and correlation coefficients are generated. The "Golden Device feature" allows you to calculate which observation or observations (in a particular data set collection) most closely matches the mean, based on some dissimilarity measure.
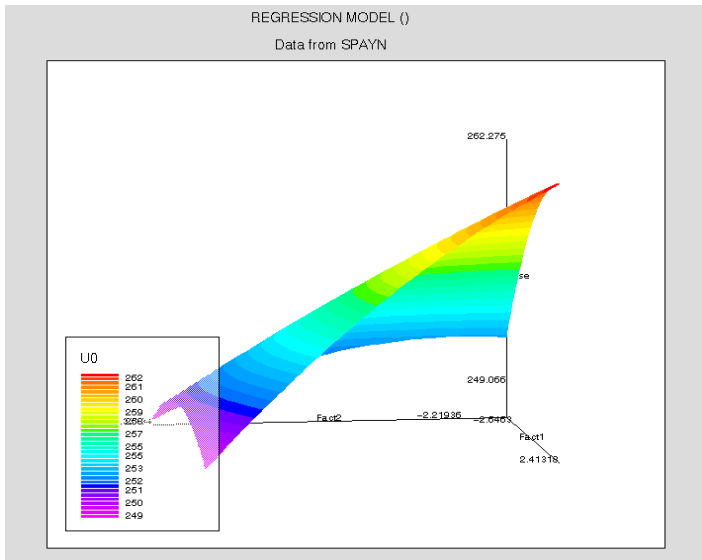
Response surface model of regression are displayed using TonyPlot.
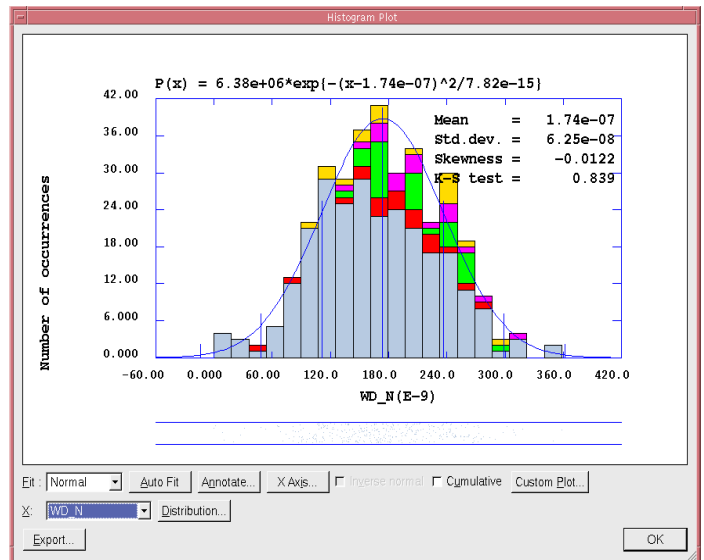
Histogram plot with attributes for selected parameters highlighted.
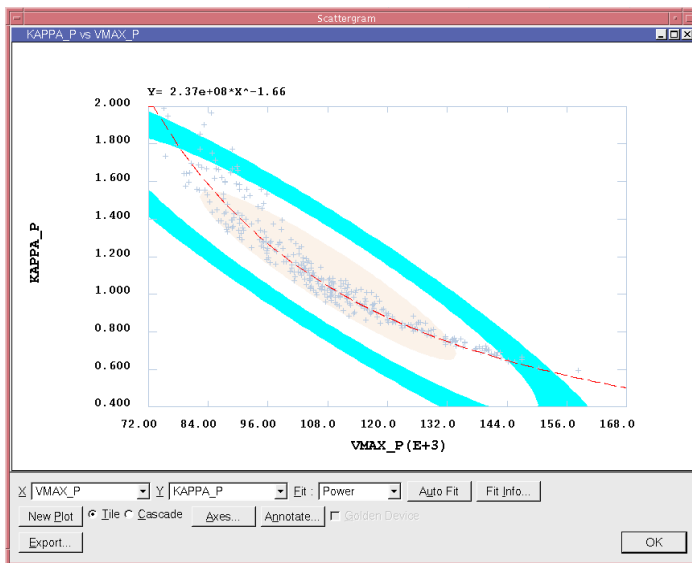
The contour plot displays ellipses representing $\pm\sigma$, $\pm2\sigma$, and $\pm 3\sigma$ distribution of parameters.
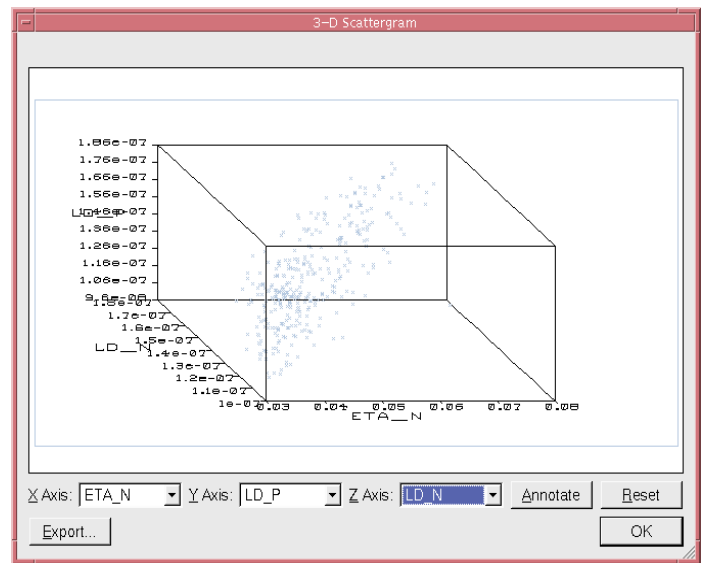
The relationship among any three selected parameters can be viewed in 3D.

