12

Compact Model Library for Circuit Simulation

12.1 Introduction

In Chapters 4 through 11, we have discussed compact model formulation for different VLSI (very-large-scale-integrated) devices. In this chapter a brief overview of the generation of compact model library for circuit simulation and compact model usage in circuit CAD (computer-aided design) is provided. A typical CMOS (complementary metal-oxide-semiconductor) technology and Berkeley Short Channel IGFET Model, version 4 (BSIM4) compact MOSFET (metal-oxide-semiconductor field-effect transistor) model are used to illustrate the methodology to build a compact model library for HSPICE (see Chapter 1) circuit CAD [1,2]. Note that the circuit CAD tools and the device models are continuously updated for improving the accuracy and simulation efficiency. So, the basic idea for compact model development presented in this chapter must be appropriately modified to the changing modeling and circuit CAD tools.

12.2 General Approach to Generate Compact Device Model

A generalized methodology to build a compact device model library is shown in Figure 12.1. As shown in Figure 12.1, the procedure involves data collection, data fitting to the target compact model, extraction of model parameters, generation of model library, and verification of model for accuracy and predictability. Each of these steps to generate a computationally robust compact model library depends on the device technology (e.g., MOSFETs), target model (e.g., BSIM4), design target (e.g., digital), and so on. In this chapter, we will use BSIM4 to illustrate the modeling methodology outlined in Figure 12.1 [2].

12.2.1 Data Collection

The first task in generating a model library is the data collection from the devices of the target technology representing the entire design space under the operating biasing conditions and ambient temperatures. Data collection

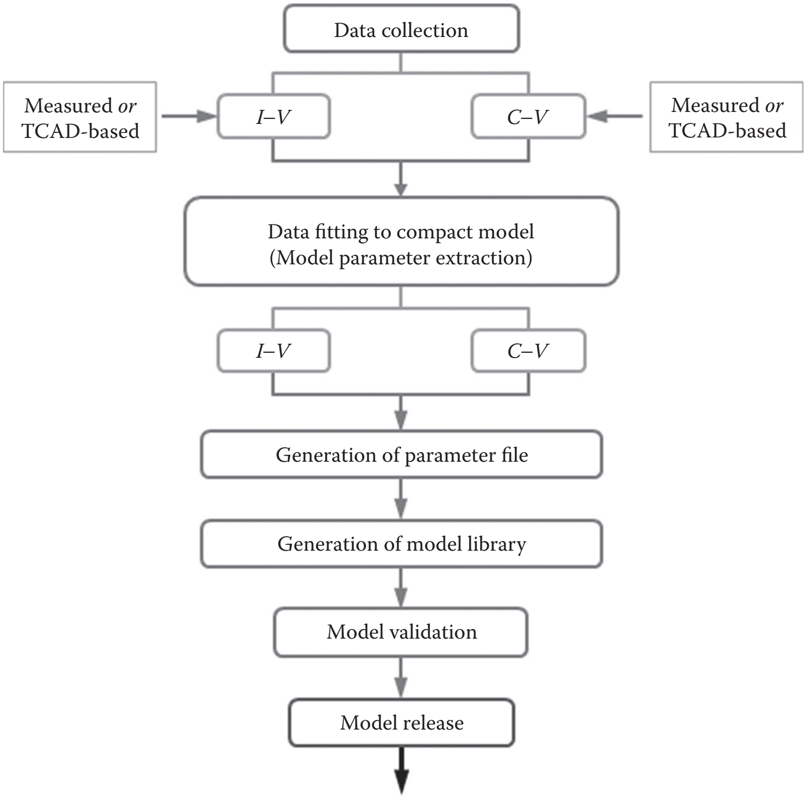


FIGURE 12.1
A generalized methodology to generate compact device model library for circuit CAD; each task in the flowchart depends on the target device technology, target compact model, and the target VLSI circuit for computer analysis.

includes the selection of an acceptable set of devices representing the entire IC (integrated circuit) design space and selection of device characteristics that account for the real-device effects to extract device model parameters to modeling physical, geometrical, and ambient temperature effects on the device performance in IC chips. The selection of devices and device characteristics for data acquisition is described in the following subsections.

12.2.1.1 Selection of Devices

In order to collect data for compact model parameter extraction, a set of devices are selected, representing the entire design space to properly characterize the detailed physics of the device operation formulated by the target compact model. These include devices to extract core model parameters

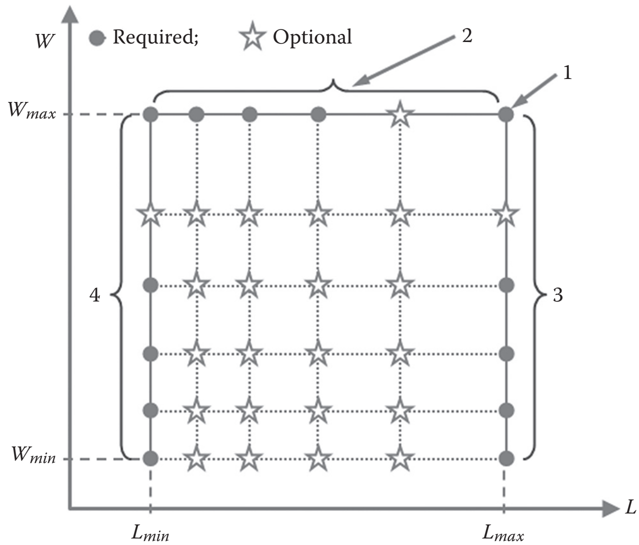


FIGURE 12.2
Typical device selection criteria for compact MOSFET models: device 1 is used to extract the core model parameters, group 2 devices are used to model the channel length dependence, group 3 devices are used to model the channel width dependence, and group 4 devices are used to model short devices; L_{min} and L_{max} represent the shortest and longest devices used in the circuit, respectively, and W_{min} and W_{max} represent the narrowest and widest devices used in the circuit, respectively; ● represents the devices required for modeling whereas ☆ represents the optional devices that can be used for model verification and further optimization of the model parameters.

and devices to extract real-device effects describing physical and geometrical effects. With reference to BSIM4 model, the device selection criteria for extracting the compact device model parameters of a target CMOS technology is shown in Figure 12.2 [2–4].

As shown in Figure 12.2, the set of selected devices must include the minimum and maximum geometries intended for IC chip design. If L_{min} and L_{max} represent the shortest and longest devices, respectively, used in the circuit and W_{min} and W_{max} represent the narrowest and widest devices, respectively, used in the circuit, then the set of devices must include $L_{min} \le L \le L_{max}$ and $W_{min} \le W \le W_{max}$. The accuracy of model library may be improved by fitting data from a large number of devices in the set. However, for efficient model generation, a minimum number of devices is selected as described in Figure 12.2 by required and optional devices. As shown in Figure 12.2, device 1 is used to extract the core model parameters independent of real-device effects, group 2 devices are used to model the channel length dependence (SCEs), group 3 devices are used to model the channel width dependence, and group 4 devices are used to model the width dependence of the shortest device. Note that in most cases, L_{min} represents the nominal device of the target technology node.

12.2.1.2 Selection of Device Characteristics

As discussed in Chapter 4 and 5 for MOSFETs and Chapter 11 for bipolar junctions transistors, the device operation is typically characterized by distinct regions, and compact models are developed to mathematically describe each region by separate equations or a single model. In most compact models, the device performance in each mode of device operation is described by a set of model parameters. Thus, a set of device characteristics such as current-voltage (I–V) and capacitance-voltage (C–V) is required to fit the model equations to each operating region of device characteristics and extract the corresponding model parameters of the selected set of devices.

Again, to illustrate the selection of device characteristics for compact modeling, let us use BSIM4 regional model. The MOSFET device is primarily characterized by subthreshold, linear, and saturation regions. Thus, to model the entire device characteristics for the selected set of devices of a target technology, the device data are obtained under the appropriate biasing conditions determined by the target supply voltage, V_{dd}, at the target operating range of the ambient temperature (T) of the devices in the IC chips. Table 12.1 shows a typical set of device characteristics required for compact modeling of the selected MOSFET devices of a specific technology under different gate-source, drain-source, and body-source voltages V_{gs}, V_{ds}, and V_{bs}, respectively.

A similar set of device data are obtained for PMOS (n-type body with p+ source-drain) devices by changing the sign of the operating applied voltages.

In addition, the source-drain pn-junction I–V and C–V characteristics are obtained for both NMOS (p-type body with n+ source-drain) and PMOS (n-type body with p+ source-drain) devices to extract the source-drain diode model parameters. The diode model is an integral part of MOSFET compact model, and therefore, diode characteristics are part of data collection for compact MOSFET modeling. For analog/RF modeling, the additional set of required device characteristics is obtained.

The *rev*0 compact model of a target technology can be generated from the numerical device simulation data for the feasibility study and early IC design evaluation [5–7]. However, in order to generate the final compact device model of a technology for product design in CAD environment and release to process design kit (PDK), the measurement data are collected from a single die, referred to as the *golden die* of a specific silicon wafer, referred to as the *golden wafer*. The golden die of the golden wafer provides the target device performance of the target technology node [6].

In order to develop a *statistical model library*, the required set of data shown in Table 12.1 is collected from different silicon die, wafers, and different wafer lots over a period of time. Then from the statistical distribution of data

TABLE 12.1

Selection of NMOS Device Characteristics for the Basic BSIM4 Compact Model Parameter Extraction: All Characteristics are Obtained in the Ambient Temperature Range −55°C < T < 125°C

Device Data	V_{ds} (V)	V_{gs} (V)	V_{bs} (V)	Objective
$I_{ds} - V_{gs}$	Constant: ~50 mV	Ramp: 0 to $1.1_* V_{dd}$ step ~ 50 mV	Constant: 0 to $-V_{dd}$, step ~ $-1.1_* V_{dd}/4$	Subthreshold region and linear region parameter extraction
$I_{ds} - V_{gs}$	Constant: $1.1_* V_{dd}$	Ramp: 0 to $1.1_* V_{dd}$ step ~ 50 mV	Constant: 0 to $-V_{dd}$, step ~ $-1.1_* V_{dd}/4$	Saturation region parameter extraction
$I_{ds} - V_{ds}$	Ramp: 0 to $1.1_* V_{dd}$, step ~50 mV	Constant: 0 to $1.1_* V_{dd}$ step ~ $1.1_* V_{dd}/4$	Constant: 0, $-V_{dd}/2$, $-V_{dd}$	High field effect parameter extraction, e.g., output resistance and early voltage parameters
$C_{gg} - V_{gs}$	0	Ramp: $-1.1_* V_{dd}$ to $+1.1_* V_{dd}$	0	Intrinsic capacitance model parameter extraction
$C_{gs} - V_{gd}$	Ramp: 0 to $1.1_* V_{dd}$	Constant: 0 to $1.1_* V_{dd}$ step ~ $1.1_* V_{dd}/4$	0	Intrinsic capacitance model parameter extraction
$C_{gd} - V_{gd}$	Ramp: 0 to $1.1_* V_{dd}$	Constant: 0 to $1.1_* V_{dd}$ step ~ $1.1_* V_{dd}/4$	0	Intrinsic capacitance model parameter extraction

set, process variability–induced device model parameters are obtained as discussed in Chapter 8 [6–9].

12.2.2 Data Fitting to Extract Compact Model Parameters

After the required data acquisition for modeling, the data set is formatted to the required format of the parameter extraction tool used for compact model parameter extraction [3,4]. The detailed parameter extraction routine is described in each tool [3,4]. A brief outline for fitting the data to the device compact model is shown in the flowchart in Figure 12.3.

Figure 12.4a–f shows the typical measured and fitted nMOSFET device characteristics of an advanced CMOS technology obtained by BSIMProPlus [3]. The fitted data are within the acceptable range of tolerance to build the model card of the representative CMOS technology.

In addition to fitting the basic device characteristics, the first and second derivatives of I–V curves are fitted to extract the model parameters related to g_m, R_{out}, and so on for both NMOS and PMOS devices.

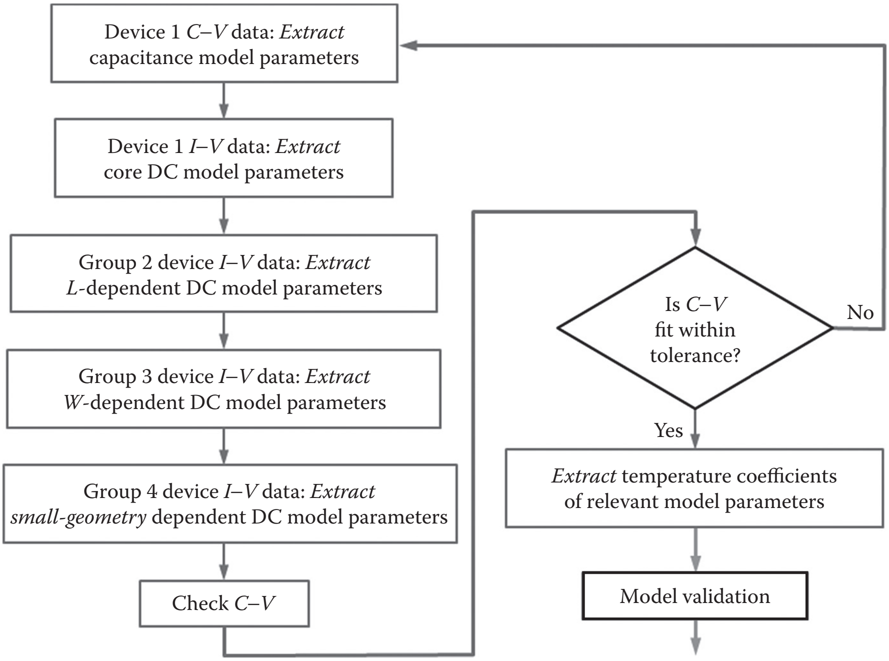


FIGURE 12.3
A general outline to extract compact MOSFET model parameters of a target VLSI technology; the regional compact MOSFET model like BSIM4 is used to illustrate the parameter extraction procedure.

12.2.3 Generation of Parameter Files

After the parameter optimization to fit the measured device characteristics with the simulation data obtained by extracted model parameters, the parameters for both NMOS and PMOS devices are saved into the respective parameter files. A typical parameter file includes device information such as W, L, device type, and the list of optimized model parameters of the compact model used.

The parameter files are verified to check the accuracy of fitting. This can be achieved graphically using the parameter extraction tool by (1) comparing the simulated device characteristics obtained by the parameter file to the measured device characteristics of a different set of device dimensions other than that used for parameter extraction, (2) comparing the simulated device characteristics with the measured device characteristics at temperatures other than that used for parameter extraction, (3) comparing the simulated device characteristics with the measured device characteristics at different bias point other than that used for extraction, (4) checking for discontinuities in the first- or second-order derivative of current (g_m, R_{out}, etc.), and (5) using external circuit CAD tool (e.g., HSPICE) to check for convergence issues. The verified parameter files are then used to generate the final model library.

12.2.4 Generation of Compact Model Library

The parameter files for both NMOS and PMOS devices obtained by fitting device characteristics with the target model (e.g., BSIM4) are assembled together to form the model card. A typical industry standard compact model library consists of a set of model cards that include logic with performance options, analog/RF, and SRAM as well as interconnect models. In this chapter, we describe the methodology to generate a simple compact MOSFET model that includes the real-device effects and process variability for device analysis in circuit CAD. To illustrate the methodology to generate compact model library, examples of a MOSFET and an SRAM model cards are presented in section, Sample Model Cards at the end of this chapter.

