18 Additional models

18.1 JUNCAP Model

18.1.1 Introduction

References

[28] Sze, S.M., *Physics of semiconductor devices*, 2nd edition, John Wiley & Sons, Inc., New York, 1981

18.1.2 Physics

In this section the elementary physics of a junction diode is summarized. An extensive survey can be found in the textbooks about semiconductor devices [28], pp 74-96. Generally, the current voltage characteristics can be represented as follows:

$$J = \{J_d(n^2{}_i) + J_g(n_i,V)\} \cdot \left[\exp\left(\frac{qV}{kT}\right) - 1\right] \tag{18.1}$$

$$n_i \sim T^{3/2} \cdot \exp\left(\frac{-E_g}{2kT}\right) \tag{18.2}$$

in which:

Quantity	**Units**	**Description**
J	Am^{-2}	Total reverse current density
J_d	Am^{-2}	Diffusion saturation current density
J_g	Am^{-2}	Generation current density
n_i	m^{-3}	Intrinsic carrier concentration
V	V	Voltage across the diode
E_g	J	Energy gap
k	JK^{-1}	Boltzmann constant
T	K	Temperature

For $V < V_D$ the charge of the junction capacitance is described by:

$$Q = Q_J \cdot \left[1 - \left(1 - \frac{V}{V_D}\right)^{(1-P)}\right] \tag{18.3}$$

In which:

Quantity	Units	Description
Q	C	Total diode junction charge
Q_J	C	Junction charge at built-in voltage
V	V	Voltage across the diode
V_D	V	Junction diffusion voltage
P	-	Junction grading coefficient

18.1.3 Parameters and constants

List of Electrical Variables

No.	Variable	Programming Name	Units	Description
1	V_A	VA	V	Potential applied to the anode
2	V_K	VK	V	Potential applied to the cathode
3	I_A	IA	A	DC current into the anode
4	I_K	IK	A	DC current into the cathode
5	Q_A	QA	C	Charge in the device attributed to the anode
6	Q_K	QK	C	Charge in the device attributed to the cathode

Parameter list

No.	Symbol	Programming Name	Units	Description
1	-	LEVEL	--	Level of this model. Must be set to 1
2	-	TYPE	--	switch (-1 or 1) to select *p* - *n* or *n* - *p* junction
3	A_{B}	AB	m^2	Diffusion area
4	L_{S}	LS	m	Length of the side-wall of the diffusion area *AB* which is not under the gate
5	L_{G}	LG	m	Length of the side-wall of the diffusion area *AB* which is under the gate
6	ΔT_{A}	DTA	^0C	Temperature offset of the JUNCAP element with respect to T_{A}
7	T_{R}	TR	^0C	Temperature at which the parameters have been determined
8	V_{R}	VR	V	Voltage at which parameters have been determined
9	J_{SGBR}	JSGBR	Am^{-2}	Bottom saturation-current density due to electron-hole generation at $V = V_{\mathrm{R}}$

No.	Symbol	Programming Name	Units	Description
10	J_{SDBR}	JSDBR	Am^{-2}	Bottom saturation-current density due to diffusion from back contact
11	J_{SGSR}	JSGSR	Am^{-1}	Sidewall saturation-current density due to electron-hole generation at $V = V_R$
12	J_{SDSR}	JSDSR	Am^{-1}	Sidewall saturation-current density due to diffusion from back contact
13	J_{SGGR}	JSGGR	Am^{-1}	Gate edge saturation-current density due to electron-hole generation at $V = V_R$
14	J_{SDGR}	JSDGR	Am^{-1}	Gate edge saturation-current density due to diffusion from back contact
15	N_B	NB	-	Emission coefficient of the bottom forward current
16	N_S	NS	-	Emission coefficient of the sidewall forward current
17	N_G	NG	-	Emission coefficient of the gate edge forward current
18	V_B	VB	V	Reverse breakdown voltage
19	C_{JBR}	CJBR	Fm^{-2}	Bottom junction capacitance at $V = V_R$
20	C_{JSR}	CJSR	Fm^{-1}	Sidewall junction capacitance at $V = V_R$
21	C_{JGR}	CJGR	Fm^{-1}	Gate edge junction capacitance at $V= V_R$
22	V_{DBR}	VDBR	V	Diffusion voltage of the bottom junction at $T = T_R$
23	V_{DSR}	VDSR	V	Diffusion voltage of the sidewall junction at $T = T_R$
24	V_{DGR}	VDGR	V	Diffusion voltage of the gate edge junction at $T = T_R$
25	P_B	PB	-	Bottom-junction grading coefficient
26	P_S	PS	-	Sidewall-junction grading coefficient
27	P_G	PG	-	Gate-edge-junction grading coeffcient