Multiple linear regression capabilities generate equations that relate one selected parameter to other sets of user-defined parameters. SPICE models card can be generated for any point in a scattergram Plot. The SmartSpice link and the user Netlist feature allow running simulation for each SPICE models card.

A correlation matrix of parameters selected for analysis. Significant correlations are highlighted in red.

Correlation Matrix

Parameter Selection: TOX_N, U0_N, LD_N, WD_N, RD_N, RS_N, THETA_N, VMAX_N, KAPPA_N, ETA_N, GAMMA_N, NFS_N, VTO_N, TOX_P, U0_P, LD_P, WD_P, RD_P, RS_P, THETA_P, VMAX_P, KAPPA_P, ETA_P, GAMMA_P, NFS_P

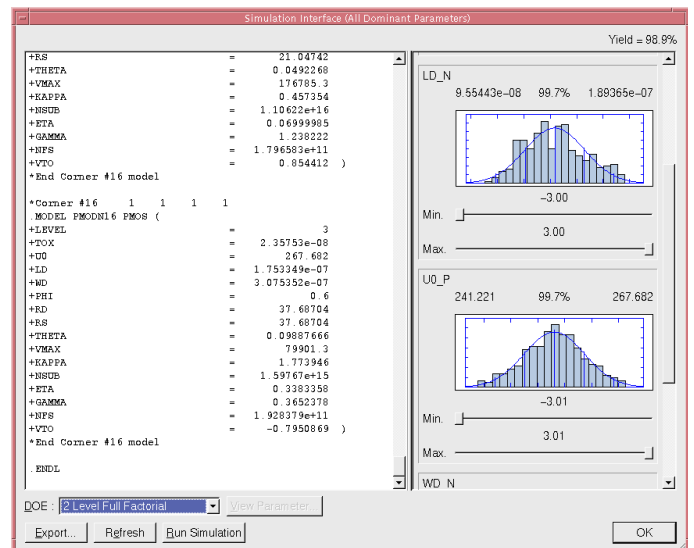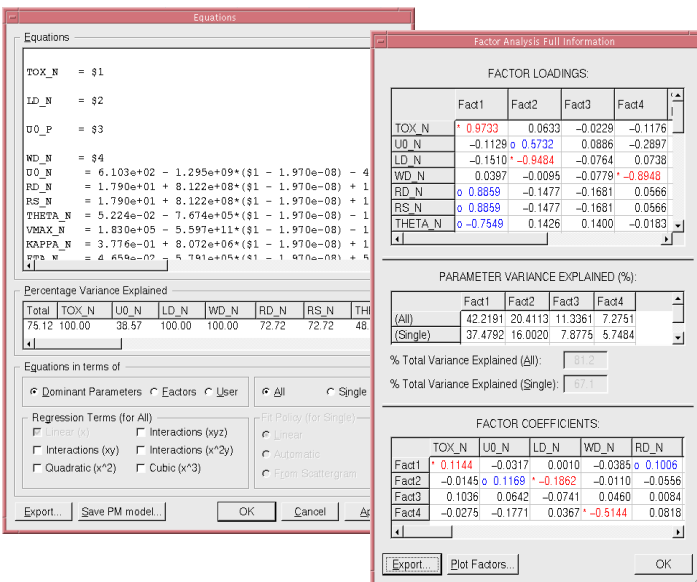| Matrix	TOX_N	U0_N	LD_N	WD_N	RD_N	RS_N	THETA_N	VMA
TOX_N	1.0000	–0.0256	–0.2064	0.1232	0.8131	0.8131	–0.6721	–0.
U0_N	–0.0256	1.0000	–0.5962	0.0976	–0.2379	–0.2379	0.3342	0.
LD_N	–0.2064	–0.5962	1.0000	–0.0521	0.0317	0.0317	0.0104	–0.
WD_N	0.1232	0.0976	–0.0521	1.0000	0.0569	0.0569	–0.0989	0.
RD_N	0.8131	–0.2379	0.0317	0.0569	1.0000	N/A	–0.7599	–0.
RS_N	0.8131	–0.2379	0.0317	0.0569	N/A	1.0000	–0.7599	–0.
THETA_N	–0.6721	0.3342	0.0104	–0.0989	–0.7599	–0.7599	1.0000	0.
VMAX_N	–0.0973	0.1547	–0.4384	0.0471	–0.2671	–0.2671	0.1904	1.