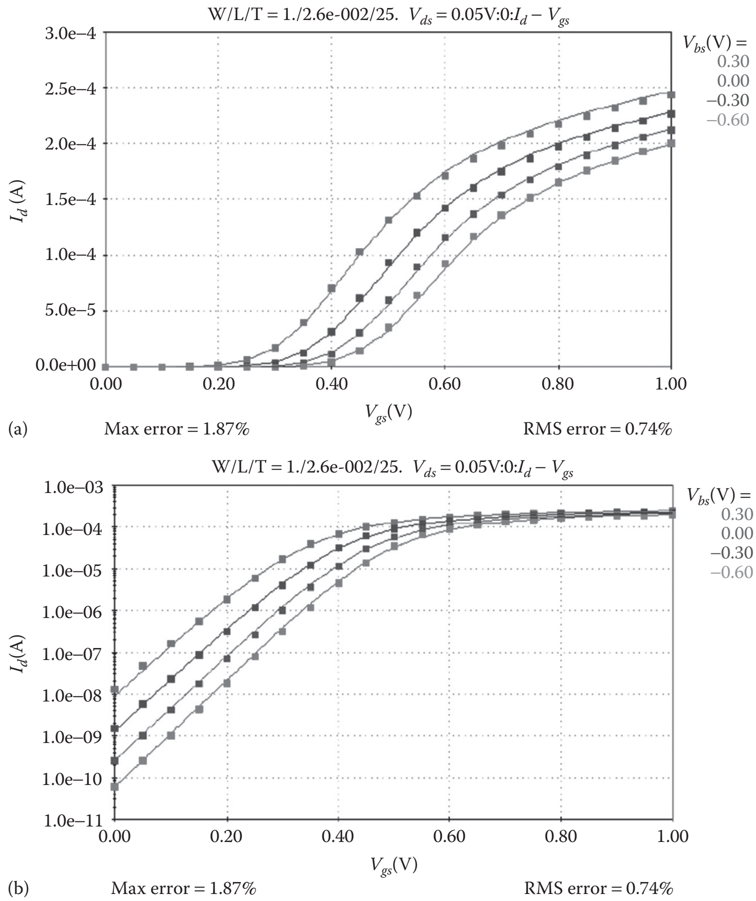
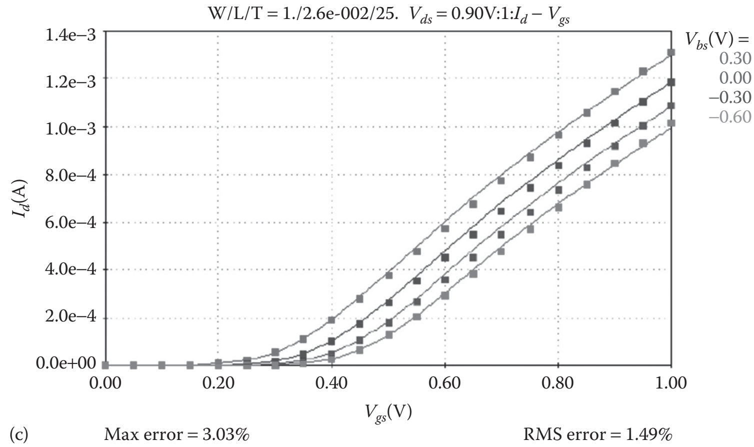


FIGURE 12.4
Measured data of an nMOSFET device with $W = 1$ μm and $L = 26$ nm fitted with BSIM4 model: (a) $I_d - V_{gs}$ characteristics at low V_{ds} to extract linear region model parameters; (b) $\log(I_d) - V_{gs}$ characteristics at low V_{ds} to extract subthreshold model parameters. (*Continued*)



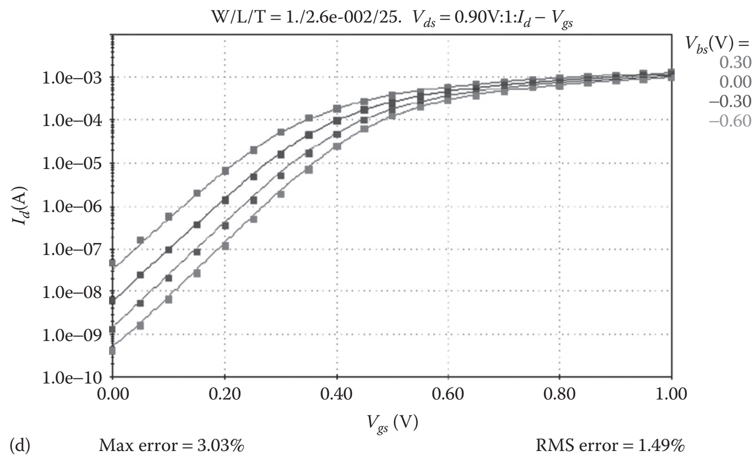
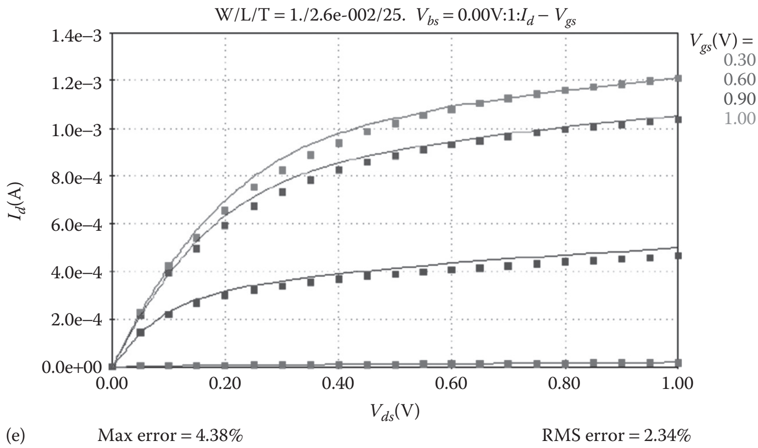


FIGURE 12.4 (Continued)
Measured data of an nMOSFET device with W = 1 μm and L = 26 nm fitted with BSIM4 model: (c) $I_d - V_{gs}$ characteristics at $V_{ds} = V_{dd}$ to extract saturation region model parameters; (d) $\log(I_d) - V_{gs}$ characteristics at low $V_{ds} = V_{dd}$ to extract off-state leakage current model parameters. (*Continued*)

A typical model card includes separate subsections describing (1) general information of the contents and usage of the model card, (2) process corners to model the device and circuit performance variability due to process variability, and finally (3) the properly parameterized model parameters to simulate different performance corners as discussed next.

12.2.4.1 Modeling Systematic Process Variability

Modeling process variation is critical in advanced ICs to design variability-aware VLSI circuits and IC chips [6–9]. The detailed modeling of process variability is described in Chapter 8 including the selection of process



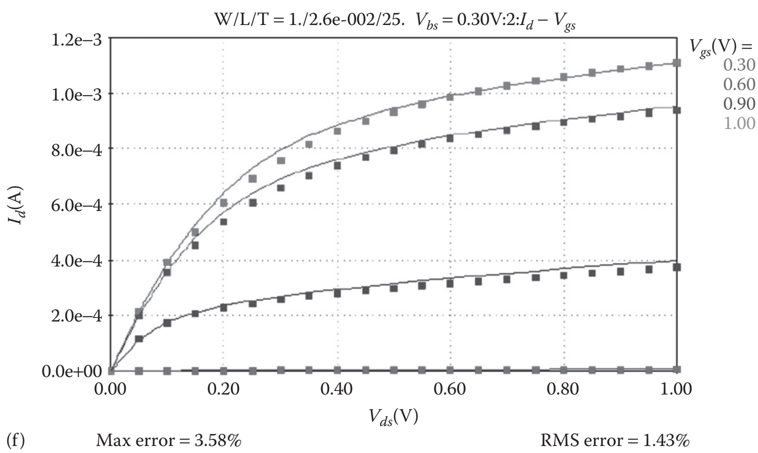


FIGURE 12.4 (Continued)
Measured data of an nMOSFET device with $W = 1$ μm and $L = 26$ nm fitted with BSIM4 model: (e) $I_d - V_{ds}$ characteristics for different V_{gs} and $V_{bs} = 0$ to extract saturation region model parameters including early voltage and output resistance model parameters; and (f) $I_d - V_{ds}$ characteristics for different V_{gs} and V_{bs} to extract body bias–dependent saturation region model parameters.

variability-sensitive model parameters for corner modeling. Table 12.2 shows a typical corner file for nMOSFETs with selected parameters to illustrate the corner file generation technique.

In Table 12.2, TT defines the *typical values* of the extracted model parameters at room temperature for NMOS and PMOS devices; SS, FF, SF, and FS define the parameters for slow NMOS and slow PMOS, fast NMOS and fast PMOS, slow NMOS and fast PMOS, and fast NMOS and slow PMOS, respectively, as described in Chapter 8 [6,7]. It is to be noted that SS, FF, SF, and FS represent the worst case speed (WS), worst case power (WP), worst case zero (WZ), and worst case one (WO), respectively [6,7]. Each instance parameter (delta) defines the variance of the corresponding model parameter. In Table 12.2,

TABLE 12.2

Example Corner Parameters in the Compact Model Library: Only a Selected List of nMOSFET Model Parameters is Shown to Illustrate the Corner Modeling Technique in BSIM4 Model Library

			TT	SS (WS)		FF (WP)		SF (WZ)	FS (WO)	
Compact Model Parameter	**Extracted Typical Value (TT)**	**Instance Parameter**	**Value**	**delta (%)**	**Value (delta)**	**delta (%)**	**Value (delta)**	**Value (delta)**	**Value (delta)**	**Statistical (delta)**
TOXE/TOXM	1.667E-09	toxen_svt	1.667E-09	2.6	1.710E-09	−2.6	1.6237E-09	1.667E-09	1.667E-09	4.2948E-11
TOXP	1.770E-09	toxpn_svt	1.770E-09	2.6	1.816E-09	−2.6	1.724E-09	1.770E-09	1.770E-09	4.5613E-11
XL	1.000E-08	dxln_svt	0	*	2.000E-09	*	−2.000E-09	1.000E-09	−1.0000E-09	2.0000E-09
XW	0	dxwn_svt	0	*	−5.000E-09	*	5.000E-09	−5.000E-09	5.000E-09	−5.0000E-09
VTH0	0.3827	dvthn_svt	0	*	−0.0079	*	0.0021	−0.0053	0.00138	−7.9330E-03
RDSW	1.597E+02	drdswn_svt	0	3.0	4.7916	−3.0	−4.7916	0	0	4.7916E+00
K1	0.5658	dk1n_svt	0	2.0	0.0113	−2.0	−0.0113	0	0	1.1317E-02
CJS/CJD	3.201E-03	cjn_svt	3.201E-03	3.0	3.297E-03	−3.0	3.105E-03	3.297E-03	3.105E-03	9.6030E-05
CJSWS/CJSWD	1.000E-14	cjswn_svt	1.000E-14	3.0	1.030E-14	−3.0	9.700E-15	1.030E-14	9.700E-15	3.0000E-16
CJSWGS/CJSWGD	1.938E-10	cjswgn_svt	1.938E-10	3.0	1.996E-10	−3.0	1.880E-10	1.997E-10	1.880E-10	5.8149E-12
CGSO/CGDO	6.206E-11	cgon_svt	6.206E-11	−3.0	6.020E-11	3.0	6.392E-11	6.020E-11	6.392E-11	−1.8619E-12
CGDL/CGSL	5.228E-11	cgln_svt	5.228E-11	−3.0	5.071E-11	3.0	5.385E-11	5.07E-11	5.385E-11	−1.5684E-12

delta is the 3σ variation of the mean value of the corresponding parameter; where σ is the variance of the statistical distribution of the model parameter.

Let us consider a typical parameter file of a standard V_{th} (*svt*) device of a CMOS technology. A typical parameter is then parameterized in the model card as: TT ± delta. Thus, the model parameter VTH0 is parameterized for SS and FF corners as

$$\text{VTH0} = \text{VTH0} \pm dvthn\_svt \tag{12.1}$$

where:

dvthn_svt defines the 3σ value of V_{th} variation of *svt* devices and is defined in the header file of a typical compact model card for each corner used in the model card

It has different values for different corners as determined by the variance shown in Table 12.2.

For *statistical compact modeling*, each instance parameter is obtained from the statistical distribution of the corresponding parameter, whereas for a *fixed corner* model, a historical standard percentage of variation of the selected parameters is used to define process corners [6,7]. For Monte Carlo (MC) and statistical corner modeling, the σ values obtained from the statistical distribution of each variability sensitive model parameters are used, as shown in Table 12.2. The detailed statistical modeling methodology and variability-aware circuit design is discussed in Chapter 8. In HSPICE circuit CAD tool, the variation for MC analysis is defined by

$$dvthn\_svt = globalmcflag \cdot (3\sigma) \cdot agauss(0,1,3) \tag{12.2}$$

where:

globalmcflag is a *switch* or *flag* that is used to turn *on* or *off* the model for circuit simulation

agauss(0,1,3) defines the probability distribution function of V_{th} variation

Equations 12.1 and 12.2 are used in the model card shown at the end of this chapter.

12.2.4.2 Modeling Mismatch

The mismatch modeling and parameter selection techniques are described in Chapter 8. Considering only threshold voltage mismatch, primarily due to random discrete doping, the mismatch in threshold voltage is given by (Equation 8.20)

$$\sigma V_{TH0,mismatch} = \frac{1}{\sqrt{2}}\sigma_{\Delta V_{TH0}} = \frac{1}{\sqrt{2}}\frac{A_{vt}}{\sqrt{WL}} \tag{12.3}$$

where:

A_{vt} is the mismatch coefficient

$\sqrt{WL}$ is the area of the device (Chapter 8)

Let us define *sigvtp_svtp* as the mismatch in V_{th} of *svt* PMOS devices, *cvtp* is the mismatch coefficient, and $1/\sqrt{WL}$ is the *geometrical factor* (*geo_fac*); then the V_{th} mismatch is modeled by

$$sigvtp\_svtp = (cvtp\_svtp) \cdot (geo\_fac) \cdot mismatchflag \tag{12.4}$$

where

cvtp_svtp = 'avtp/1.414214';

lef = 'l-5.6E-09'; wef = 'w/n_fingers+0E-09'; and *geo_fac* = '1/sqrt(multi*n_fingers*lef*wef)' with

lef and wef are used to define the effective channel length and width (w), respectively, n_fingers represents the number of gate geometries in the layout of a transistor, and multi is a number.

Again, the *mismatchflag* is used to turn on and off the model in circuit analysis.

In corner simulation, only geometry dependent fixed mismatch can be modeled by using a flag to appropriately call the model if desired without MC simulation use

$$'sigvtp\_vtp = (cvtp\_svtp) \cdot (geo\_fac) \cdot globalsigmavtflag \tag{12.5}$$

For MC statistical model the mismatch is modeled by one-sigma variation of the parameter in space

$$'sigvtp\_svtp = (cvtp\_svtp) \cdot (geo\_fac) \cdot agaus(0,1,1) \cdot mismatchflag \tag{12.6}$$

where the mismatch parameter, *avtp*, for *p*-channel devices is extracted from the sigma(delta_vt) versus $1/\sqrt{WL}$ plots. The expressions given in Equations 12.4 through 12.6 are used in generating compact model cards in the examples shown at the end of this chapter.

12.2.4.3 Generate Model Card

Finally, use the above formulations to develop a compact model card for circuit CAD. In reality, the corner files, header files, and other files can be kept separate in the model library and a simple script file can be used to call the relevant models for circuit analysis. In this chapter all the relevant files are integrated into a single comprehensive compact model card. To illustrate the basic procedure, a compact MOSFET model card *ex1mod*0*p*1.*l* and an SRAM model card *sram*127*hp.l* are presented at the end of this chapter. Note that due to continuous updates of compact model formulations and CAD environment, appropriate changes in the parameters of the model library may be needed to use the model for circuit CAD. Again, the model cards represent BSIM4 model for HSPICE circuit CAD tool. The model parameters are defined in BSIM4 user's manual [2–4].

The model card *ex1mod*0*p*1.*l* is a statistical model that can be used for corner analysis of a VLSI circuit as well as MC statistical analysis of the circuit by selecting appropriate switches or flags. The different flags are described in the header section of the model card. The model card can be set up for corner simulation by turning off all the flags for MC simulation. Different flags used for MC simulation and their functions are summarized in Table 12.3. Some of the parameters are repeated in the following section (Figure 12.5).

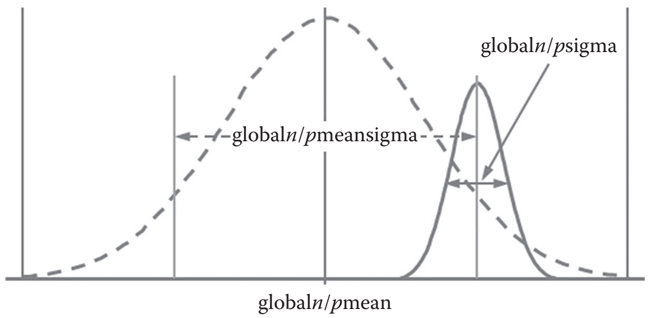


FIGURE 12.5
The parameters of the systematic and random Gaussian distribution functions used in generating the compact model card using HSPICE circuit CAD.