No.	Symbol	Programming Name	Units	Description
28	I_{MAX}	IMAX	A	Explosion current
29	$MULT$	MULT	-	Multiplication factor

List of Internal Variables and Parameters

No.	Parameter	Programming Name	Units	Description
1	V_{DB}	VDB	V	Diffusion voltage of bottom area A_B
2	V_{DS}	VDS	V	Diffusion voltage of Locos-edge L_S
3	V_{DG}	VDG	V	Diffusion voltage of gate-edge L_G
4	C_{JB}	CJB	F	Capacitance of bottom area A_B
5	C_{JS}	CJS	F	Capacitance of Locos-edge L_S
6	C_{JG}	CJG	F	Capacitance of gate-edge L_G
7	I_{SDB}	ISDB	A	Diffusion saturation-current of bottom area A_B
8	I_{SDS}	ISDS	A	Diffusion saturation-current of Locos-edge L_S
9	I_{SDG}	ISDG	A	Diffusion saturation-current of gate-edge L_G
10	I_{SGB}	ISGB	A	Generation saturation-current of bottom area A_B
11	I_{SGS}	ISGS	A	Generation saturation-current of Locos-edge L_S
12	I_{SGG}	ISGG	A	Generation saturation-current of gate-edge L_G
13	T_A	TA	^0C	Ambient circuit temperature
14	T_{KD}	TKD	K	Absolute temperature of the junction/device
15	V	V	V	Diode bias voltage ($V = V_A - V_K$)

16	I	I	A	Total DC current from anode to cathode ($I = I_A = - I_K$)
17	Q	Q	C	Total junction charge ($Q = Q_{\mathrm{A}} = - Q_K$)
18	V_{EXPL}	VEXPL	V	Explosion voltage

Default and clipping values

The default values and clipping values as used for the juncap model are listed below.

Position in list	Parameter name	Units	Default	Clip low	Clip high
1	*LEVEL*	-	1	-	-
2	*AB*	m^2	1.00×10^{-12}	0.00	-
3	*LS*	m	1.00×10^{-6}	0.00	-
4	*LG*	m	1.00×10^{-6}	0.00	-
5	*DTA*	°C	0.00	-	-
6	*TR*	°C	25.00	-273.15	-
7	*VR*	V	0.00	-	-
8	*JSGBR*	Am^{-2}	1.00×10^{-3}	0.00	-
9	*JSDBR*	Am^{-2}	1.00×10^{-3}	0.00	-
10	*JSGSR*	Am^{-1}	1.00×10^{-3}	0.00	-
11	*JSDSR*	Am^{-1}	1.00×10^{-3}	0.00	-
12	*JSGGR*	Am^{-1}	1.00×10^{-3}	0.00	-
13	*JSDGR*	Am^{-1}	1.00×10^{-3}	0.00	-
14	*NB*	-	1.00	0.1	-
15	*NS*	-	1.00	0.1	-
16	*NG*	-	1.00	0.1	-
17	*VB**	V	0.90	-	-
18	*CJBR*	Fm^{-2}	1.00×10^{-12}	0.00	-
19	*CJSR*	Fm^{-1}	1.00×10^{-12}	0.00	-
20	*CJGR*	Fm^{-1}	1.00×10^{-12}	0.00	-
21	*VDBR*	V	1.00	0.05	-
22	*VDSR*	V	1.00	0.05	-