KAPPA_N	0.2610	–0.2289	0.5623	0.0138	0.2998	0.2998	–0.2008	–0.
ETA_N	–0.2531	–0.3691	0.8648	–0.0912	–0.0671	–0.0671	0.1454	–0.
GAMMA_N	0.9610	–0.0744	–0.2403	0.1613	0.7663	0.7663	–0.7036	–0.
NFS_N	–0.9751	–0.0301	0.2148	–0.0818	–0.7984	–0.7984	0.6152	0.
VTO_N	0.9265	–0.0959	–0.0604	0.1683	0.7551	0.7551	–0.7208	–0.
TOX_P	1.0000	–0.0256	–0.2064	0.1232	0.8131	0.8131	–0.6721	–0.
U0_P	0.0338	0.0110	–0.0362	–0.0660	–0.1273	–0.1273	0.1127	0.
LD_P	–0.3002	–0.4345	0.8986	0.0981	–0.1593	–0.1593	0.0956	–0.
WD_P	0.2769	0.1881	–0.2096	0.6785	0.1807	0.1807	–0.1616	0.
RD_P	0.7631	0.0606	–0.3592	0.0864	0.6695	0.6695	–0.4773	–0.
RS_P	0.7631	0.0606	–0.3592	0.0864	0.6695	0.6695	–0.4773	–0.
THETA_P	–0.8628	–0.0899	0.2841	–0.1876	–0.7547	–0.7547	0.6555	0.
VMAX_P	–0.5775	0.0751	–0.0492	–0.2550	–0.5529	–0.5529	0.5191	0

Export...   OK   Cancel   Apply

Advanced PCA/ PFA – Principal Component and Factor Analysis

Spayn identifies dominant parameters and/or factors of variations. The data is then automatically grouped so that each parameter in a specific group is controlled by the same source of variation. Analysis of each parameter group then identifies relationships between process input, process monitoring, device, circuit, and manufacturing parameters within the group.