TABLE 12.3
Definition of Different Parameters and Their Functions as Used in the Model Card

Parameter	Description
globalnmean	Sets the mean of the systematic variation agauss for NMOS in MC simulation; e.g., global*n*mean = 2 for a mean of 2-sigma (default = 0)
globalpmean	Sets the mean of the systematic variation agauss for PMOS in MC simulation; e.g., global*p*mean = 2 for a mean of 2-sigma (default = 0)
globalnsigma	Sets the width of the local systematic variation agauss for NMOS (default: 1)
globalpsigma	Sets the width of the local systematic variation agauss for PMOS (default: 1)
globalnmeansigma	Sets the spread of the distribution of die means for NMOS in total MC variation (default: 2.8284) (die-to-die)
globalpmeansigma	Sets the spread of the distribution of die means for PMOS in total MC variation (default: 2.8284) (die-to-die)
globalsigmavtflag = 1	Adds a fixed 1-sigma VTH variation offset to a fixed systematic corner (default)
globalmismatchflag = 1	Enables mismatch (random variation) in MC simulations
globalmismatchnsigma	Set the width of the mismatch agauss (random variation) for NMOS (default: 3)
globalmismatchpsigma	Set the width of the mismatch agauss (random variation) for PMOS (default: 3)
mismatchflag = 1	Enables mismatch per device (instance parameter)
sigmavt	Sets the point on the distribution for VTH for a fixed corner per device (instance parameter); this includes ONLY RDD and LER

12.2.5 Model Validation

After the generation of the model library, a number of simulation experiments are performed to verify the accuracy and predictability of the model prior to release to production for circuit CAD. Different model cards (e.g., logic and SRAM) have different requirements for model validation and there are several ways to check the robustness of the extracted model. In general, the model validation includes (1) verification of the simulated device performance matrix such I_{on}, I_{off}, V_{th}, and ring-oscillator speed to the target specifications; (2) scalability of device performance; and (3) compatibility with external circuit simulation tools to ensure convergence of circuit simulation.

12.3 Model Usage

The usage of the model cards or library is described in the example model library. The model card similar to *ex1mod0p1.l* can be used for corner simulation using systematic ±3σ extreme corners (SS, FF) and (FS, SF) intermediate corners defined in Table 12.2 as well as MC statistical analysis. In order to select appropriate simulation setup (e.g., corners or MC), the appropriate input command must be used to select the flags in HSPICE netlist. The appropriate switches (flags) to turn on or off the target method of simulation using *ex1mod0p1.l* are shown in Table 12.4.

Thus, for circuit analysis using the model card in *ex1mod0p1.l*, the following commands are used in HSPICE circuit input file or netlist.

TABLE 12.4

Assignment of Different Flags in the HSPICE Netlist to Set up Circuit Analysis Using the Compact Model in Example1

Variation	Corner	global-mismatch-flag	global-sigmavt-flag	global-mcflag	global [n/p]-mean	global [n/p] meansigma	global [n/p]sigma
Systematic	Fixed corners	0	0	0	*	*	*
Total variation	Fixed corners	0	1	0	*	*	*
Total variation	MC	1	0	1	Systematic mean	Die-to-die spread	Within die spread
Variation around mean	MC	1	0	1	Systematic mean	0	Within die spread
Variation around a corner	MC	1	0	0	*	*	*

```
.lib 'lib' TT (or SS, FF, FS, and SF)
.param globalmismatchflag = 0     $ disable MC mismatch
.param globalsigmavtflag = 1      $ enable fixed Vth mismatch
                                    offset
.param globalmcflag = 0    $ disable MC systematic variation
```

Figure 12.6a shows the simulated corner points along with the simulated TT values of *n*MOSFET on current, IONN versus *p*MOSFET on current, IONP for an advanced CMOS technology.

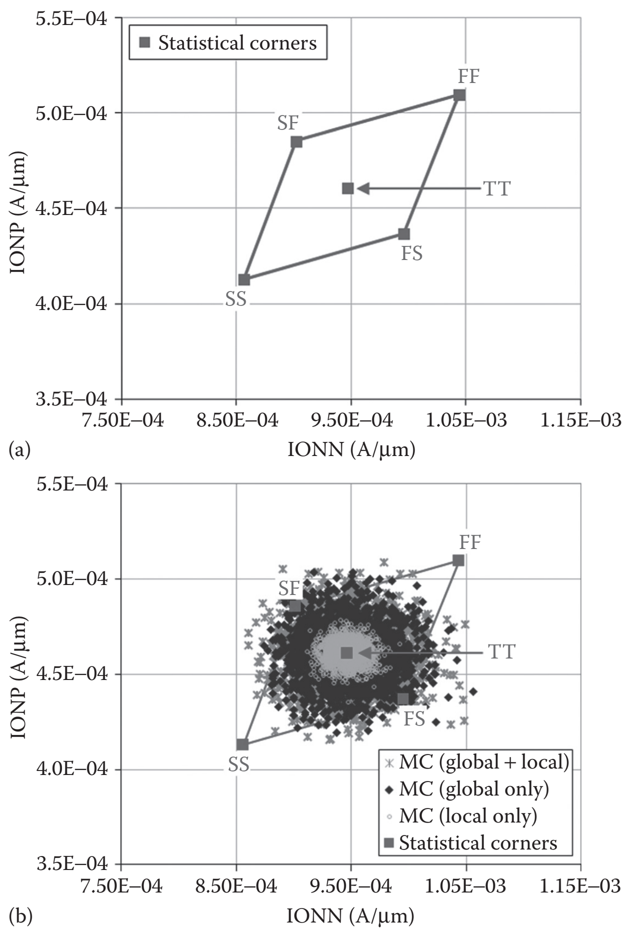


FIGURE 12.6
Simulated IONN versus IONP of a typical CMOS technology obtained by HSPICE circuit CAD using a model card similar to *ex1mod0p1.l*: (a) corner simulation and (b) MC analysis with simulated corner values superimposed.

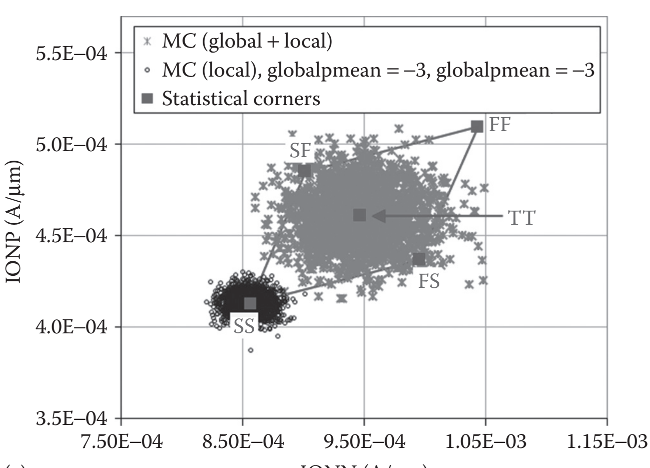
For MC simulation using ±3σ distribution for systematic variation and ±1σ variation in mismatch, we can use the following commands in the HSPICE netlist

```
.lib 'lib' MC
.param globalmismatchflag = 1     $ enable MC mismatch
.param globalsigmavtflag = 0      $ disable fixed Vth mismatch
                                    offset
.param globalmcflag = 1    $ enable MC systematic variation
```

Figure 12.6b shows the MC simulation results of IONN versus IONP for the same CMOS technology. The corner values are shown for comparison only.

Figure 12.7a and b show the simulated distribution of IONN versus IONP obtained by MC (local and global) analysis around TT and MC mismatch simulation around SS and FF corners, respectively. Again, the corner values are shown for comparison only. The simulated mismatch distribution in Figure 12.7a shows that some of the worst-case (SS) speed die are pulled toward the TT values. This offers realistic prediction of actual speed since all transistors are not pinned to the worst-case device value. Similarly, the simulated mismatch distribution in Figure 12.7b shows that some of the worst-power (FF) die are pulled toward the TT values, thus offering a better estimate of average power of the FF devices.

Table 12.5 presents a qualitative evaluation of simulation outcome using different options for modeling process variability in advanced CMOS technology.



(a)

FIGURE 12.7
Simulated IONN versus IONP of a typical CMOS technology obtained by HSPICE circuit CAD using a model card similar to *ex1mod0p1.l*: (a) total MC distribution around the TT values and MC mismatch distribution at SS corner. (*Continued*)

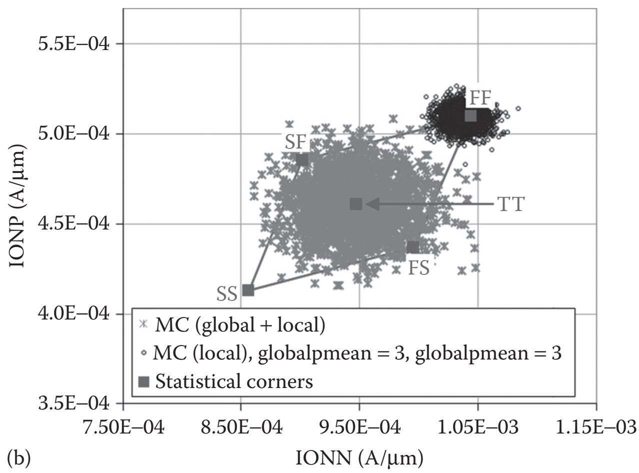


FIGURE 12.7 (Continued)
Simulated IONN versus IONP of a typical CMOS technology obtained by HSPICE circuit CAD using a model card similar to *ex1mod0p1.l*: (b) total MC distribution around the TT values and MC mismatch distribution at FF corner.

TABLE 12.5
Comparison of Nanoscale MOSFET Circuit Simulation Results using Different Methods for Process Variability Modeling

Simulation Method	Simulation Results	Model Set	Model Extraction	Simulation Time
Worst-case fixed corner	Pass/Fail: pessimistic	Discrete; artificial	Easy	Fast to moderate
Statistical corner	Pass/Fail: realistic	Discrete wafer data	Complex	Moderate
Monte Carlo	Yield: mismatch	Distribution	Complex	Long

12.4 Summary

A brief overview of generating statistical compact MOSFET model library and its usage is described. The generation of compact model library involves selection of device structures and device characteristics to capture the real-device effects in describing the device performance in IC chips. The data acquisition and data fitting to generate the model parameters and parameterization of the process variability-sensitive model parameters are critical for statistical compact model. It is shown that a comprehensive simple statistical model library can be developed and used by implementing different switches or flags to turn on or off the relevant models for circuit CAD. The example model files are provided to expose readers to the statistical models and model development from a minimum set of devices and device characteristics.