23	*VDGR*	V	1.00	0.05	-
24	*PB*	-	0.40	0.05	0.99
25	*PS*	-	0.40	0.05	0.99
26	*PG*	-	0.40	0.05	0.99
27	*IMAX*	A	1000	-	-
28	*TYPE*	-	-1	-1	1
29	*MULT*	-	1.00	0.00	-

* The value for *VB* is **(NOT USED)!**

18.1.4 Model equations

The JUNCAP model is intended to describe the behaviour of the diodes that are formed by the source, drain or well-to-bulk junctions in MOS devices. The model is limited to the case of reverse biasing of these junctions. Similarly to the MOS model, the current equations are formulated and AC effects are modeled via charge equations using the quasi-static approximation. In order to include the effects from differences in the sidewall, bottom and gate-edge-junction profiles, these three contributions are calculated separately in the JUNCAP model. Both the diffusion and the generation currents are treated in the model, each with its own temperature and voltage dependence.

In the JUNCAP model a part of the total charge comes from the gate-edge junction very close to the surface. This charge is also included in the MOS-model charge equations, and is therefore counted twice. However this results in only a very minor error.

In the next section the model equations are presented. Correct operation of the model in a circuit-simulator environment requires some numerical additions, that are described in the section on the implementation. Finally any fixed capacitance that is present on a node - e.g. the metal-1-to-substrate capacitance - must appear in a fixed-capacitor statement or must be included in INTCAP. They no longer form a part of the JUNCAP model in contrast to the old NODCAP model.

Temperature, Geometry and Voltage Dependence

The general scaling rules, which apply to all three components of the JUNCAP model, are:

$$T_{KR} = T_0 + T_R \tag{18.4}$$

$$T_{KD} = T_0 + T_A + \Delta T_A \tag{18.5}$$

$$\phi_{TR} = \frac{k \cdot T_{KR}}{q} \tag{18.6}$$

$$\phi_{TD} = \frac{k \cdot T_{KD}}{q} \tag{18.7}$$

$$\phi_{gR} = 1.16 - \frac{7.02 \cdot 10^{-4} \cdot T_{KR}^2}{1108.0 + T_{KR}} \tag{18.8}$$

$$\phi_{gD} = 1.16 - \frac{7.02 \cdot 10^{-4} \cdot T_{KD}^2}{1108.0 + T_{KD}} \tag{18.9}$$

$$F_{TD} = \left(\frac{T_{KD}}{T_{KR}}\right)^{1.5} \cdot \exp\left(\frac{\phi_{gR}}{2\phi_{TR}} - \frac{\phi_{gD}}{2\phi_{TD}}\right) \tag{18.10}$$

The internal reference parameters for the bottom component are specified by:

$$V_{DB} = V_{DBR} \cdot \frac{T_{KD}}{T_{KR}} - 2 \cdot \phi_{TD} \cdot \ln F_{TD} \tag{18.11}$$

$$C_{JB} = C_{JBR} \cdot A_B \cdot \left(\frac{V_{DBR} - V_R}{V_{DB}}\right)^{P_B} \tag{18.12}$$

$$I_{SGB} = J_{SGBR} \cdot F_{TD} \cdot A_B \cdot \left(\frac{V_{DB}}{V_{DBR} - V_R}\right)^{P_B} \tag{18.13}$$

$$I_{SDB} = J_{SDBR} \cdot F_{TD}^2 \cdot A_B \tag{18.14}$$

Similar formulations hold for the locos-edge and the gate-edge components; one has to replace the index *B* by *S* and *G*, and the area A_B by L_S and L_G, so for the locos-edge:

$$V_{DS} = V_{DSR} \cdot \frac{T_{KD}}{T_{KR}} - 2 \cdot \phi_{TD} \cdot \ln F_{TD} \tag{18.15}$$

$$C_{JS} = C_{JSR} \cdot L_S \cdot \left(\frac{V_{DSR} - V_R}{V_{DS}}\right)^{P_S} \tag{18.16}$$

$$I_{SGS} = J_{SGSR} \cdot F_{TD} \cdot L_S \cdot \left(\frac{V_{DS}}{V_{DSR} - V_R}\right)^{P_S} \tag{18.17}$$

$$I_{SDS} = J_{SDSR} \cdot F_{TD}^2 \cdot L_S \tag{18.18}$$

for the gate-edge:

$$V_{DG} = V_{DGR} \cdot \frac{T_{KD}}{T_{KR}} - 2 \cdot \phi_{TD} \cdot \ln F_{TD} \tag{18.19}$$

$$C_{JG} = C_{JGR} \cdot L_G \cdot \left(\frac{V_{DGR} - V_R}{V_{DG}}\right)^{P_G} \quad (18.20)$$

$$I_{SGG} = J_{SGGR} \cdot F_{TD} \cdot L_G \cdot \left(\frac{V_{DG}}{V_{DGR} - V_R}\right)^{P_G} \quad (18.21)$$

$$I_{SDG} = J_{SDGR} \cdot F_{TD}^2 \cdot L_G \quad (18.22)$$

In subsequent sections we will show the equations only for the bottom component.

JUNCAP - Capacitor and Leakage Current Model

- Junction capacitance of the source or drain diode

In the charge description the following internal parameter is defined:

$$Q_{JDB} = \frac{C_{JB} \cdot V_{DB}}{1 - P_B} \quad (18.23)$$

In order to prevent an unlimited increase of the voltage derivative of the charge, the charge description is divided in two parts: the original power function and a supplemented quadratic function. At the cross-over point between these regions, indicated by $V_L\ldots$, the following parameters are defined:

$$F_{CB} = 1 - \left(\frac{1 + P_B}{3}\right)^{\frac{1}{P_B}} \quad (18.24)$$

$$V_{LB} = F_{CB} \cdot V_{DB} \quad (18.25)$$

$$C_{LB} = C_{JB}(1 - F_{CB})^{-P_B} \quad (18.26)$$

$$Q_{LB} = Q_{JDB}\left\{1-(1-F_{CB})^{1-P_B}\right\} \tag{18.27}$$

$$Q_{JBV} = \begin{cases} Q_{JDB}\cdot\left\{1-\left(1-\dfrac{V}{V_{DB}}\right)^{1-P_B}\right\}, & V < V_{LB} \\ Q_{LB}+C_{LB}(V-V_{LB})\cdot\left\{1+\dfrac{P_B(V-V_{LB})}{2\cdot V_{DB}(1-F_{CB})}\right\}, & V \geq V_{LB} \end{cases} \tag{18.28}$$

and similar expressions for the locos-edge and gate-edge charges, Q_{JSV} and Q_{JGV}. The total charge characteristic can be described by:

$$Q = Q_{JBV}+Q_{JSV}+Q_{JGV}$$

Using elementary mathematics we can derive from Eqn. (18.28) simple equations for the capacitance of the bottom area:

$$C_{JBV} = \begin{cases} C_{JB}\cdot\dfrac{1}{\left(1-\dfrac{V}{V_{DB}}\right)^{P_B}}, & V < V_{LB} \\ C_{LB}+\dfrac{C_{LB}\cdot P_B\cdot(V-V_{LB})}{V_{DB}\cdot(1-F_{CB})}, & V \geq V_{LB} \end{cases} \tag{18.29}$$

and similar expressions for C_{JSV} and C_{JGV}.