The following analysis features are available:

- Advanced Principal Component and Factor Analysis
- Dominant parameter identification
- VARIMAX and QUARTIMAX rotations
- Histograms or scatter plots using components/factors
- PCA parameter weights and sensitivity analysis
- Unique user-defined dominant parameter selection and equations

Equations

```
TOX_N   = $1
LD_N    = $2
U0_P    = $3
WD_N    = $4
U0_N    = 6.103e+02 – 1.295e+09*($1 – 1.970e–08) – 4
RD_N    = 1.790e+01 + 8.122e+08*($1 – 1.970e–08) + 1
RS_N    = 1.790e+01 + 8.122e+08*($1 – 1.970e–08) + 1
THETA_N = 5.224e–02 – 7.674e+05*($1 – 1.970e–08) – 1
VMAX_N  = 1.830e+05 – 5.597e+11*($1 – 1.970e–08) – 1
KAPPA_N = 3.776e–01 + 8.072e+06*($1 – 1.970e–08) + 1
ETA_N   = 4.659e–02 – 5.791e+05*($1 – 1.970e–08) + 5
```

Percentage Variance Explained

Total	TOX_N	U0_N	LD_N	WD_N	RD_N	RS_N	THI
75.12	100.00	38.57	100.00	100.00	72.72	72.72	48

Equations in terms of
- Dominant Parameters Factors User All Single

Regression Terms (for All)
- Linear (x)
- Interactions (xy)
- Quadratic (x^2)
- Interactions (xyz)
- Interactions (x^2y)
- Cubic (x^3)

Fit Policy (for Single)
- Linear
- Automatic
- From Scattergram

Export...   Save PM model...   OK   Cancel

Factor Analysis Full Information

FACTOR LOADINGS:

	Fact1	Fact2	Fact3	Fact4
TOX_N	0.9733	0.0633	–0.0229	–0.1176
U0_N	–0.1129	0.5732	0.0886	–0.2897
LD_N	–0.1510	–0.9484	–0.0764	0.0738
WD_N	0.0397	–0.0095	–0.0779	–0.8948
RD_N	0.8859	–0.1477	–0.1681	0.0566
RS_N	0.8859	–0.1477	–0.1681	0.0566
THETA_N	–0.7549	0.1426	0.1400	–0.0183

PARAMETER VARIANCE EXPLAINED (%):

	Fact1	Fact2	Fact3	Fact4
(All)	42.2191	20.4113	11.3361	7.2751
(Single)	37.4792	16.0020	7.8775	5.7484

% Total Variance Explained (All): 81.2
% Total Variance Explained (Single): 67.1

FACTOR COEFFICIENTS:

	TOX_N	U0_N	LD_N	WD_N	RD_N
Fact1	0.1144	–0.0317	0.0010	–0.0385	0.1006
Fact2	–0.0145	0.1169	–0.1862	–0.0110	–0.0556
Fact3	0.1036	0.0642	–0.0741	0.0460	0.0084
Fact4	–0.0275	–0.1771	0.0367	–0.5144	0.0818

Export...   Plot Factors...   OK

Simulation Interface (All Dominant Parameters)   Yield = 98.9%

```
+RS       =       21.04742
+THETA    =        0.0492268
+VMAX     =       176785.3
+KAPPA    =        0.457354
+NSUB     =        1.10622e+16
+ETA      =        0.06999905
+GAMMA    =        1.238222
+NFS      =        1.796583e+11
+VTO      =        0.854412  )
*End Corner #16 model

*Corner #16    1   1   1   1
.MODEL PMODN16 PMOS (
+LEVEL    =        3
+TOX      =        2.35753e–08
+U0       =       267.682
+LD       =        1.753349e–07
+WD       =        3.075352e–07
+PHI      =        0.6
+RD       =       37.68704
+RS       =       37.68704
+THETA    =        0.09887666
+VMAX     =       79901.3
+KAPPA    =        1.773946
+NSUB     =        1.59767e+15
+ETA      =        0.3393355
+GAMMA    =        0.3652378
+NFS      =        1.928379e+11
+VTO      =       –0.7950869  )
*End Corner #16 model

.ENDL
```

LD_N   9.55443e–08   99.7%   1.89365e–07
–3.00
Min.   3.00
Max.

U0_P   241.221   99.7%   267.682
–3.01
Min.   3.01
Max.

WD_N

DOE: 2 Level Full Factorial   View Parameter
Export...   Refresh   Run Simulation   OK

PCA/PFA capabilities allows you to define dominant parameters or identify them automatically, and then generate linear or non-linear equations.

Powerful factor analysis, coupled with built-in SPICE model equations, delivers unmatched statistical modeling capabilities.