Sample Model Cards

1. Compact Model of an Advanced CMOS Technology

```
*************************************************************
* Example1: 20 nm CMOS technology node MOS Hspice model library
*************************************************************
* Version:   ex1mod0p1.l   *** January 21, 2015 ***
* MODEL:     BSIM4 ( V4.5 )
*************************************************************
* Model Information
*************************************************************
* This Rev0 version of sample SPICE model is based on two-
* dimensional numerical device simulation
*************************************************************
*.LIB INTERNAL
*------------------------------------------------------------
* History of model updates
*------------------------------------------------------------
* Jan 20, 2015: model created from TCAD-based data – only
* selected parameters are shown in the model card to illustrate
* the basic procedure for the generation of compact model
* library
*------------------------------------------------------------
*.ENDL INTERNAL
*************************************************************
* Begin header
*************************************************************
* Usage:
*
* Hspice Version: 2007.03, 2008.03, 2009.03
*
* Library includes standard-Vth (svt) corner libraries:
* .lib 'ex1mod0p1.l' TT
* .lib 'ex1mod0p1.l' FF
* .lib 'ex1mod0p1.l' SS
* .lib 'ex1mod0p1.l' SF
* .lib 'ex1mod0p1.l' FS
* .lib 'ex1mod0p1.l' MC
*
* .options scale=1
* XXX = svt
* Transistor sub-circuits
*  p4_XXX : PMOS XXX vt Ldrawn = 0.026-u, Wdrawn = 1-u
*      x0 d g s b
*      +p4_svt w=w l=l           $$ REQUIRED
*
```

```
* -------------------------- optional --------------------------
*        + z=z                    $$ default = 0.1n: s/d length from
* channel
*        + ad=ad as=as pd=pd ps=ps  $$ default = function of w, l, z
*        + n_fingers=#fingers     $$ default=1
*        + sigmavt=(instance sigvt) $$ default=0
*        + mismatchflag=(0|1)     $$ default=0
*
* n4_XXX : NMOS XXX vt Ldrawn = 0.026u, Wdrawn = 1u
*        x0 d g s b
*        +n4_svt w=w l=l          $$ REQUIRED
*
*--------------------------optional----------------------------
*        + z=z                    $$ default = 0.1n : s/d length from
* channel
*        + ad=ad as=as pd=pd ps=ps  $$ default = function of w, l, z
*        + n_fingers=#fingers     $$ default=1
*        + sigmavt=(instance sigvt) $$ default=0
*        + mismatchflag=(0|1)     $$ default=0
*
* For statistical modeling using Monte Carlo simulation, use:
* .lib 'ex1mod0p1.l' MC
*
* Use flags to simulate different sources of process
* variability, For example, to simulate local variation, set
* the following flags
*
* .param globalsigmavtflag=0
* .param globalmcflag=0
* .param globalmismatchflag=1
*
* MC simulations     globalsigmavtflag  globalmcflag  globalmismatchflag
* --------------     -----------------  ------------  ------------------
* MC (Global + Local)     0                 1               1
* MC (Global)             0                 1               0
* MC (Local)              0                 0               1
*
* Example of user-defined (mismatch parameter) "avt" values in
* Hspice netlist:
*         .param avtp=1.0e-9
*         .param avtn=1.0e-9
*
* Use the following command to include the appropriate library
* for typical N and typical P (TT) models
* .lib 'ex1mod0p1.l' TT
*
* Temperature Range : 25C
* Vds Range         : 0 ~ 0.9 V
```

```
* Vbsn Range        : 0.3 V (forward) ~ -0.5 V (reverse)
* Vbsp Range        :-0.3 V (forward) ~ 0.5 V (reverse)
*
*************************************************************
* end header
*************************************************************
.LIB TT
.lib 'ex1mod0p1.l' MOD_GLOBAL
.lib 'ex1mod0p1.l' TT_svt
.ENDL TT
*
.LIB SS
.lib 'ex1mod0p1.l' MOD_GLOBAL
.lib 'ex1mod0p1.l' SS_svt
.ENDL SS
*
.LIB FF
.lib 'ex1mod0p1.l' MOD_GLOBAL
.lib 'ex1mod0p1.l' FF_svt
.ENDL FF
*
.LIB SF
.lib 'ex1mod0p1.l' MOD_GLOBAL
.lib 'ex1mod0p1.l' SF_svt
.ENDL SF
*
.LIB FS
.lib 'ex1mod0p1.l' MOD_GLOBAL
.lib 'ex1mod0p1.l' FS_svt
.ENDL FS
*
.LIB MC
.lib 'ex1mod0p1.l' MOD_GLOBAL
.lib 'ex1mod0p1.l' MC_svt
.ENDL MC

.LIB MOD_GLOBAL
*************************************************************
* global model parameters
*************************************************************
.param globalmcflag=0

.param
+globalnmean=0
+globalpmean=0
+globalnsigma=1
+globalpsigma=1
+globalnmeansigma=2.8284
+globalpmeansigma=2.8284
```

```
.param globalsigmavtflag=1
.param globalmismatchflag=0
.param globalmismatchpsigma=3
.param globalmismatchnsigma=3

.param wmin_p_svt=0.99e-8
.param wmax_p_svt=10.01e-6
.param wmin_n_svt=0.99e-8
.param wmax_n_svt=10.01e-6

.ENDL MOD_GLOBAL
***************************************************************
* VT TYPE = SVT (standard VT)
***************************************************************

**************** SVT Library of Typical Case *****************
.LIB TT_svt

.param sdvtncorn = 0
.param sdvtpcorn = 0

** Need these defined since the parameters created for MC are
*  in the sub-circuit
** Sub-circuit will therefore, over-ride 'tox, dxl, dxw, dvth,
*  cj, cjsw, cjswn, cgo, cgl' in this LIB.
** g[np]sigma is always 0 when using fixed corners
.param gnmean = 0
.param gpmean = 0
.param gnsigma = 0
.param gpsigma = 0
*
.param
+toxn_svt = 1.0800E-09     dxln_svt = 0
+dxwn_svt = 0              dvthn_svt = 0
+cjn_svt =  3.2010E-03     cjswn_svt = 1.0000E-14
+cjswgn_svt = 1.9383E-10   cgon_svt = 1.5000E-11
+cgln_svt = 1.0000E-11     drdswn_svt = 0
.param
+toxp_svt = 1.1398E-09     dxlp_svt = 0
+dxwp_svt = 0              dvthp_svt = 0
+cjp_svt = 3.9056E-03      cjswp_svt = 1.0000E-14
+cjswgp_svt = 2.5218E-10   cgop_svt = 3.3205E-12
+cglp_svt =  6.4850E-12    drdswp_svt = 0
*
.lib 'ex1mod0p1.l' SUBCKTS_SVT
.ENDL TT_svt

********** SVT Library of SNSP Corner Case with RDD **********
```

```
.LIB SS_svt

.param sdvtncorn = 1
.param sdvtpcorn = 1

** Need these defined since the parameters created for MC are
*  in the sub-circuit
** Sub-circuit will therefore, over-ride 'tox, dxl, dxw, dvth,
*  cj, cjsw, cjswn,cgo, cgl' in this LIB.
** g[np]sigma is always 0 when using fixed corners
.param gnmean = 1
.param gpmean = 1
.param gnsigma = 0
.param gpsigma = 0
*
.param
+toxn_svt = 1.1081E-09     dxln_svt = 1.2000E-09
+dxwn_svt = -2.7000E-09    dvthn_svt = 1.5058E-02
+cjn_svt = 3.4251E-03      cjswn_svt = 1.0700E-14
+cjswgn_svt = 2.0740E-10   cgon_svt = 1.3950E-11
+cgln_svt = 9.3000E-12     drdswn_svt = 4.9500E+00
.param
+toxp_svt = 1.1683E-09     dxlp_svt = 1.2000E-09
+dxwp_svt = -2.7000E-09    dvthp_svt = -2.3075E-02
+cjp_svt = 4.1799E-03      cjswp_svt = 1.0700E-14
+cjswgp_svt = 2.6983E-10   cgop_svt = 3.0881E-12
+cglp_svt = 6.0311E-12     drdswp_svt = 5.3496E+00
*
.lib 'ex1mod0p1.l' SUBCKTS_SVT
.ENDL SS_svt

********* SVT Library of FNFP Corner Case with RDD *********
.LIB FF_svt

.param sdvtncorn = -1
.param sdvtpcorn = -1

** Need these defined since the parameters created for MC are
*  in the sub-circuit
** Sub-circuit will therefore, over-ride 'tox, dxl, dxw, dvth,
*  cj, cjsw, cjswn, cgo, cgl' in this LIB.
** g[np]sigma is always 0 when using fixed corners
.param gnmean = -1
.param gpmean = -1
.param gnsigma = 0
.param gpsigma = 0
```

```
*
.param
+toxn_svt = 1.0519E-09     dxln_svt = -1.2000E-09
+dxwn_svt = 2.7000E-09     dvthn_svt = -1.5058E-02
+cjn_svt = 2.9769E-03      cjswn_svt = 9.3000E-15
+cjswgn_svt = 1.8026E-10   cgon_svt = 1.6050E-11
+cgln_svt = 1.0700E-11     drdswn_svt = -4.9500E+00
.param
+toxp_svt = 1.1113E-09     dxlp_svt = -1.2000E-09
+dxwp_svt = 2.7000E-09     dvthp_svt = 2.3075E-02
+cjp_svt = 3.6313E-03      cjswp_svt = 9.3000E-15
+cjswgp_svt = 2.3453E-10   cgop_svt = 3.5529E-12
+cglp_svt = 6.9390E-12     drdswp_svt = -5.3496E+00
*
.lib 'ex1mod0p1.l' SUBCKTS_SVT
.ENDL FF_svt

********** SVT Library of SNFP Corner Case with RDD **********
.LIB SF_svt

.param sdvtncorn = 0
.param sdvtpcorn = -0

** Need these defined since the parameters created for MC are
*  in the sub-circuit
** Sub-circuit will therefore, over-ride 'tox, dxl, dxw, dvth,
*  cj, cjsw, cjswn, cgo, cgl' in this LIB.
** g[np]sigma is always 0 when using fixed corners
.param gnmean = 1
.param gpmean = -1
.param gnsigma = 0
.param gpsigma = 0
*
.param
+toxn_svt = 1.0800E-09     dxln_svt = 0
+dxwn_svt = -2.7000E-09    dvthn_svt = 1.0040E-02
+cjn_svt = 3.4251E-03      cjswn_svt = 1.0700e-14
+cjswgn_svt = 2.0740E-10   cgon_svt = 1.3950E-11
+cgln_svt =  9.3000E-12    drdswn_svtc = 0
.param
+toxp_svt = 1.1398e-09     dxlp_svt = 0
+dxwp_svt = -2.7000E-09    dvthp_svt = 1.5380E-02
+cjp_svt = 3.6313E-03      cjswp_svt = 9.3000E-15
+cjswgp_svt = 2.3453E-10   cgop_svt = 3.5529E-12
+cglp_svt = 6.9390E-1      drdswp_svt =  0
*
.lib 'ex1mod0p1.l' SUBCKTS_SVT
.ENDL SF_svt
```

```
********** SVT Library of FNSP Corner Case with RDD **********
.LIB FS_svt

.param sdvtncorn = -0
.param sdvtpcorn = 0

** Need these defined since the parameters created for MC are
*  in the sub- circuit
** Sub-circuit will therefore, over-ride 'tox, dxl, dxw, dvth,
*  cj, cjsw, cjswn, cgo, cgl' in this LIB.
** g[np]sigma is always 0 when using fixed corners
.param gnmean = -1
.param gpmean = 1
.param gnsigma = 0
.param gpsigma = 0
*
.param
+toxn_svt = 1.0800E-09     dxln_svt = 0
+dxwn_svt = 2.7000E-09     dvthn_svt = -1.0040E-02
+cjn_svt = 2.9769E-03      cjswn_svt = 9.3000E-15
+cjswgn_svt = 1.8026E-10   cgon_svt = 1.6050e-11
+cgln_svt = 1.0700E-11     drdswn_svt = 0
.param
+toxp_svt = 1.1398e-09     dxlp_svt = 0
+dxwp_svt = -2.7000e-09    dvthp_svt = -1.5380E-02
+cjp_svt = 4.1799E-03      cjswp_svt = 1.0700e-14
+cjswgp_svt = 2.6983E-10   cgop_svt = 3.0881E-12
+cglp_svt = 6.0311E-12     drdswp_svt = 0
*
.lib 'ex1mod0p1.l' SUBCKTS_SVT
.ENDL FS_svt

*************************************************************
*                   SVT MC MODEL LIBRARY                    *
*************************************************************
.lib MC_svt

** create 1 gnmean agauss and 1 gpmean agauss
.param grandom0n=agauss(0,1,3)
.param grandom0p=agauss(0,1,3)

.param Agmn='grandom0n*(globalmcflag==1)'
.param Agmp='grandom0p*(globalmcflag==1)'

** globalp/nmean=n shifts mean of systematic agauss by n*sigma
** global[pn]meansigma variation of mean to be added to g[np]sigma
```

```
** defaults are g[np]sigma=1, g[np]msigma=2.83
** sampling should be the same for each iteration (i.e. not
   instance based)
.param gnmean='(globalmcflag==1)*((Agmn*globalnmeansigma) +
globalnmean)/3'
.param gpmean='(globalmcflag==1)*((Agmp*globalpmeansigma) +
globalpmean)/3'

** globalp/nsigma=m multiplies stdev of systematic agauss by m
** this scale factor is passed to subcircuit to vary systematic
*  variation by instance
.param gnsigma=globalnsigma*(globalmcflag==1)/3
.param gpsigma=globalpsigma*(globalmcflag==1)/3

.param sdvtpcorn = 0
.param sdvtncorn = 0

.LIB 'ex1mod0p1.l' SUBCKTS_SVT
.endl MC_svt

.LIB SUBCKTS_SVT

**************************************************************
* Subcircuit references
**************************************************************
*
* weff = w/nf
* wnflag = 1 size bin w/nf
* wnflag = 0 size bin w
*
* fixed nf=1 and use instance mult factor to capture folding
* setting instance of these subckts with parameter nf!=1 have
* no effect area/peri default calculation assumes nf=1

.subckt p4_svt D G S B
.param w=0 l=0 z=0.100e-6 multi=1
.param pd='2*(w+z)' ad='w*z'
.param ps='2*(w+z)' as='w*z'
.param pw='2*((2*z)+l+w)' aw='((2*z)+l)*w'
.param lw='(2*z)+l'
.param n_fingers=1
*
.param mismatchflag=0
.param avtp=1.12e-09
** must make default sigmavt=0, i.e., no instance parameter
** sdvtp/ncorn in TT,SS,... takes care of corners sigvt when
*  globalsigmavtflag=1
```

```
.param sigmavt=0
.param delvto=0

** systematic **
** instance based sampling of systematic variation
** g[pn]mean varying in clock step for each instance
** defined in calling library MC_svt using global[np]mean and
*  global[np]meansigma
** existing global[np]sigma varies by instance  and is defined by
*  global[np]sigma
.param random0p=agauss(0,1,3)
.param random1p=agauss(0,1,3)
.param random2p=agauss(0,1,3)
.param random3p=agauss(0,1,3)
.param random4p=agauss(0,1,3)
.param random5p=agauss(0,1,3)
.param random6p=agauss(0,1,3)
.param random7p=agauss(0,1,3)
.param random8p=agauss(0,1,3)
.param random9p=agauss(0,1,3)
.param A0p='random0p*(globalmcflag==1)'
.param A1p='random1p*(globalmcflag==1)'
.param A2p='random2p*(globalmcflag==1)'
.param A3p='random3p*(globalmcflag==1)'
.param A4p='random4p*(globalmcflag==1)'
.param A5p='random5p*(globalmcflag==1)'
.param A6p='random6p*(globalmcflag==1)'
.param A7p='random7p*(globalmcflag==1)'
.param A8p='random8p*(globalmcflag==1)'
.param A9p='random9p*(globalmcflag==1)'
.param
+toxp_svt = '1.1398E-009 + ( 2.8414E-011*((A0p*gpsigma) + gpmean))'
+dxlp_svt = '0.0000E+000 + ( 1.2000E-009*((A1p*gpsigma) + gpmean))'
+dxwp_svt = '0.0000E+00 + (-2.7000E-009*((A2p*gpsigma) + gpmean))'
+dvthp_svt = '0.0000E+00 + (-2.3075E-002*((A3p*gpsigma) + gpmean))'
+cjp_svt = '3.9056E-003 + ( 2.7427E-004*((A4p*gpsigma) + gpmean))'
+cjswp_svt = '1.0000E-014 + ( 7.0000E-016*((A5p*gpsigma) + gpmean))'
+cjswgp_svt = '2.5218E-01 + ( 1.7653E-011*((A6p*gpsigma) + gpmean))'
+cgop_svt = '3.3205E-012 + (-2.3244E-013*((A7p*gpsigma) + gpmean))'
+cglp_svt = '6.4850E-012 + (-4.5395E-013*((A8p*gpsigma) + gpmean))'
+drdswp_svt = '0.0000E+00 + ( 5.3496E-000*((A9p*gpsigma) + gpmean))'

*** mismatch ***
.param AM0=agauss(0,1,1)

.param
+cvtp_svt='avtp/1.414214'
+lef='l-8.3256E-11' wef='w/n_fingers+0E-09'
+geo_fac='1/sqrt(multi*n_fingers*lef*wef)'
```

```
+sigvtp_svt='AM0*cvtp_svt*geo_fac*globalmismatchpsigma/3 *
((globalmismatchflag==1)||(mismatchflag==1))'

** fixed sigmavt offset **
.param
+sdvtp_svt='-cvtp_svt*geo_fac*((sigmavt*(globalsigmavtflag==0)) +
(sdvtpcorn*(globalsigmavtflag==1)))'

** no width effect
mp_svt D G S B pch_svt w=1e-6 l=l pd=pd ad=ad ps=ps as=as
m='w/1.0e-6' nf=n_fingers wnflag=1 delvto=delvto
** width effect
*mp_svt D G S B pch_svt w=w l=l pd=pd ad=ad ps=ps as=as
nf=n_fingers wnflag=1 delvto=delvto

**************************************************************
* BSIM4.5.0 model card for p-type devices
**************************************************************
.model  pch_svt.1 pmos  ( level = 54
**************************************************************
*                 MODEL FLAG PARAMETERS
**************************************************************
+lmin = 2.59e-008     lmax = 2.51e-007    wmin = 'wmin_p_svt'
+wmax = 'wmax_p_svt'  version = 4.5       binunit = 1
+paramchk = 1         mobmod = 1          capmod = 2
+igcmod = 2           igbmod = 1          geomod = 0
+diomod = 1           rdsmod = 0          rbodymod= 0
+rgeomod = 0          rgatemod= 0         permod = 1
+acnqsmod= 0          trnqsmod= 0
**************************************************************
*               GENERAL MODEL PARAMETERS