The total capacitance can be described by:

$$C = C_{JBV}+C_{JSV}+C_{JGV}$$

- Bulk to source or bulk to drain diode current

With the scaled parameters of the preceding section, the diffusion and generation current components can be expressed as:

$$I_{DB} = I_{SDB} \cdot \left\{ \exp\left(\frac{V}{N_B \cdot \phi_{TD}}\right) - 1 \right\} \tag{18.30}$$

$$I_{GB} = \begin{cases} I_{SGB} \cdot \left(\frac{V_{DB} - V}{V_{DB}}\right)^{P_B} \cdot \left\{ \exp\left(\frac{V}{N_B \cdot \phi_{TD}}\right) - 1 \right\}, & V \leq V_{DB} \\ 0\,, & V > V_{DB} \end{cases} \tag{18.31}$$

The first relation concerning the diffusion component, is valid over the whole operating range.

The exponential formula for I_{DB} in (18.30) is used until I_{DB} reaches a maximum (explosion) current IMAX. The explosion voltage for which this happens is called V_{EXPL}^{DB}. From (18.30) the value of V_{EXPL}^{DB} can be derived:

$$V_{EXPL}^{DB} = N_B \Phi_{TD} log\left(\frac{I_{MAX}}{I_{SDB}} + 1\right). \tag{18.32}$$

For $V > V_{EXPL}^{DB}$ the following linear expression is used for I_{DB}:

$$I_{DB} = I_{MAX} + \left(V - V_{EXPL}^{DB}\right) \frac{I_{SDB}}{N_B \Phi_{TD}} \exp\left(\frac{V_{EXPL}^{DB}}{N_B \Phi_{TD}}\right) \tag{18.33}$$

The second relation, describing the generation current, shows an unlimited increase in the derivative of this function at $V = V_{DB}$. Therefore the power function is merged at $V = 0.0$ with a hyperbolic function in the forward bias range and the exponential part is divided by $\exp\left(\frac{V}{N_B \cdot \phi_{TD}}\right)$. This enables a gradual decrease in the generation current component.

The hyperbolic function: $I_{HYP} = F_{SB}\ (\ V + V_{AB}\ )^{-B}$ is used. The parameter B controls the decrease of the current for voltages V>0.0 for all generation components. The value of B is fixed and set to 2 in the model. The continuity constraints of function and derivative in the merge point lead to the following relations for F_{SB} and V_{AB}:

$$V_{AB} = \frac{B \cdot V_{DB}}{P_B} \tag{18.34}$$

$$F_{SB} = I_{SGB} \cdot V_{AB}^{B} \tag{18.35}$$

Now the generation current voltage characteristic in the forward region becomes:

$$I_{GB} = \frac{F_{SB}}{(V + V_{AB})^B} \cdot \left\{1 - \exp\left(\frac{-V}{N_B \cdot \phi_{TD}}\right)\right\} \tag{18.36}$$

and the final model equations for the currents of the bottom area are:

$$I_{DB} = \begin{cases} I_{SDB}\left(\exp\left(\frac{V}{N_B \cdot \phi_{TD}}\right) - 1\right), V \le V_{\substack{DB \\ EXPL}} \\ I_{MAX} + \left(V - V_{\substack{DB \\ EXPL}}\right)\frac{I_{SDB}}{N_B \phi_{TD}} \exp\left(\frac{V_{\substack{DB \\ EXPL}}}{N_B \phi_{TD}}\right), V > V_{\substack{DB \\ EXPL}} \end{cases} \tag{18.37}$$

$$I_{GB} = \begin{cases} I_{SGB} \cdot \left(\dfrac{V_{DB} - V}{V_{DB}}\right)^{P_B} \cdot \left\{ \exp\left(\dfrac{V}{N_B \cdot \phi_{TD}}\right) - 1 \right\}, & V \leq 0.0 \\ I_{SGB} \cdot \left(\dfrac{V_{AB}}{V + V_{AB}}\right)^{B} \cdot \left\{ 1 - \exp\left(\dfrac{-V}{N_B \cdot \phi_{TD}}\right) \right\}, & V > 0.0 \end{cases} \quad (18.38)$$