Worst-Case and Corner SPICE Model Generation

Spayn generates equations relating each parameter under analysis to the uncorrelated dominant factors or dominant parameters. These independent variables are interactively or automatically perturbed to produce realistic "corner" and "worst-case" models using built-in SPICE model equations.
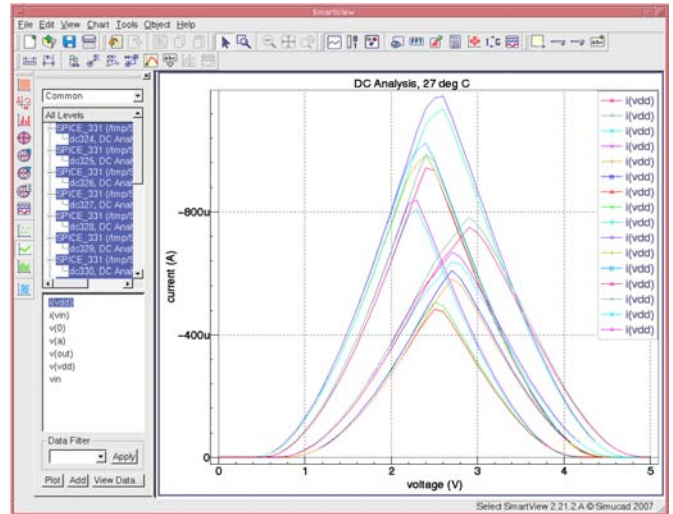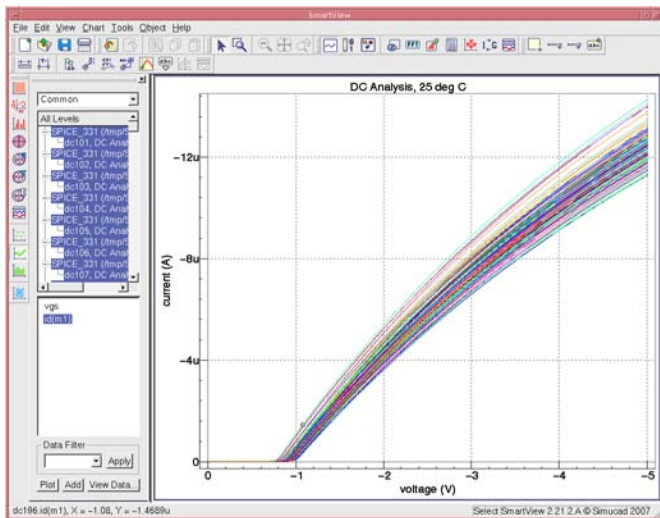

User-defined, Monte Carlo (left figure), corner (right figure), or worst-case simulations can be performed using the fast SmartSpice API. Single device or very complex circuits can be simulated and many types of analysis are possible.