**************************************************************
+tnom = 25            toxe = 'toxp_svt'   toxp = 1.012e-009
+toxm = 'toxp_svt'    dtox = 2.5e-010     epsrox = 3.9
+toxref = 1.2e-009    wmlt = 1            wint = 0
+lint = 4.1628e-011   ll = 0              wl = 0
+lln = 1              wln = 1             lw = 0
+ww = 0               lwn = 1             wwn = 1
+lwl = 0              wwl = 0             xl = '0+dxlp_svt'
+xw = '0+dxwp_svt'    dlc = 2.6887e-009   dwc = 0
+xpart = 0
**************************************************************
*                        DC PARAMETERS
**************************************************************
+vth0 = '-0.46149+dvthp_svt+sdvtp_svt+sigvtp_svt'  k1 = 0.35256
+lk1 = -0.0024567     k2 = 0.017398       k3 = 0.27044
+k3b = 0.07434        w0 = 1e-007         dvt0 = 0.52272
+dvt1 = 0.50091       dvt2 = -0.021065    dvt0w = 0.013
+dvt1w = 5984800      dvt2w = 0.05        dsub = 4.1202
```

```
+minv = 0.69601          voffl = -8.0716e-011  dvtp0 = 1e-013
+dvtp1 = 1e-013          lpe0 = 1.5509e-011    lpeb = 4.606e-008
+vbm = -3                xj = 5.81e-008        ngate = 1.5e+022
+ndep = 1.7e+017         nsd = 1e+020          phin = 0
+cdsc = 0.0036589        cdscb = 0.001341      cdscd = 0.00027994
 +cit = -3.2858e-018     voff = -0.11885       nfactor = 4.1034
+eta0 = 1.6875           etab = -19.429        u0 = 0.0056074
+lu0 = 0.0026234         ua = 1.1889e-009      lua = 1.448e-011
+ub = 2.8685e-019        uc = -0.11407         eu = 1
+vsat = 127540           a0 = 3.7101           ags = 2.4363
+lags = -0.25867         a1 = 0                a2 = 1
+b1 = 0                  keta = 0.057369       lketa = 0.0049156
+dwg = 0                 dwb = 0               pclm = 0.14801
+pdiblc1 = 0.028077      pdiblc2 = 0.00016557  pdiblcb = 0.029513
+drout = 0.51504         pvag = 0              delta = 0.002695
+ldelta = 0.0004167      pscbe1 = 7.884e+008   pscbe2 = 1.9903e-006
+fprout = 0              pdits = 0             pditsd = 0
+pditsl = 0              rsh = 0
+rdsw = '178.32+drdswp_svt'                    rsw = 100
+rdw = 100               rdswmin = 0           rdwmin = 0
+rswmin = 0              prwg = 0.0031883      prwb = 0.25478
+wr = 1                  alpha0 = 7e-011       alpha1 = 7.2e-011
+beta0 = 18.96           agidl = 1.4811e-010   bgidl = 2250600
+cgidl = 433.08          egidl = 0.021835      aigbacc = 0.43
+bigbacc = 0.054         cigbacc = 0.075       nigbacc = 1
+aigbinv = 0.35          bigbinv = 0.03        cigbinv = 0.006
+eigbinv = 1.1           nigbinv = 3           aigc = 0.43
+bigc = 0.054            cigc = 0.075          aigsd = 0.43
+bigsd = 0.054           cigsd = 0.075         nigc = 1
+poxedge = 1             pigcd = 1             ntox = 1
**************************************************************
*                  CAPACITANCE PARAMETERS
**************************************************************
+cgso = 'cgop_svt'       cgdo = 'cgop_svt'     cgbo = 1.7739e-009
+cgdl = 'cglp_svt'       cgsl = 'cglp_svt'     clc = 1.2714e-011
+cle = 1                 ckappas = 0.12        ckappad = 0.12
+vfbcv = -0.5008         acde = 0.414          moin = 3.2553
+noff = 2.8698           voffcv = -0.01272     lvoffcv = 0.0024
**************************************************************
*                  TEMPERATURE PARAMETERS
**************************************************************
+kt1 = -0.47607          kt1l = -1.025e-010    kt2 = -0.050313
+ute = -1.75             ua1 = 4.187e-011      ub1 = -2.882e-019
+uc1 = -6.5038e-010      prt = 0               at = 71599
**************************************************************
*                     NOISE PARAMETERS
**************************************************************
+fnoimod = 1             tnoimod = 0           em = 4.1e+007
+ef = 1                  noia = 6.25e+041      noib = 3.125e+026
+noic = 8.75e+009        ntnoi = 1
```

```
*************************************************************
*                      DIODE PARAMETERS
*************************************************************
+jss = 7.6065e-005     jsws = 6.8173e-014     jswgs = 0
+njs = 1.2059          ijthsfwd= 0.017908     ijthsrev= 0.1
+bvs = 10              xjbvs = 1              pbs = 1.6835
+cjs = 'cjp_svt'       mjs = 0.72601          pbsws = 1
+cjsws = 'cjswp_svt'   mjsws = 0.5            pbswgs = 0.76056
+cjswgs = 'cjswgp_svt' mjswgs = 0.424         cjd = 'cjp_svt'
+cjswd = 'cjswp_svt'   cjswgd = 'cjswgp_svt'  tpb = 0.0020847
+tcj = 0.00098         tpbsw = 0              tcjsw = 0
+pbswg = 6e-005        tcjswg = 0.00047385    xtis = 3
*************************************************************
*                 LAYOUT RELATED PARAMETERS
*************************************************************
+dmcg = 0              dmdg = 0               dmcgt = 0
+xgw = 0               xgl = 0
*************************************************************
*                       RF PARAMETERS
*************************************************************
+rshg = 0.1            gbmin = 1e-012         rbpb = 50
+rbpd = 50             rbps = 50              rbdb = 50
+rbsb = 50             ngcon = 1              xrcrg1 = 12
+xrcrg2 = 1
*************************************************************
*                     STRESS PARAMETERS
*************************************************************
+saref = 1e-006        sbref = 1e-006         wlod = 0
+kvth0 = 0             lkvth0 = 0             wkvth0 = 0
+pkvth0 = 0            llodvth = 0            wlodvth = 0
+stk2 = 0              lodk2 = 1              lodeta0 = 1
+ku0 = 0               lku0 = 0               wku0 = 0
+pku0 = 0              llodku0 = 0            wlodku0 = 0
+kvsat = 0             steta0 = 0             tku0 = 0     )
.ends
*
.subckt n4_svt D G S B
.param w=0 l=0 z=0.100e-6 multi=1
.param pd='2*(w+z)'ad='w*z'
.param ps='2*(w+z)'as='w*z'
.param pw='2*((2*z)+l+w)'aw='((2*z)+l)*w'
.param lw='(2*z)+l'
.param n_fingers=1

.param mismatchflag=0
.param avtn=1.12e-09

** must make default sigmavt=0, i.e. no instance parameter
** sdvtp/ncorn in TT,SS,... takes care of corners sigvt when
*  globalsigmavtflag=1
```

```
.param sigmavt=0
.param delvto=0

** systematic **
** instance based sampling of systematic variation
** g[pn]mean varying in clock step for each instance
** defined in calling library MC_svt using globap[np]mean and
*  global[np]meansigma
** existing global[np]sigma varys by instance  and is defined by
*  global[np]sigma
.param random0n=agauss(0,1,3)
.param random1n=agauss(0,1,3)
.param random2n=agauss(0,1,3)
.param random3n=agauss(0,1,3)
.param random4n=agauss(0,1,3)
.param random5n=agauss(0,1,3)
.param random6n=agauss(0,1,3)
.param random7n=agauss(0,1,3)
.param random8n=agauss(0,1,3)
.param random9n=agauss(0,1,3)

.param A0n='random0n*(globalmcflag==1)'
.param A1n='random1n*(globalmcflag==1)'
.param A2n='random2n*(globalmcflag==1)'
.param A3n='random3n*(globalmcflag==1)'
.param A4n='random4n*(globalmcflag==1)'
.param A5n='random5n*(globalmcflag==1)'
.param A6n='random6n*(globalmcflag==1)'
.param A7n='random7n*(globalmcflag==1)'
.param A8n='random8n*(globalmcflag==1)'
.param A9n='random9n*(globalmcflag==1)'

.param
+toxn_svt = '1.0800E-009 + ( 2.7831E-011*((A0n*gnsigma) + gnmean))'
+dxln_svt = '0.0000E+000 + ( 1.2000E-009*((A1n*gnsigma) + gnmean))'
+dxwn_svt = '0.0000E+000 + (-2.7000E-009*((A2n*gnsigma) + gnmean))'
+dvthn_svt = '0.0000E+000 + ( 1.5058E-002*((A3n*gnsigma) + gnmean))'
+cjn_svt = '3.2010E-003 + ( 2.2407E-004*((A4n*gnsigma) + gnmean))'
+cjswn_svt = '1.0000E-014 + ( 7.0000E-016*((A5n*gnsigma) + gnmean))'
+cjswgn_svt = '1.9383E-010 + ( 1.3568E-011*((A6n*gnsigma) + gnmean))'
+cgon_svt = '1.5000E-011 + (-1.0500E-012*((A7n*gnsigma) + gnmean))'
+cgln_svt = '1.0000E-011 + (-7.0000E-013*((A8n*gnsigma) + gnmean))'
+drdswn_svt = '0.0000E+00 + ( 4.9500E-000*((A9n*gnsigma) + gnmean))'

*** mismatch ***
.param AM0=agauss(0,1,1)

.param
+cvtn_svt='avtn/1.414214'
```

```
+lef='l-7.5802E-09' wef='w/n_fingers+0E-09'
+geo_fac ='1/sqrt(multi*n_fingers*lef*wef)'
+sigvtn_svt='AM0*cvtn_svt*geo_fac*globalmismatchnsigma/3 *
((globalmismatchflag==1)||(mismatchflag==1))'

** fixed sigmavt offset **
.param
+sdvtn_svt='cvtn_svt*geo_fac*((sigmavt*(globalsigmavtflag==0)) +
(sdvtncorn*(globalsigmavtflag==1)))'

** no width effect
mn_svt D G S B nch_svt w=1e-6 l=l pd=pd ad=ad ps=ps as=as
m='w/1.0e-6' nf=n_fingers wnflag=1  delvto=delvto
** width effect
*mn_svt D G S B nch_svt w=w l=l pd=pd ad=ad ps=ps as=as
nf=n_fingers wnflag=1 delvto=delvto

**************************************************************
* BSIM4.5.0 model card for n-type devices
**************************************************************
.model  nch_svt.1 nmos  ( level = 54
*
**************************************************************
*                  MODEL FLAG PARAMETERS
**************************************************************
+lmin = 2.59e-008     lmax = 2.51e-007   wmin = 'wmin_n_svt'
+wmax = 'wmax_n_svt'  version = 4.5      binunit = 1
+paramchk= 1          mobmod = 1         capmod = 2
+igcmod = 2           igbmod = 1         geomod = 0
+diomod = 1           rdsmod = 0         rbodymod= 0
+rgeomod = 0          rgatemod= 0        permod = 1
+acnqsmod= 0          trnqsmod= 0
**************************************************************
*                 GENERAL MODEL PARAMETERS
**************************************************************
+tnom = 25              toxe = 'toxn_svt'   toxp = 1.05e-009
+toxm = 'toxn_svt'      dtox = 2.3e-010     epsrox = 3.9
+toxref = 9.043737e-010 wmlt = 1            wint = 0
+lint = 4.1539e-009     ll = 2.455641e-024  wl = 0
+lln = 1.000054         wln = 1             lw = 0
+ww = 0                 lwn = 1             wwn = 1
+lwl = 0                wwl = 0             xl = '0+dxln_svt'
+xw = '0+dxwn_svt'      dlc = 1.1811e-009   dwc = 1e-009
+xpart = 0
**************************************************************
*                      DC PARAMETERS
**************************************************************
+vth0 = '0.30116+dvthn_svt+sdvtn_svt+sigvtn_svt' k1 = 0.40102
+lk1 = -0.0018       k2 = 0.036607       k3 = 80
```

```
+k3b = 11.372        w0 = 1.4976e-008    dvt0 = 0.030258
+dvt1 = 0.27353      dvt2 = -0.1292      dvt0w = 0
+dvt1w = 10000000    dvt2w = 0.01        dsub = 0.079604
+minv = 0.57893      voffl = -3.2236e-015 dvtp0 = 0
+dvtp1 = 0           lc = 5e-009         lambda = 0
+vtl = 200000        lpe0 = 0            lpeb = 9.7128e-009
+vbm = -3            xj = 5.81e-008      ngate = 1.1557e+021
+ndep = 1.7e+017     nsd = 1e+020        phin = 0
+cdsc = 0.00038013   cdscb = 0.00029951  cdscd = 0
+cit = 0.00029514    voff = -0.091517    nfactor = 4.6201
+eta0 = 0.00011433   etab = -0.00018655  u0 = 0.053874
+ua = 1.3724e-009    ub = 2.4451e-021    uc = -0.3327
+eu = 1.67           vsat = 81402        a0 = 4.034
+ags = 0.51          a1 = 1e-005         a2 = 1
+b0 = 6.0098e-015    b1 = 0              keta = 0.010603
+lketa = 0.0030012   dwg = 0             dwb = 0
+pclm = 0.26825      lpclm = 0.0057      pdiblc1 = 0.030607
+pdiblc2 = 2.582e-005 pdiblcb = 0.01     drout = 1.1625
+pvag = 0            delta = 0.0045611   ldelta = 0.0002262
+pscbe1 = 1.1753e+009 pscbe2 = 1e-005    fprout = 0.01
+pdits = 0           pditsd = 0          pditsl = 0
+rsh = 0             rdsw = '159.72+drdswn_svt'
+rsw = 100           rdw = 100           rdswmin = 0
+rdwmin = 0          rswmin = 0          prwg = 0.15293
+prwb = 0.080695     wr = 1              alpha0 = 0
+alpha1 = 0          beta0 = 30          agidl = 2.6078e-010
+bgidl = 4984400     cgidl = 1974.8      egidl = 0.057969
+aigbacc = 0.43      bigbacc = 0.054     cigbacc = 0.075
+nigbacc = 1         aigbinv = 0.35      bigbinv = 0.03
+cigbinv = 0.006     eigbinv = 1.1       nigbinv = 3
+aigc = 0.43         bigc = 0.054        cigc = 0.075
+aigsd = 0.43        bigsd = 0.054       cigsd = 0.075
+nigc = 1            poxedge = 1         pigcd = 1
+ntox = 1
**************************************************************
*                 CAPACITANCE PARAMETERS
**************************************************************
+cgso = 'cgon_svt'   cgdo = 'cgon_svt'   cgbo = 2.191e-009
+cgdl = 'cgln_svt'   cgsl = 'cgln_svt'   clc = 2.905e-010
+cle = 1             ckappas = 0.6       ckappad = 0.6
+vfbcv = -1.1698     acde = 0.37365      lacde = -0.00145
+moin = 3.8485       lmoin = 0.022       noff = 2.118
+lnoff = 0.0114      voffcv = 0.048569   lvoffcv = 0.00012324
**************************************************************
*                 TEMPERATURE PARAMETERS
**************************************************************
+kt1 = -0.38457      kt1l = -9.0624e-012  kt2 = -0.029313
+ute = -2.895        ua1 = 1.4986e-009    ub1 = -3.2473e-018
```

```
+uc1 = -3.5e-011    prt = 67.655          at = 36837
+lat = 16049
*************************************************************
*                     NOISE PARAMETERS
*************************************************************
+fnoimod = 1        tnoimod = 0         em = 4.1e+007
+ef = 1             noia = 6.25e+041    noib = 3.125e+026
+noic = 8.75e+009   ntnoi = 1
*************************************************************
*                     DIODE PARAMETERS
*************************************************************
+jss = 8.2539e-005    jsws = 7.9765e-012    jswgs = 8e-012
+njs = 1.2512         ijthsfwd= 4.5539e-005  ijthsrev= 0.1818
+bvs = 10             xjbvs = 1.08          pbs = 0.91838
+cjs = 'cjn_svt'      mjs = 0.3616          pbsws = 1
+cjsws = 'cjswn_svt'  mjsws = 0.5           pbswgs = 0.73407
+cjswgs = 'cjswgn_svt' mjswgs = 0.3464      cjd = 'cjn_svt'
+cjswd = 'cjswn_svt'  cjswgd = 'cjswgn_svt' tpb = 0.0019412
+tcj = 0.00075514991  tpbsw = 0             tcjsw = 0
+tpbswg = 1.5577e-017 tcjswg = 1.0211e-017  xtis = 3
*************************************************************
*                 LAYOUT RELATED PARAMETERS
*************************************************************
+dmcg = 0           dmdg = 0            dmcgt = 0
+xgw = 0            xgl = 0
*************************************************************
*                      RF PARAMETERS
*************************************************************
+rshg = 0.1         gbmin = 1e-012      rbpb = 50
+rbpd = 50          rbps = 50           rbdb = 50
+rbsb = 50          ngcon = 1           xrcrg1 = 12
+xrcrg2 = 1
*************************************************************
*                    STRESS PARAMETERS
*************************************************************
+saref = 1e-006     sbref = 1e-006      wlod = 0
+kvth0 = 0          lkvth0 = 0          wkvth0 = 0
+pkvth0 = 0         llodvth = 0         wlodvth = 0
+stk2 = 0           lodk2 = 1           lodeta0 = 1
+ku0 = 0            lku0 = 0            wku0 = 0
+pku0 = 0           llodku0 = 0         wlodku0 = 0
+kvsat = 0          steta0 = 0          tku0 = 0        )
.ends
*
.ENDL SUBCKTS_SVT
*************************************************************
```