With similar expressions for the locos-edge and gate-edge components, the total junction current can be expressed as:

$$I = (I_{DB} + I_{GB}) + (I_{DS} + I_{GS}) + (I_{DG} + I_{GG}) \quad (18.39)$$

The same current limiting applies to the calculation of I_{DS} and I_{DG}, leading to different explosion voltages V_{EXPL}^{DS} and V_{EXPL}^{DG}. The actual value of V_{EXPL} used for all three currents I_{DB}, I_{DS} and I_{DG} is the minimum of the three explosion voltages:

$$V_{EXPL} = \min\left(V_{EXPL}^{DB}, V_{EXPL}^{DS}, V_{EXPL}^{DG}\right).$$

Numerical Adaptation

To implement the model in a circuit simulator, care must be taken of the numerical stability of the simulation program. A small non-physical conductance, G_{min}, is connected parallel to the conductance G. The value of the conductance G_{min} is 10^{-15} [1/Ω].

18.1.5 DC operating point output

The DC operating point output facility gives information on the state of a device at its operation point.

Quantity	Equation	Description
G		Conductance
C		Capacitance
Lx1		Current
Lx3		Charge
Lx5		Capacitance

Remark: The conductance G_{min} is connected parallel to the conductance *G*. This conductance influences the DC operating output.
Remark: The quantities *Lx1*, *Lx3* and *Lx5* are supplied specifically for use by some simulators (e.g. *UltraSim*) in their calculations.

18.1.6 Simulator specific items

Pstar syntax

juncap_n (a,k) level=1, type=1, <parameters>
juncap_n (a,k) level=1, type=-1, <parameters>

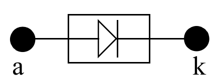
n	:	occurrence indicator
<parameters>	:	list of model parameters

a and k are anode and cathode terminals respectively.

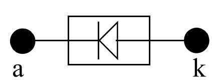
3 **Note**

The type parameter indicates the position of the diode.

When type = -1:



When type = 1:



The default type for Juncap level 1 is -1.

⚠ Care

When assignment by position is used, the order of the parameters must be equal to the order specified in the model definition. Readability is improved if assignment by name is used.

Spectre syntax

model modelname juncap type=p <modpar> componentname a k modelname <inpar>
model modelname juncap type=n <modpar> componentname a k modelname <inpar>

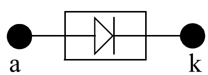
modelname	:name of model, user defined
componentname	:occurrence indicator
<modpar>	:list of model parameters
<inpar>	:list of instance parameters

a and k are anode and cathode terminals respectively.

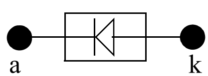
3 Note

The type parameter indicates the position of the diode.

When type = p:



When type = n:



The default type for Juncap level 1 is n.

Warning! In Spectre, use only the parameter statements type=n or type=p. Using any other string and/or numbers will result in unpredictable and possibly erroneous results.

ADS syntax

model modelname juncap gender=0 <modpar>
modelname: componentname a k <instpar>
model modelname juncap gender=1 <modpar>
modelname: componentname a k <instpar>

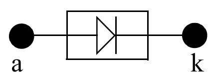
modelname	:	name of model, user defined
componentname	:	occurrence indicator
<modpar>	:	list of model parameters
<instpar>	:	list of instance parameters

a and k are anode and cathode terminals respectively.

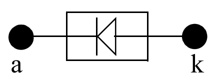
3 Note

The gender parameter indicates the position of the diode.

When gender = 0:



When gender = 1:



The default gender for Juncap level 1 is 1, which is n-type.

The ON/OFF condition for Pstar

The solution for a circuit involves a process of successive calculations. The calculations are started from a set of 'initial guesses' for the electrical quantities of the nonlinear elements. A simplified DCAPPROX mechanism for devices using ON/OFF keywords is given in [9]. By default the devices start in the default state.