Statistical Process Control and Yield Analysis

Spayn can be used to determine the underlying statistical nature of IC manufacturing processes and their impact on device performance.
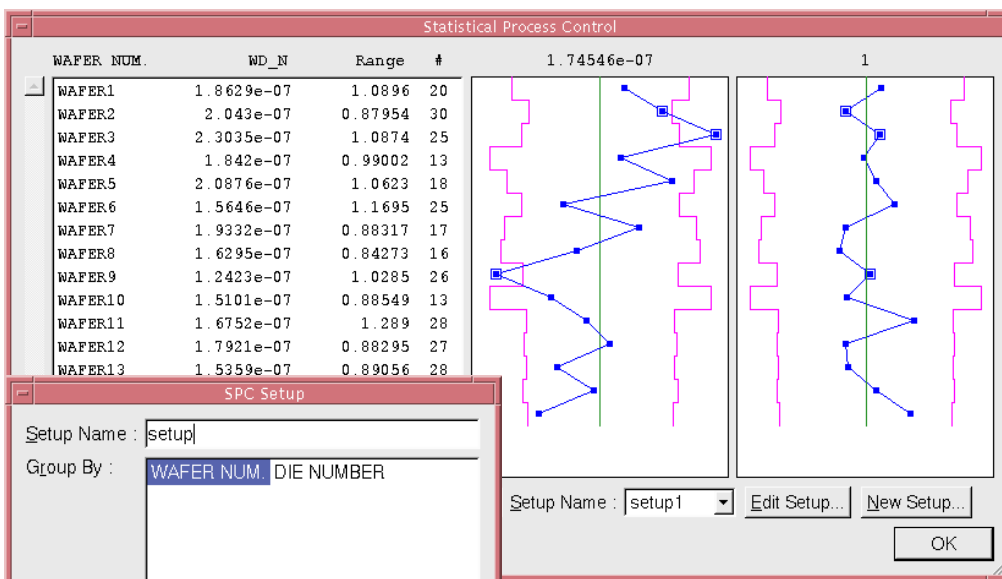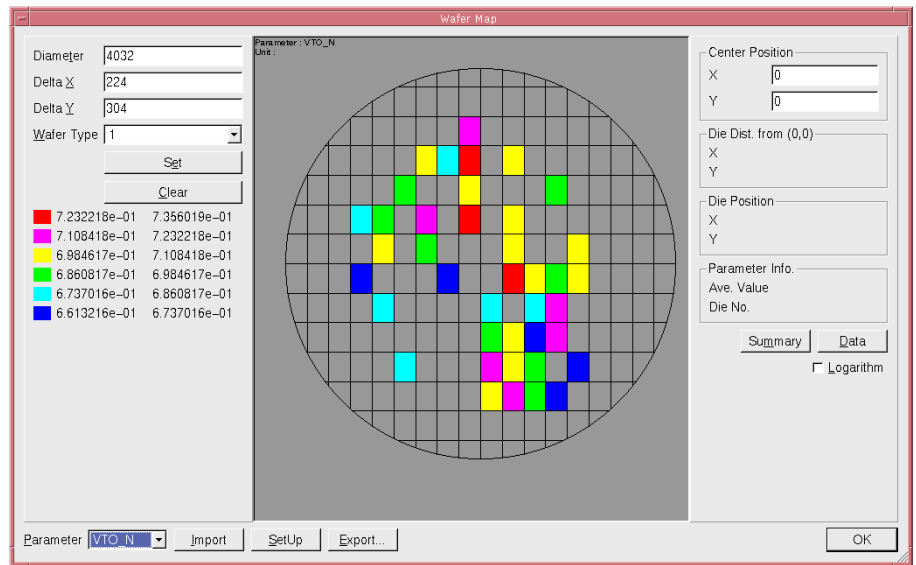
Spayn creates statistical process control (SPC) and process monitor (PM) charts to track the variation of dominant parameters or factors over selected wafers or lots. SPC charts plot and store Shewhart mean and range/sigma data with the parameters grouped in terms of their attributes.