2. Sample SRAM Compact Model of an Advanced CMOS Technology

```
***************************************************************
* Example2: 20-nm CMOS technology node SRAM Hspice model library
***************************************************************
* Version:   sram127hp.l *** January 20, 2015 ***
* MODEL:   BSIM4 ( V4.5)
***************************************************************
* Model Information
***************************************************************
* This Rev0 version of sample SPICE model is based on
  two-dimensional
* numerical device simulation
***************************************************************
.LIB INTERNAL
*------------------------------------------------------------------
* History of model updates
*------------------------------------------------------------------
* Jan 20, 2015: model created from TCAD-based model
*             : bit cell127: wxn_pd = 76.5; wxn_pg = 63.9;
                wxp_pu = 50.4; *  L = 35.1 (nm)
*------------------------------------------------------------------
.ENDL INTERNAL
***************************************************************
* Begin header
***************************************************************
* Usage:
*
* Hspice Version: 2007.03, 2008.03, 2009.03
*
* .lib 'sram127hp.l' TT
* .lib 'sram127hp.l' FF
* .lib 'sram127hp.l' SS
* .lib 'sram127hp.l' SF
* .lib 'sram127hp.l' FS
* .lib 'sram127hp.l' MC
*
* .options scale=1
*
* Transistor sub-circuits
* p4_pu_svt : PMOS PULL UP Ldrawn = 0.0351um,
* Wdrawn = 0.0504u
*      x0 d g s b
*      +p4_pu_svt w = w  l = l    $$ REQUIRED
*
*---------------------------optional------------------------------
*      + z=z                      $$ default = 0.1n: s/d length from
* channel
*      + ad=ad as=as pd=pd ps=ps  $$ default = function of w, l, z
*      + n_fingers=#fingers       $$ default=1
```

```
*      + sigmavt=(instance sigvt)   $$ default=0
*      + mismatchflag=(0|1)         $$ default=0
*
* n4_pd_svt : NMOS PULL DOWN  Ldrawn = 0.0351u,
* Wdrawn = 0.0765u
*      x0 d g s b
*      +n4_pd_svt w=w  l=l          $$ REQUIRED
*
*---------------------------optional------------------------------
*    + z=z                          $$ default = 0.1n: s/d length from
* channel
*    + ad=ad as=as pd=pd ps=ps      $$ default = function of w, l, z
*    + n_fingers=#fingers           $$ default=1
*    + sigmavt=(instance sigvt)     $$ default=0
*    + mismatchflag=(0|1)           $$ default=0
*
* n4_pg_svt : NMOS PASS GATE Ldrawn = 0.0351u,
* Wdrawn = 0.0639u
*      x0 d g s b
*      + n4_pg_svt w=w  l=l  $$ REQUIRED
*
*---------------------------optional------------------------------
*    + z=z                          $$ default = 0.1n: s/d length from
* channel
*    + ad=ad as=as pd=pd ps=ps    $$ default = function of w, l, z
*    + n_fingers=#fingers         $$ default=1
*    + sigmavt=(instance sigvt)   $$ default=0
*    + mismatchflag=(0|1)         $$ default=0
*
* For statistical modeling using Monte Carlo simulation, use:
* .lib 'sram127hp.l' MC
*
* Example of user-defined (mismatch parameter) "avt" values in Hspice
* netlist:
*         :.param avtp=1.0e-9
*         :.param avtn=1.0e-9
*
***********************************************************
* end header
***********************************************************
.LIB TT
.lib 'sram127hp.l' MOD_GLOBAL
.lib 'sram127hp.l' TT_svt
.ENDL TT
*
.LIB SS
.lib 'sram127hp.l' MOD_GLOBAL
.lib 'sram127hp.l' SS_svt
.ENDL SS
```

```
*
.LIB FF
.lib 'sram127hp.l' MOD_GLOBAL
.lib 'sram127hp.l' FF_svt
.ENDL FF
*
.LIB SF
.lib 'sram127hp.l' MOD_GLOBAL
.lib 'sram127hp.l' SF_svt
.ENDL SF
*
.LIB FS
.lib 'sram127hp.l' MOD_GLOBAL
.lib 'sram127hp.l' FS_svt
.ENDL FS
*
.LIB MC
.lib 'sram127hp.l' MOD_GLOBAL
.lib 'sram127hp.l' MC_svt
.ENDL MC

.LIB MOD_GLOBAL
*************************************************************
* global model parameters
*************************************************************
.param globalmcflag=0

.param
+globalnmean=0
+globalpmean=0
+globalnsigma=1
+globalpsigma=1
+globalnmeansigma=2.8284
+globalpmeansigma=2.8284

.param globalsigmavtflag=1
.param globalmismatchflag=0
.param globalmismatchpsigma=3
.param globalmismatchnsigma=3

.param wmin_n_pd_svt=0.999e-6
.param wmax_n_pd_svt=1.01e-6
.param wmin_n_pg_svt=0.999e-6
.param wmax_n_pg_svt=1.01e-6
.param wmin_p_pu_svt=0.999e-6
.param wmax_p_pu_svt=1.01e-6

.ENDL MOD_GLOBAL
*************************************************************
* SVT SRAM - Bitcell127
```

```
***************** Library of Typical Case ******************
.LIB TT_svt

.param sdvtncorn = 0
.param sdvtpcorn = 0

** Need these defined since the parameters created for MC are
*  in the sub-circuit
** Sub-circuit will therefore, over-ride 'tox, dxl, dxw, dvth,
*  cj, cjsw, cjswn,cgo, cgl' in this LIB.
** g[np]sigma is always 0 when using fixed corners
.param gnmean = 0
.param gpmean = 0
.param gnsigma = 0
.param gpsigma = 0
*
*device: pull down
.param
+toxn_pd_svt = 1.6e-09       dxln_pd_svt = 0.0
+dxwn_pd_svt = 0             dvthn_pd_svt = 0
+cjn_pd_svt = 0.0030468587   cjswn_pd_svt = 1.000E-14
+cjswgn_pd_svt = 3.0727e-010   cgon_pd_svt = 9.8e-12
+cgln_pd_svt = 4.05e-11
*
*device: pull up
.param
+toxp_pu_svt = 1.6e-09       dxlp_pu_svt = 0.0
+dxwp_pu_svt = 0             dvthp_pu_svt = 0
+cjp_pu_svt = 0.0033668797   cjswp_pu_svt = 1.000e-014
+cjswgp_pu_svt = 3.10333e-010   cgop_pu_svt = 1.0505e-012
+cglp_pu_svt = 5.3856e-011
*
*device: pass gate
.param
+toxn_pg_svt = 1.6e-09       dxln_pg_svt = 0.0
+dxwn_pg_svt = 0             dvthn_pg_svt = 0
+cjn_pg_svt = 0.0030468587   cjswn_pg_svt = 1.000E-14
+cjswgn_pg_svt = 3.0727e-010   cgon_pg_svt = 9.8e-12
+cgln_pg_svt = 4.05e-11
*
.LIB 'sram127hp.l' SUBCKTS_SVT
.ENDL TT_svt

************ Library of SNSP Corner Case with RDD ************
.LIB SS_svt

.param sdvtncorn = 1
.param sdvtpcorn = 1

** Need these defined since the parameters created for MC are
```

```
*  in the sub-circuit
** Sub-circuit will therefore, over-ride 'tox, dxl, dxw, dvth,
*  cj, cjsw, cjswn, cgo, cgl' in this LIB.
** g[np]sigma is always 0 when using fixed corners
.param gnmean = 1
.param gpmean = 1
.param gnsigma = 0
.param gpsigma = 0
*
*device: pull down
.param
+toxn_pd_svt = 1.6412E-09    dxln_pd_svt = 1.2E-09
+dxwn_pd_svt = -2.70E-09     dvthn_pd_svt = 1.6768E-02
+cjn_pd_svt = 0.003260       cjswn_pd_svt = 1.070E-14
+cjswgn_pd_svt = 3.2878e-010  cgon_pd_svt = 9.114e-12
+cgln_pd_svt = 3.7665e-011
*
*device: pull down
.param
+toxp_pu_svt = 1.6399E-09    dxlp_pu_svt = 1.2E-09
+dxwp_pu_svt = -2.70E-09     dvthp_pu_svt = -1.8080E-02
+cjp_pu_svt = 0.003603       cjswp_pu_svt = 1.070E-14
+cjswgp_pu_svt = 3.3206e-010  cgop_pu_svt = 9.7696E-13
+cglp_pu_svt = 5.0086E-11
*
*device: pass gate
.param
+toxn_pg_svt = 1.6412E-09    dxln_pg_svt = 1.2E-09
+dxwn_pg_svt = -2.70E-09     dvthn_pg_svt = 1.6768E-02
+cjn_pg_svt = 0.003260       cjswn_pg_svt = 1.070E-14
+cjswgn_pg_svt = 3.2878e-010  cgon_pg_svt = 9.114e-12
+cgln_pg_svt = 3.7665e-011
*
.LIB 'sram127hp.l' SUBCKTS_SVT
.ENDL SS_svt

************* Library of FNFP Corner Case with RDD **************
.LIB FF_svt

.param sdvtncorn = -1
.param sdvtpcorn = -1

** Need these defined since the parameters created for MC are
*  in the sub-circuit
** Sub-circuit will therefore, over-ride 'tox, dxl, dxw, dvth,
```

```
*  cj, cjsw, cjswn, cgo, cgl' in this LIB.
** g[np]sigma is always 0 when using fixed corners
.param gnmean = -1
.param gpmean = -1
.param gnsigma = 0
.param gpsigma = 0
*
*device: pull down
.param
+toxn_pd_svt = 1.5588E-09    dxln_pd_svt = -1.2E-09
+dxwn_pd_svt = 2.70E-09      dvthn_pd_svt = -1.6768E-02
+cjn_pd_svt = 0.002834       cjswn_pd_svt = 9.3e-015
+cjswgn_pd_svt = 2.8576e-010  cgon_pd_svt = 1.0486E-11
+cgln_pd_svt = 4.3335E-11
*
*device: pull up
.param
+toxp_pu_svt = 1.5601E-09    dxlp_pu_svt = -1.2E-09
+dxwp_pu_svt = 2.70E-09      dvthp_pu_svt = 1.8080E-02
+cjp_pu_svt = 0.003130       cjswp_pu_svt = 9.3e-015
+cjswgp_pu_svt = 2.8861E-010  cgop_pu_svt = 1.124E-12
+cglp_pu_svt = 5.7626E-11
*
*device: pass gate
.param
+toxn_pg_svt = 1.5588E-09    dxln_pg_svt = -1.2E-09
+dxwn_pg_svt = 2.70E-09      dvthn_pg_svt = -1.6768E-02
+cjn_pg_svt = 0.002834       cjswn_pg_svt = 9.3e-015
+cjswgn_pg_svt = 2.8576e-010 cgon_pg_svt = 1.0486E-11
+cgln_pg_svt = 4.3335E-11
*
.LIB 'sram127hp.l' SUBCKTS_SVT
.ENDL FF_svt

************ Library of SNFP Corner Case with RDD ************
.LIB SF_svt

.param sdvtncorn = 1
.param sdvtpcorn = -1

** Need these defined since the parameters created for MC are
*  in the sub-circuit
** Sub-circuit will therefore, over-ride 'tox, dxl, dxw, dvth,
*  cj, cjsw, cjswn, cgo, cgl' in this LIB.
** g[np]sigma is always 0 when using fixed corners
```

```
.param gnmean = 1
.param gpmean = -1
.param gnsigma = 0
.param gpsigma = 0
*
*device: pull down
.param
+toxn_pd_svt = 1.6E-09        dxln_pd_svt = 0.0
+dxwn_pd_svt = -2.70E-09      dvthn_pd_svt = 1.1179E-02
+cjn_pd_svt = 0.003260        cjswn_pd_svt = 1.070E-14
+cjswgn_pd_svt = 3.2878e-010   cgon_pd_svt = 9.114E-12
+cgln_pd_svt = 3.767e-11
*
*device: pull up
.param
+toxp_pu_svt = 1.6e-09        dxlp_pu_svt = 0.0
+dxwp_pu_svt = 2.70E-09       dvthp_pu_svt = 1.2053E-02
+cjp_pu_svt = 0.003130        cjswp_pu_svt = 9.3E-15
+cjswgp_pu_svt = 2.8861E-010  cgop_pu_svt = 1.124E-12
+cglp_pu_svt = 5.7626E-11
*
*device: pass gate
.param
+toxn_pg_svt = 1.6E-09        dxln_pg_svt = 0.0
+dxwn_pg_svt = -2.70E-09      dvthn_pg_svt = 1.1179E-02
+cjn_pg_svt = 0.003260        cjswn_pg_svt = 1.070E-14
+cjswgn_pg_svt = 3.2878e-010  cgon_pg_svt = 9.114E-12
+cgln_pg_svt = 3.767e-11
*
.LIB 'sram127hp.l' SUBCKTS_SVT
.ENDL SF_svt

************ Library of FNSP Corner Case with RDD ************
.LIB FS_svt

.param sdvtncorn = -1
.param sdvtpcorn = 1

** Need these defined since the parameters created for MC are
*  in the sub-circuit
** Sub-circuit will therefore, over-ride 'tox, dxl, dxw, dvth,
*  cj, cjsw, cjswn, cgo, cgl' in this LIB.
** g[np]sigma is always 0 when using fixed corners
.param gnmean = -1
.param gpmean = 1
.param gnsigma = 0
.param gpsigma = 0
*
*device: pull down
```

```
.param
+toxn_pd_svt = 1.6E-09       dxln_pd_svt = 0.0
+dxwn_pd_svt = 2.70E-09      dvthn_pd_svt = -1.1179E-02
+cjn_pd_svt = 0.002834       cjswn_pd_svt = 9.3E-15
+cjswgn_pd_svt = 2.8576e-010  cgon_pd_svt = 1.049E-11
+cgln_pd_svt = 4.3335E-11
*
*device: pull up
.param
+toxp_pu_svt = 1.6e-09       dxlp_pu_svt = 0.0
+dxwp_pu_svt = -2.70E-09     dvthp_pu_svt = -1.2053E-02
+cjp_pu_svt = 0.003603       cjswp_pu_svt = 1.070E-14
+cjswgp_pu_svt = 3.3206e-010  cgop_pu_svt = 9.7696E-13
+cglp_pu_svt = 5.0086E-11
*
*device: pass gate
.param
+toxn_pg_svt = 1.6E-09       dxln_pg_svt = 0.0
+dxwn_pg_svt = 2.70E-09      dvthn_pg_svt = -1.1179E-02
+cjn_pg_svt = 0.002834       cjswn_pg_svt = 9.3E-15
+cjswgn_pg_svt = 2.8576e-010  cgon_pg_svt = 1.049E-11
+cgln_pg_svt = 4.3335E-11
*
.LIB 'sram127hp.l' SUBCKTS_SVT
.ENDL FS_svt
*************************************************************
*                    SRAM MC MODEL LIBRARY                  *
*************************************************************
.lib MC_svt

** create 1 gnmean agauss and 1 gpmean agauss
.param grandom0n=agauss(0,1,3)
.param grandom0p=agauss(0,1,3)

.param Agmn='grandom0n*(globalmcflag==1)'
.param Agmp='grandom0p*(globalmcflag==1)'

** globalp/nmean=n shifts mean of systematic agauss by n*sigma
** global[pn]meansigma variation of mean to be added to g[np]sigma
** defaults are g[np]sigma=1, g[np]msigma=2.83
** sampling should be the same for each iteration (i.e., not
*  instance based)
.param gnmean='(globalmcflag==1)*((Agmn*globalnmeansigma) +
globalnmean)/3'
.param gpmean='(globalmcflag==1)*((Agmp*globalpmeansigma) +
globalpmean)/3'

** globalp/nsigma=m multiplies stdev of systematic agauss by m
** this scale factor is passed to subckt to vary systematic
```

```
*  variation by instance
.param gnsigma=globalnsigma*(globalmcflag==1)/3
.param gpsigma=globalpsigma*(globalmcflag==1)/3

.param sdvtpcorn = 0
.param sdvtncorn = 0

.LIB ‘sram127hp.l’ SUBCKTS_SVT
.endl MC_svt

.LIB SUBCKTS_SVT

**************************************************************
* Subcircuit references
**************************************************************
*
* weff = w/nf
* wnflag = 1  size bin w/nf
* wnflag = 0  size bin w
*
* fixed nf=1 and use instance mult factor to capture folding
* setting instance of these subckts with parameter nf!=1 have
  no effect
* area/peri default calculation assumes nf=1

* DEVICE: PULL UP
.subckt p4_pu_svt D G S B
.param w=0  l=0  z=0.100e-6  multi=1
.param pd='2*(w+z)' ad='w*z'
.param ps='2*(w+z)' as='w*z'
.param pw='2*((2*z)+l+w)' aw='((2*z)+l)*w'
.param lw='(2*z)+l'
.param n_fingers=1

.param mismatchflag=0
.param avtp=2.8e-09

** must make default sigmavt=0, ie, no instance parameter
** sdvtp/ncorn in TT,SS,... takes care of corners sigvt when
** globalsigmavtflag=1
.param sigmavt=0
.param delvto=0

** systematic **
** instance based sampling of systematic variation
** g[pn]mean varying in lock step for each instance
** defined in calling library MC_svt using globap[np]mean and
** global[np]meansigma
** existing global[np]sigma varies by instance and is defined by
```