Spayn helps to identify an efficient process monitoring strategy by identifying the minimum set of dominant factors that must be monitored in production in order to control the yield. Process monitoring charts are then used to view these parameters.
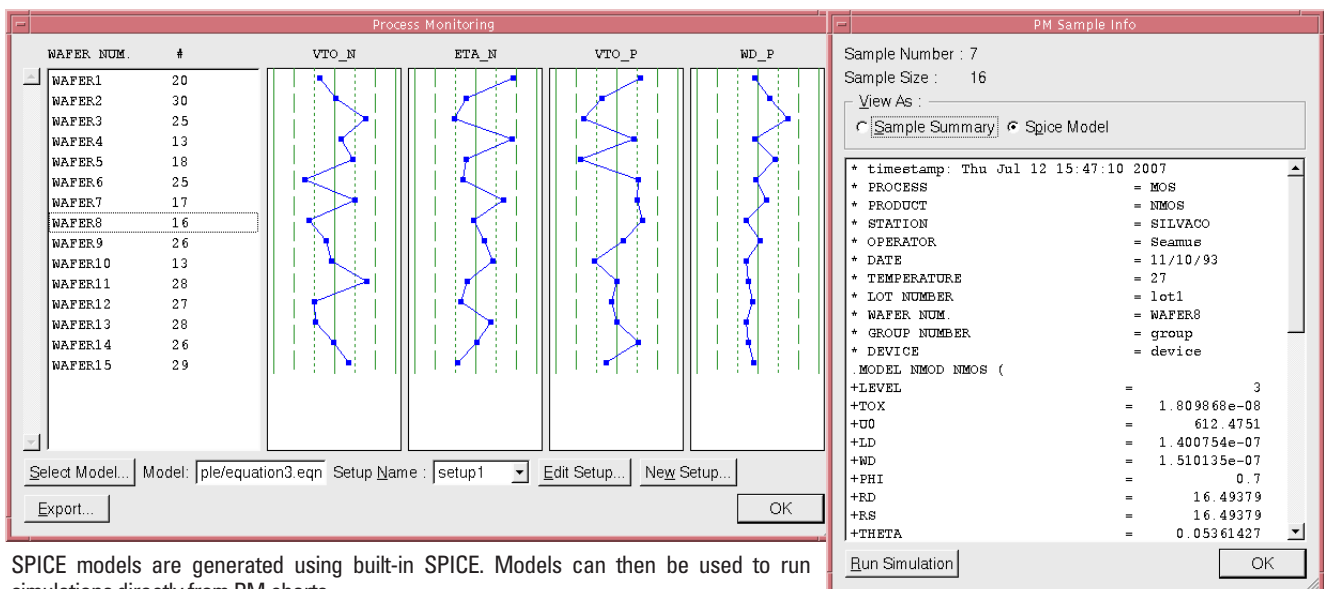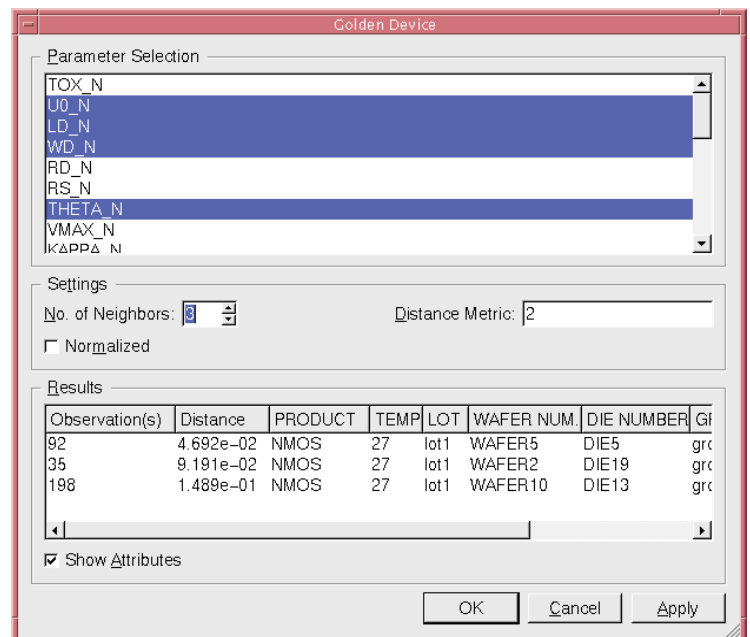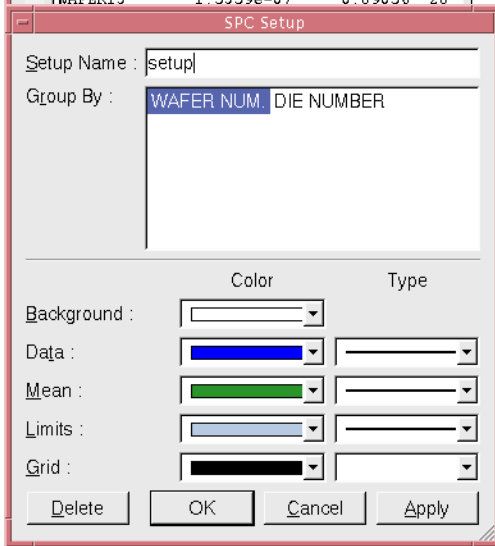

SPICE models are generated using built-in SPICE. Models can then be used to run simulations directly from PM charts.

Wafer Map displays parameters, or any other measured data together with their distributions over die locations.

Wafer Map

Diameter	4032
Delta X	224
Delta Y	304
Wafer Type	1

Set
Clear

Parameter : VTO_N
Unit :

7.232216e-01	7.356019e-01
7.108418e-01	7.232218e-01
6.984617e-01	7.108418e-01
6.860817e-01	6.984617e-01
6.737016e-01	6.860817e-01
6.613216e-01	6.737016e-01

Center Position
X 0
Y 0

Die Dist. from (0,0)
X
Y

Die Position
X
Y

Parameter Info.
Ave. Value
Die No.