```
*  global[np]sigma
.param random0p=agauss(0,1,3)
.param random1p=agauss(0,1,3)
.param random2p=agauss(0,1,3)
.param random3p=agauss(0,1,3)
.param random4p=agauss(0,1,3)
.param random5p=agauss(0,1,3)
.param random6p=agauss(0,1,3)
.param random7p=agauss(0,1,3)
.param random8p=agauss(0,1,3)
.param A0p='random0p*(globalmcflag==1)'
.param A1p='random1p*(globalmcflag==1)'
.param A2p='random2p*(globalmcflag==1)'
.param A3p='random3p*(globalmcflag==1)'
.param A4p='random4p*(globalmcflag==1)'
.param A5p='random5p*(globalmcflag==1)'
.param A6p='random6p*(globalmcflag==1)'
.param A7p='random7p*(globalmcflag==1)'
.param A8p='random8p*(globalmcflag==1)'

.param
+toxp_pu_svt = '1.600E-09 + (3.9886E-011*((A0p*gpsigma) + gpmean))'
+dxlp_pu_svt = '0.000E+00 + (1.2000E-009*((A1p*gpsigma) + gpmean))'
+dxwp_pu_svt = '0.00E+00 + (-2.700E-009*((A2p*gpsigma) + gpmean))'
+dvthp_pu_svt = '0.00E+00 + (-1.8080E-02*((A3p*gpsigma) + gpmean))'
+cjp_pu_svt = '3.3669E-003 + (2.3644E-04*((A4p*gpsigma) + gpmean))'
+cjswp_pu_svt = '1.00E-014 + (7.000E-016*((A5p*gpsigma) + gpmean))'
+cjswgp_pu_svt = '3.103E-10 + (2.172e-11*((A6p*gpsigma) + gpmean))'
+cgop_pu_svt = '1.0505E-12 + (-7.354E-14*((A7p*gpsigma) + gpmean))'
+cglp_pu_svt = '5.3856E-11 + (-3.770E-12*((A8p*gpsigma) + gpmean))'

*** mismatch ***
.param AM0=agauss(0,1,1)

.param
+cvtp_svt='avtp/1.414214'
+lef='l-5.6E-09' wef='w/n_fingers+0E-09'
+geo_fac='1/sqrt(multi*n_fingers*lef*wef)'
+sigvtp_pu_svt='AM0*cvtp_svt*geo_fac*globalmismatchpsigma/3 *
((globalmismatchflag==1)||(mismatchflag==1))'

** fixed sigmavt offset **
.param
+sdvtp_pu_svt='-cvtp_svt*geo_fac*((sigmavt*(globalsigmavtflag=
=0)) + (sdvtpcorn*(globalsigmavtflag==1)))'

** no width effect
mp_pu_svt D G S B pch_svt w=1e-6 l=l pd=pd ad=ad ps=ps as=as
m='w/1.0e-6' nf=n_fingers wnflag=1 delvto=delvto
```

```
** width effect
*mp_pu_svt D G S B pch_svt w=w l=l pd=pd ad=ad ps=ps as=as
nf=n_fingers wnflag=1 delvto=delvto

**************************************************************
* BSIM4.5.0 model card for p-type devices
**************************************************************
*
.model pch_svt.1 pmos ( level = 54
**************************************************************
*                   MODEL FLAG PARAMETERS
**************************************************************
+lmin = 3e-008      lmax = 3.999e-008    wmin = 'wmin_p_pu_svt'
+wmax = 'wmax_p_pu_svt' version = 4.5   binunit = 1
+paramchk= 1        mobmod = 0           capmod = 2
+igcmod = 2         igbmod = 1           geomod = 0
+diomod = 1         rdsmod = 0           rbodymod= 0
+rgeomod = 0        rgatemod= 0          permod = 1
+acnqsmod= 0        trnqsmod= 0
**************************************************************
*                  GENERAL MODEL PARAMETERS
**************************************************************
+tnom = 27          toxe = 'toxp_pu_svt' toxp = 1.35e-009
+toxm = 'toxp_pu_svt' dtox = 2.5e-010    epsrox = 3.9
+toxref = 1.2e-009  wmlt = 1             wint = 0
+lint = 2.8175e-009 ll = 0               wl = 0
 +lln = 1           wln = 1              lw = 0
+ww = 0             lwn = 1              wwn = 1
+lwl = 0            wwl = 0              xl = '0+dxlp_pu_svt'
+xw = '0+dxwp_pu_svt'                    dlc = 4.0311e-009
+dwc = 2.2731e-009                       xpart = 0
**************************************************************
*                       DC PARAMETERS
**************************************************************
+vth0 = '-0.452+dvthp_pu_svt+sdvtp_pu_svt+sigvtp_pu_svt'
+k1 = 0.3           k2 = -0.06           k3 = 0.27044
+k3b = 0.07434      w0 = 1e-007          dvt0 = 0.01345
+dvt1 = 0.070243    dvt2 = -0.038        dvt0w = 0.013
+dvt1w = 5984800    dvt2w = 0.05         dsub = 1.7101
+minv = 0           voffl = -8.0716e-011 dvtp0 = 1e-013
+dvtp1 = 1e-013     lpe0 = 1.5509e-011   lpeb = 4.606e-008
+vbm = -3           xj = 5.81e-008       ngate = 0
+ndep = 1.7e+017    nsd = 1e+020         phin = 0
+cdsc = 2.2788e-007 cdscb = 6.9999e-006  cdscd = 2.6e-005
+cit = 0.0006652    voff = 0.01155       lvoff = -9e-005
+nfactor = 1        lnfactor= 0.205      eta0 = 1.45
+etab = -0.59359    u0 = 0.0054227       ua = 2.3103e-011
+ub = 5.0326e-020   uc = -2.2601e-010    eu = 1
+vsat = 342000      lvsat = -3620        a0 = 1.7533
+ags = 1.28         a1 = 0               a2 = 1
```

```
+b0 = 6.0098e-015   b1 = 0              keta = 0.17583
+lketa = -0.0019227  dwg = 0            dwb = 0
+pclm = 0.2423      pdiblc1 = 0.0012528 pdiblc2 = 0.0006
+pdiblcb = 0.029513 drout = 0.59157     pvag = 0
+delta = 0.047796   pscbe1 = 7.884e+008 pscbe2 = 1.9903e-06
+fprout = 0         pdits = 0           pditsd = 0
+pditsl = 0         rsh = 0             rdsw = 251.13
+rsw = 100          rdw = 100           rdswmin = 0
+rdwmin = 0         rswmin = 0          prwg = 0.068211
+prwb = -0.60085    wr = 1              alpha0 = 7e-011
+alpha1 = 7.2e-011  beta0 = 18.96       agidl = 2.0464e-009
+bgidl = 2250600    cgidl = 3149.6      egidl = 0.016014
+aigbacc = 0.43     bigbacc = 0.054     cigbacc = 0.075
+nigbacc = 1        aigbinv = 0.35      bigbinv = 0.03
+cigbinv = 0.006    eigbinv = 1.1       nigbinv = 3
+aigc = 0.43        bigc = 0.054        cigc = 0.075
+aigsd = 0.43       bigsd = 0.054       cigsd = 0.075
+nigc = 1           poxedge = 1         pigcd = 1
+ntox = 1
**************************************************************
*                  CAPACITANCE PARAMETERS
**************************************************************
+cgso = 'cgop_pu_svt'  cgdo = 'cgop_pu_svt'
+cgbo = 1.8e-012    cgdl = 'cglp_pu_svt'
+cgsl = 'cglp_pu_svt'  clc = 1.2714e-011     cle = 1
+ckappas = 0.12     ckappad = 0.12        vfbcv = -0.5008
+acde = 0.45177     moin = 14.182         noff = 3.1539
+voffcv = 0.12863
**************************************************************
*                  TEMPERATURE PARAMETERS
**************************************************************
+kt1 = -0.47607     kt1l = -1.025e-010  kt2 = -0.050313
+ute = -1.75        ua1 = 4.187e-011    ub1 = -2.882e-019
+uc1 = -6.5038e-010  prt = 0            at = 71599
+lat = -200
**************************************************************
*                     NOISE PARAMETERS
**************************************************************
+fnoimod = 1        tnoimod = 0         em = 4.1e+007
+ef = 1             noia = 6.25e+041    noib = 3.125e+026
+noic = 8.75e+009   ntnoi = 1
**************************************************************
*                     DIODE PARAMETERS
**************************************************************
+nigc = 1           poxedge = 1         pigcd = 1
+jss = 2.628e-005   jsws = 6.6059e-014  jswgs = 0
+njs = 0.97789      ijthsfwd= 0.1       ijthsrev= 0.1
+bvs = 10           xjbvs = 1           pbs = 0.9353
+cjs = 'cjp_pu_svt' mjs = 0.44398       pbsws = 1
+cjsws = 'cjswp_pu_svt'                 mjsws = 0.5
```

```
+pbswgs = 0.76458   cjswgs = 'cjswgp_pu_svt'
+mjswgs = 0.44846   cjd = 'cjp_pu_svt'
+cjswd = 'cjswp_pu_svt'          cjswgd = 'cjswgp_pu_svt'
+tpb = 0.0020847    tcj = 0.00098       tpbsw = 0
+tcjsw = 0          tpbswg = 6e-005     tcjswg = 0.00047385
+xtis = 3
**************************************************************
*                LAYOUT RELATED PARAMETERS
**************************************************************
+dmcg = 0           dmdg = 0            dmcgt = 0
+xgw = 0            xgl = 0
**************************************************************
*                       RF PARAMETERS
**************************************************************
+rshg = 0.1         gbmin = 1e-012      rbpb = 50
+rbpd = 50          rbps = 50           rbdb = 50
+rbsb = 50          ngcon = 1
+xrcrg1 = 12        xrcrg2 = 1
**************************************************************
*                     STRESS PARAMETERS
**************************************************************
+saref = 1e-006     sbref = 1e-006      wlod = 0
+kvth0 = 0          lkvth0 = 0          wkvth0 = 0
+pkvth0 = 0         llodvth = 0         wlodvth = 0
 +stk2 = 0          lodk2 = 1           lodeta0 = 1
+ku0 = 0            lku0 = 0            wku0 = 0
+pku0 = 0           llodku0 = 0         wlodku0 = 0
+kvsat = 0          steta0 = 0          tku0 = 0     )
.ends

* DEVICE: PULL DOWN
.subckt n4_pd_svt D G S B
.param w=0 l=0 z=0.100e-6 multi=1
.param pd='2*(w+z)' ad='w*z'
.param ps='2*(w+z)' as='w*z'
.param pw='2*((2*z)+l+w)' aw='((2*z)+l)*w'
.param lw='(2*z)+l'
.param n_fingers=1

.param mismatchflag=0
.param avtn=2.8e-09

** must make default sigmavt=0, ie, no instance parameter
** sdvtp/ncorn in TT,SS,... takes care of corners sigvt when
*  globalsigmavtflag=1
.param sigmavt=0
.param delvto=0

** systematic **
** instance based sampling of systematic variation
```

```
** g[pn]mean varying in lock step for each instance
** defined in calling library MC_svt using globap[np]mean and
*  global[np]meansigma
** existing global[np]sigma varys by instance  and is defined by
*  global[np]sigma
.param random0n=agauss(0,1,3)
.param random1n=agauss(0,1,3)
.param random2n=agauss(0,1,3)
.param random3n=agauss(0,1,3)
.param random4n=agauss(0,1,3)
.param random5n=agauss(0,1,3)
.param random6n=agauss(0,1,3)
.param random7n=agauss(0,1,3)
.param random8n=agauss(0,1,3)

.param A0n='random0n*(globalmcflag==1)'
.param A1n='random1n*(globalmcflag==1)'
.param A2n='random2n*(globalmcflag==1)'
.param A3n='random3n*(globalmcflag==1)'
.param A4n='random4n*(globalmcflag==1)'
.param A5n='random5n*(globalmcflag==1)'
.param A6n='random6n*(globalmcflag==1)'
.param A7n='random7n*(globalmcflag==1)'
.param A8n='random8n*(globalmcflag==1)'

.param
+toxn_pd_svt = '1.600E-009 + (4.1231E-011*((A0n*gnsigma) + gnmean))'
+dxln_pd_svt = '0.000E+00 + (1.2000E-009*((A1n*gnsigma) + gnmean))'
+dxwn_pd_svt = '0.000E+00 + (-2.700E-009*((A2n*gnsigma) + gnmean))'
+dvthn_pd_svt = '0.000E+00 + (1.6768E-002*((A3n*gnsigma) + gnmean))'
+cjn_pd_svt = '3.0469E-003 + (2.1328E-004*((A4n*gnsigma) + gnmean))'
+cjswn_pd_svt = '1.000E-014 + (7.000E-016*((A5n*gnsigma) + gnmean))'
+cjswgn_pd_svt = '3.073E-10 + (2.1509e-11*((A6n*gnsigma) + gnmean))'
+cgon_pd_svt = '9.800E-012 + (-6.860E-013*((A7n*gnsigma) + gnmean))'
+cgln_pd_svt = '4.050E-011 + (-2.835E-012*((A8n*gnsigma) + gnmean))'

*** mismatch ***
.param AM0=agauss(0,1,1)

.param
+cvtn_svt='avtn/1.414214'
+lef='l-2.0E-09' wef='w/n_fingers+0E-09'
+geo_fac ='1/sqrt(multi*n_fingers*lef*wef)'
+sigvtn_pd_svt='AM0*cvtn_svt*geo_fac*globalmismatchnsigma/3 *
((globalmismatchflag==1)||(mismatchflag==1))'

** fixed sigmavt offset **
.param
```

```
+sdvtn_pd_svt='cvtn_svt*geo_fac*((sigmavt*(globalsigmavtflag==0)) +
(sdvtncorn*(globalsigmavtflag==1)))'

** no width effect
mn_pd_svt D G S B nch_svt w=1e-6 l=l pd=pd ad=ad ps=ps as=as
m='w/1.0e-6' nf=n_fingers wnflag=1  delvto=delvto
** width effect
*mn_pd_svt D G S B nch_svt w=w l=l pd=pd ad=ad ps=ps as=as
nf=n_fingers wnflag=1 delvto=delvto

**************************************************************
* BSIM4.5.0 model card for n-type devices
**************************************************************
.model  nch_svt.1 nmos  ( level = 54
**************************************************************
*                   MODEL FLAG PARAMETERS
**************************************************************
+lmin = 30.0e-009    lmax = 39.99e-009    wmin = 'wmin_n_pd_svt'
+wmax = 'wmax_n_pd_svt'      version = 4.5 binunit = 1
+paramchk= 1         mobmod = 0           capmod = 2
+igcmod = 2          igbmod = 1           geomod = 0
+diomod = 1          rdsmod = 0           rbodymod= 0
+rgeomod = 0         rgatemod= 0          permod = 1
+acnqsmod= 0         trnqsmod= 0
**************************************************************
*                  GENERAL MODEL PARAMETERS
**************************************************************
+tnom = 27           toxe = 'toxn_pd_svt' toxp = 1.1822e-009
+toxm = 'toxn_pd_svt+ 1.6e-10'            dtox = 2.3e-010
+epsrox = 3.9        toxref = 1.1822e-009  wmlt = 1
+wint = 0            lint = 1.288e-009    ll = 0
+wl  = 0             lln = 1              wln = 1
+lw = 0              w = 0                lwn = 1
+wwn = 1             lwl = 0              wwl = 0
+xl  = '0+dxln_pd_svt'                    xw = '0+dxwn_pd_svt'
+dlc = 4.877e-009    dwc = 0              xpart = 0
**************************************************************
*                        DC PARAMETERS
**************************************************************
+vth0 = '0.4192+dvthn_pd_svt+sdvtn_pd_svt+sigvtn_pd_svt'
+k1 = 0.4991         k2 = -0.0050218      k3 = 80
+k3b = 11.372        w0 = 1.4976e-008     dvt0 = 35.565
+dvt1 = 1.8          dvt2 = 0.064         dvt0w = 1.577
+dvt1w = 10000000    dvt2w = 0.01         dsub = 0.079604
+minv = 0            voffl = -3.2236e-015 dvtp0 = 0
+dvtp1 = 0           lc = 5e-009          lambda = 0
+vtl = 200000        lpe0 = 3.0161e-008   lpeb = 9.9848e-009
+vbm = -3            xj = 5.81e-008       ngate = 0
+ndep = 1.7e+017     nsd = 1e+020         phin = 0
+cdsc = 7.3987e-005 cdscb = -0.058894     cdscd = 0.066319
```

```
+cit = 0.0023514    voff = -0.013951    nfactor = 3.1059
+lnfactor= 0.12517  eta0 = 0.0014643    etab = 8.2903e-005
+u0 = 0.12346       ua = 1e-009         ub = 7.5477e-018
+uc = 1.0139e-009   eu = 1.67           vsat = 430000
+lvsat = -6065.7    a0 = 1              ags = 30.591
+a1 = 0             a2 = 1              b0 = 6.0098e-015
+b1 = 0             keta = -0.51811     lketa = 0.015916
+dwg = 0            dwb = 0             pclm = 0.00312
+pdiblc1 = 0.16186  pdiblc2 = 0         pdiblcb = 0.01
+drout = 2.7295     pvag = 0.12445      delta = 0.11364
+pscbe1 = 6.9889e+08 pscbe2 = 1e-005    fprout = 0.01
+pdits = 0          pditsd = 0          pditsl = 0
+rsh = 0            rdsw = 265.78       rsw = 100
+rdw = 100          rdswmin = 0         rdwmin = 0
+rswmin = 0         prwg = 0.15168      prwb = 0.10181
+wr = 1             alpha0 = 0          alpha1 = 0
+beta0 = 30         agidl = 1.1566e-011 bgidl = 4984400
+cgidl = 267.18     egidl = 0.057969    aigbacc = 0.43
+bigbacc = 0.054    cigbacc = 0.075     nigbacc = 1
+aigbinv = 0.35     bigbinv = 0.03      cigbinv = 0.006
+eigbinv = 1.1      nigbinv = 3         aigc = 0.43
+bigc = 0.054       cigc = 0.075        aigsd = 0.43
+bigsd = 0.054      cigsd = 0.075       nigc = 1
+poxedge = 1        pigcd = 1           ntox = 1
**************************************************************
*                  CAPACITANCE PARAMETERS
**************************************************************
+cgso = 'cgon_pd_svt' cgdo = 'cgon_pd_svt'  cgbo = 1.2078e-09
+cgdl = 'cgln_pd_svt' cgsl = 'cgln_pd_svt'  clc = 2.9050e-010
+cle = 1            ckappas = 0.13608   ckappad = 0.13608
+vfbcv = -1.016     acde = 0.57228      moin = 8.6897
+noff = 2.7073      voffcv = 0.08287    lvoffcv = 0.001368
**************************************************************
*                  TEMPERATURE PARAMETERS
**************************************************************
+kt1 = -0.43841     kt1l = 2.175e-009   kt2 = -0.023067
+ute = -1.5         ua1 = 2.0242e-008   ub1 = -1.4227e-017
+uc1 = -7.6509e-010 prt = 41.946        at = 153850
+lat = 1000
**************************************************************
*                     NOISE PARAMETERS
**************************************************************
+fnoimod = 1        tnoimod = 0         em = 4.1e+007
+ef = 1             noia = 6.25e+041    noib = 3.125e+026
+noic = 8.75e+009   ntnoi = 1
**************************************************************
*                     DIODE PARAMETERS
**************************************************************
+jss = 0.0001       jsws = 9e-012       jswgs = 0
+njs = 1            ijthsfwd= 0.1       ijthsrev= 0.1
```

```
+bvs = 10           xjbvs = 1            pbs = 0.71899
+cjs = 0.00346      mjs = 0.3515         pbsws = 1
+cjsws = 1e-014     mjsws = 0.5          pbswgs = 0.6134
+cjswgs = 5.0727e-10 mjswgs = 0.41349    cjd = 0.00346
+cjswd = 1e-014     cjswgd = 5.0727e-010 tpb = 0.0015686
+tcj = 0.00076331   tpbsw = 0            tcjsw = 0
+tpbswg = 0         tcjswg = 0           xtis = 3
***************************************************************
*                LAYOUT RELATED PARAMETERS
***************************************************************
+dmcg = 0           dmdg = 0             dmcgt = 0
+xgw = 0            xgl = 0
***************************************************************
*                      RF PARAMETERS
***************************************************************
+rshg = 0.1         gbmin = 1e-012       rbpb = 50
+rbpd = 50          rbps = 50            rbdb = 50
+rbsb = 50          ngcon = 1            xrcrg1 = 12
+xrcrg2 = 1
***************************************************************
*                     STRESS PARAMETERS
***************************************************************
+saref = 1e-006     sbref = 1e-006       wlod = 0
+kvth0 = 0          lkvth0 = 0           wkvth0 = 0
+pkvth0 = 0         llodvth = 0          wlodvth = 0
+stk2 = 0           lodk2 = 1            lodeta0 = 1
+ku0 = 0            lku0 = 0             wku0 = 0
+pku0 = 0           llodku0 = 0          wlodku0 = 0
+kvsat = 0          steta0 = 0           tku0 = 0     )
.ends

* DEVICE: PASS GATE
.subckt n4_pg_svt D G S B
.param w=0  l=0  z=0.100e-6  multi=1
.param pd='2*(w+z)' ad='w*z'
.param ps='2*(w+z)' as='w*z'
.param pw='2*((2*z)+l+w)' aw='((2*z)+l)*w'
.param lw='(2*z)+l'
.param n_fingers=1

.param mismatchflag=0
.param avtn=2.8e-09

** must make default sigmavt=0, ie, no instance parameter
** sdvtp/ncorn in TT,SS,... takes care of corners sigvt when
** globalsigmavtflag=1
.param sigmavt=0
.param delvto=0

** systematic **
```

```
** instance based sampling of systematic variation
** g[pn]mean varying in lock step for each instance
** defined in calling library MC_svt using globap[np]mean and
*  global[np]meansigma
** existing global[np]sigma varys by instance  and is defined by
*  global[np]sigma
.param random0n=agauss(0,1,3)
.param random1n=agauss(0,1,3)
.param random2n=agauss(0,1,3)
.param random3n=agauss(0,1,3)
.param random4n=agauss(0,1,3)
.param random5n=agauss(0,1,3)
.param random6n=agauss(0,1,3)
.param random7n=agauss(0,1,3)
.param random8n=agauss(0,1,3)
.param A0n='random0n*(globalmcflag==1)'
.param A1n='random1n*(globalmcflag==1)'
.param A2n='random2n*(globalmcflag==1)'
.param A3n='random3n*(globalmcflag==1)'
.param A4n='random4n*(globalmcflag==1)'
.param A5n='random5n*(globalmcflag==1)'
.param A6n='random6n*(globalmcflag==1)'
.param A7n='random7n*(globalmcflag==1)'
.param A8n='random8n*(globalmcflag==1)'

.param
+toxn_pg_svt = '1.600E-09 + (4.1231E-011*((A0n*gnsigma) + gnmean))'
+dxln_pg_svt = '0.000E+00 + (1.2000E-09*((A1n*gnsigma) + gnmean))'
+dxwn_pg_svt = '0.000E+00 + (-2.700E-09*((A2n*gnsigma) + gnmean))'
+dvthn_pg_svt = '0.000E+00 + (1.6768E-02*((A3n*gnsigma) + gnmean))'
+cjn_pg_svt = '3.0469E-03 + (2.1328E-004*((A4n*gnsigma) + gnmean))'
+cjswn_pg_svt = '1.000E-014 + (7.000E-16*((A5n*gnsigma) + gnmean))'
+cjswgn_pg_svt = '3.073E-10 + (2.1509e-11*((A6n*gnsigma) + gnmean))'
+cgon_pg_svt = '9.800E-012 + (-6.86E-013*((A7n*gnsigma) + gnmean))'
+cgln_pg_svt = '4.050E-011 + (-2.835E-012*((A8n*gnsigma) + gnmean))'

*** mismatch ***
.param AM0=agauss(0,1,1)

.param
+cvtn_svt='avtn/1.414214'
+lef='l-2.0E-09' wef='w/n_fingers+0E-09'
+geo_fac ='1/sqrt(multi*n_fingers*lef*wef)'
+sigvtn_pg_svt='AM0*cvtn_svt*geo_fac*globalmismatchnsigma/3 *
((globalmismatchflag==1)||(mismatchflag==1))'

** fixed sigmavt offset **
.param
+sdvtn_pg_svt='cvtn_svt*geo_fac*((sigmavt*(globalsigmavtflag==0)) +
(sdvtncorn*(globalsigmavtflag==1)))'
```

```
** no width effect
mn_pg_svt D G S B nch_svt w=1e-6 l=l pd=pd ad=ad ps=ps as=as
m='w/1.0e-6' nf=n_fingers wnflag=1  delvto=delvto
** width effect
*mn_pg_svt D G S B nch_svt w=w l=l pd=pd ad=ad ps=ps as=as
nf=n_fingers wnflag=1 delvto=delvto

**************************************************************
* BSIM4.5.0 model card for n-type devices
**************************************************************
.model  nch_svt.2 nmos  ( level = 54
**************************************************************
*                   MODEL FLAG PARAMETERS
**************************************************************
+lmin = 40.0e-009   lmax = 45.10e-009   wmin = 'wmin_n_pg_svt'
+wmax = 'wmax_n_pg_svt' version = 4.5   binunit = 1
+paramchk= 1        mobmod = 0          capmod = 2
+igcmod = 2         igbmod = 1          geomod = 0
+diomod = 1         rdsmod = 0          rbodymod= 0
+rgeomod = 0        rgatemod= 0         permod = 1
+acnqsmod= 0        trnqsmod= 0
**************************************************************
*                  GENERAL MODEL PARAMETERS
**************************************************************
+tnom = 27          toxe = 'toxn_pg_svt' toxp = 1.1822e-009
+toxm = 'toxn_pg_svt+ 1.6e-10'          dtox = 2.3e-010
+epsrox = 3.9       toxref = 1.1822e-009 wmlt = 1
+wint = 0           lint = 1.288e-009   ll = 0
+wl = 0             lln = 1             wln = 1
+lw = 0             ww = 0              lwn = 1
+wwn = 1            lwl = 0             wwl = 0
+xl = '0+dxln_pg_svt'                   xw = '0+dxwn_pg_svt'
+dlc = 4.877e-009   dwc = 0             xpart = 0
**************************************************************
*                       DC PARAMETERS
**************************************************************
+vth0 = '0.4192+dvthn_pg_svt+sdvtn_pg_svt+sigvtn_pg_svt'
+k1 = 0.4991        k2 = -0.0050218     k3 = 80
+k3b = 11.372       w0 = 1.4976e-008    dvt0 = 33.065
+dvt1 = 1.5462      dvt2 = 0.0613       dvt0w = 1.577
+dvt1w = 10000000   dvt2w = 0.01        dsub = 0.079604
+minv = 0           voffl = -3.2236e-015 dvtp0 = 0
 +dvtp1 = 0         lc = 5e-009         lambda = 0
+vtl = 200000       lpe0 = 3.0161e-008  lpeb = 9.9848e-009
+vbm = -3           xj = 5.81e-008      ngate = 0
+ndep = 1.7e+017    nsd = 1e+020        phin = 0
+cdsc = 7.3987e-05  cdscb = -0.058894   cdscd = 0.066319
+cit = -0.00015514  voff = 0.0060067    nfactor = 3.1059
+lnfactor= 0.22042  eta0 = 0.001923     etab = 8.2903e-005
+u0 = 0.12346       ua = 1e-009         ub = 7.5477e-018
```

```
+uc = 1.0139e-009   eu = 1.67           vsat = 602800
+lvsat = -6065.7    a0 = 1              ags = 30.591
+a1 = 0             a2 = 1              b0 = 6.0098e-015
+b1 = 0             keta = -0.42485     lketa = 0.015916
+dwg = 0            dwb = 0             pclm = 0.00312
+pdiblc1 = 0.16186  pdiblc2 = 0         pdiblcb = 0.01
+drout = 2.7295     pvag = 0.12445      delta = 0.11364
+pscbe1 = 6.9889e+08 pscbe2 = 1e-005    fprout = 0.01
+pdits = 0          pditsd = 0          pditsl = 0
+rsh = 0            rdsw = 265.78       rsw = 100
+rdw = 100          rdswmin = 0         rdwmin = 0
+rswmin = 0         prwg = 0.15168      prwb = 0.10181
+wr = 1             alpha0 = 0          alpha1 = 0
+beta0 = 30         agidl = 3.5057e-010 bgidl  = 4984400
+cgidl = 267.18     egidl = 0.057969    aigbacc = 0.43
+bigbacc = 0.054    cigbacc = 0.075     nigbacc = 1
+aigbinv = 0.35     bigbinv = 0.03      cigbinv = 0.006
+eigbinv = 1.1      nigbinv = 3         aigc = 0.43
+bigc = 0.054       cigc = 0.075        aigsd = 0.43
+bigsd = 0.054      cigsd = 0.075       nigc = 1
+poxedge = 1        pigcd = 1           ntox = 1
**************************************************************
*                  CAPACITANCE PARAMETERS
**************************************************************
+cgso = 'cgon_pg_svt'   cgdo = 'cgon_pg_svt'    cgbo = 1.2078e-09
+cgdl = 'cgln_pg_svt'   cgsl = 'cgln_pg_svt'    clc = 2.9050e-010
+cle = 1                ckappas = 0.13608       ckappad = 0.13608
+vfbcv = -1.016         acde = 0.57228          moin = 8.6897
+noff = 2.7073          voffcv = 0.08287        lvoffcv = 0.001368
**************************************************************
*                  TEMPERATURE PARAMETERS
**************************************************************
+kt1 = -0.43841     kt1l = 2.175e-009   kt2 = -0.023067
+ute = -1.5         ua1 = 2.0242e-008   ub1 = -1.4227e-017
+uc1 = -7.6509e-010 prt = 41.946        at = 153850
+lat = 1000
**************************************************************
*                     NOISE PARAMETERS
**************************************************************
+fnoimod = 1        tnoimod = 0         em = 4.1e+007
+ef = 1             noia = 6.25e+041    noib = 3.125e+026
+noic = 8.75e+009   ntnoi = 1
**************************************************************
*                     DIODE PARAMETERS
**************************************************************
+jss = 0.0001       jsws = 9e-012       jswgs = 0
+njs = 1            ijthsfwd= 0.1       ijthsrev= 0.1
+bvs = 10           xjbvs = 1           pbs = 0.71899
+cjs = 0.00346      mjs = 0.3515        pbsws = 1
```

```
+cjsws = 1e-014     mjsws = 0.5         pbswgs = 0.6134
+cjswgs = 5.073e-10 mjswgs = 0.41349    cjd = 0.00346
+cjswd = 1e-014     cjswgd = 5.0727e-010 tpb = 0.0015686
+tcj = 0.00076331   tpbsw = 0           tcjsw = 0
+tpbswg = 0         tcjswg = 0          xtis = 3
**************************************************************
*                 LAYOUT RELATED PARAMETERS
**************************************************************
+dmcg = 0           dmdg = 0            dmcgt = 0
+xgw = 0            xgl = 0
**************************************************************
*                       RF PARAMETERS
**************************************************************
+rshg = 0.1         gbmin = 1e-012      rbpb = 50
+rbpd = 50          rbps = 50           rbdb = 50
+rbsb = 50          ngcon = 1           xrcrg1 = 12
+xrcrg2 = 1
**************************************************************
*                     STRESS PARAMETERS
**************************************************************
+saref = 1e-006     sbref = 1e-006      wlod = 0
+kvth0 = 0          lkvth0 = 0          wkvth0 = 0
+pkvth0 = 0         llodvth = 0         wlodvth = 0
+stk2 = 0           lodk2 = 1           lodeta0 = 1
+ku0 = 0            lku0 = 0            wku0 = 0
+pku0 = 0           llodku0 = 0         wlodku0 = 0
+kvsat = 0          steta0 = 0          tku0 = 0      )
*
.ends
.ENDL SUBCKTS_SVT
```