Summary   Data
☐ Logarithm

Parameter VTO_N   Import   SetUp   Export...   OK

Statistical Process Control

WAFER NUM.	WD_N	Range	#
WAFER1	1.8629e-07	1.0896	20
WAFER2	2.043e-07	0.87954	30
WAFER3	2.3035e-07	1.0874	25
WAFER4	1.842e-07	0.99002	13
WAFER5	2.0876e-07	1.0623	18
WAFER6	1.5646e-07	1.1695	25
WAFER7	1.9332e-07	0.88317	17
WAFER8	1.6295e-07	0.84273	16
WAFER9	1.2423e-07	1.0285	26
WAFER10	1.5101e-07	0.88549	13
WAFER11	1.6752e-07	1.289	28
WAFER12	1.7921e-07	0.88295	27
WAFER13	1.5359e-07	0.89056	28

1.74546e-07   1

Setup Name : setup1   Edit Setup...   New Setup...
OK

Data points lying outside process control limits (outlier) are marked with a square.

SPC Setup

Setup Name : setup
Group By :   WAFER NUM.   DIE NUMBER

|	Color	Type
Background :		
Data :		
Mean :		
Limits :		
Grid :		

Delete   OK   Cancel   Apply

Golden Device feature calculates which observation or observations most closely match the mean, based on some dissimilarity measure, i.e., the measured device that best describes the given data sets collection.
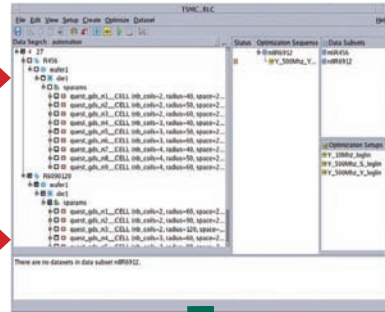
Golden Device

Parameter Selection
TOX_N
U0_N
LD_N
WD_N
RD_N
RS_N
THETA_N
VMAX_N
KAPPA_N

Settings
No. of Neighbors: 3   Distance Metric: 2
☐ Normalized

Results

Observation(s)	Distance	PRODUCT	TEMP	LOT	WAFER NUM.	DIE NUMBER	GI
92	4.692e-02	NMOS	27	lot1	WAFER5	DIE5	gro
35	9.191e-02	NMOS	27	lot1	WAFER2	DIE19	gro
198	1.489e-01	NMOS	27	lot1	WAFER10	DIE13	gro

☑ Show Attributes

OK   Cancel   Apply

Three neighbors of Golden Device computed and Attributes displayed.

Spayn in Silvaco Inductor PDK Flow

Quest
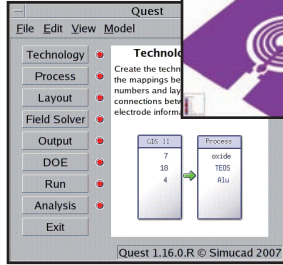
Measurements

Utmost
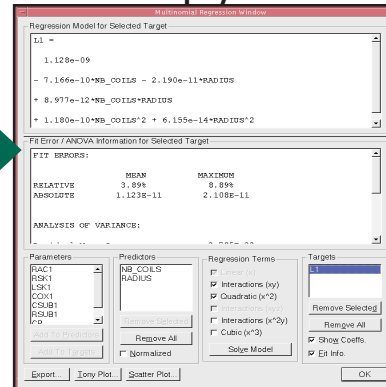
Spayn

Inductor PDK (scaling rules)
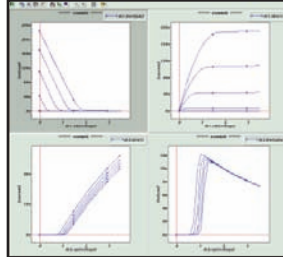
User Inductor SPICE Model

Spayn Inputs/Outputs

Utmost → Spayn → SmartSpice

Quest → Spayn → SmartView

Measurements → Spayn → TonyPlot

TCAD → Spayn