JUNCAP2			
	Default	ON	OFF
V_{AK}	-0.1	0.7	-0.1

The ON/OFF condition for Spectre

JUNCAP2			
	Default	ON	OFF
V_{AK}	-0.1	0.7	0.0

The ON/OFF condition for ADS

JUNCAP2			
	Default	ON	OFF
V_{AK}	0.0	0.0	0.0

18.1.7 Parameter extraction

18.2 JUNCAP2 Model

18.2.1 History of model and documentation

Introduction

The first version of the compact MOS model JUNCAP2, Level 200, has been released to the public domain in April 2005. Changes and additions to the model are documented by adapting or extending the documentation in this Report.

History of the model

April 2005 Release of JUNCAP2, level 200 as part of SiMKit 2.1. A Verilog-A implementation is made available as well.

August 2005 Release of JUNCAP2, level 200.1 as part of SiMKit 2.2. Similar to the previous version, a Verilog-A implementation of the JUNCAP2-model is made available as well. Focus of this release was mainly on the optimization of the evaluation speed of JUNCAP2. This new version is fully parameter compatible with the previous version.

The following changes have been made:

- limiting of charge model and of $w_{SRH,step}$ is now based on the minimum of three built-in voltages, instead of separate limiting for bottom, STI-edge, and gate-edge component;
- limiting of V_j to $V_{j,SRH}$ in Shockley-Read-Hall model replaced by adopting VMAX/IMAX construction of ideal-current model; subsequently the original $V_{j,SRH2}$ has been renamed into $V_{j,SRH}$;
- limiting of V_{AK} to V_j in charge model changed from ln-exp type into so-called hyp_5 function; limiting of V_{AK} to $V_{j,SRH}$ (i.e. the previous $V_{j,SRH2}$) in Shockley-Read-Hall model changed from ln-exp type into so-called hyp_2 function.
- expression for Δw_{SRH} rewritten im more concise form (mathematically identical to previous version), see Eq. (18.51).

History of the documentation

April 2005 First release of JUNCAP2, level 200 documentation.

August 2005 Documentation updated for JUNCAP2, level 200.1 release. Section 18.2.6 has been added to document the so-called hyp-functions introduced in level 200.1.

18.2.2 Introduction

The JUNCAP2 model is intended to describe the behavior of the diodes that are formed by the source, drain, or well-to-bulk junctions in MOSFETs. It is the successor of the JUNCAP level=1 model [29].

Whereas the JUNCAP level=1 model gives a satisfactory description of the junction capacitances, its description of diode leakage currents is rather poor for present-day CMOS technologies. This is due to ever increasing doping concentrations in the junctions, leading to increasing electric fields. Due to these high electric fields, leakage mechanisms such as trap-assisted tunneling and band-to-band tunneling have gained importance to such an extent, that they are starting to contribute to the MOSFET off-state current. Thus, accurate modelling of these leakage currents is called for.

In addition to its relevance for advanced CMOS technologies, accurate junction modelling is also relevant for partially depleted SOI (PDSOI). Here, a small positive voltage at the floating body exists, which is determined by the equilibrium between impact ionization and gate current on one hand and current through the source junction on the other hand. Due to the back-gate effect, this small positive floating body voltage gives rise to additional drain current, where it is visible as the so-called "kink effect". Thus, for PDSOI applications, accurate junction modelling in the low-forward regime is required.

References

[29] JUNCAP:
`http://www.semiconducors.philips.com/Philips_Models/`

[30] G.A.M. Hurkx, D.B.M. Klassen and M.P.G. Knuvers, *A new recombination model for device simulation including tunneling*, IEEE Trans. El. Dev., Vol.39, No.2, pp.331-338, February 1992.

[31] W. Jin, C.H. Chan, S.K.H. Fung, and P.K. Ko, *Shot-noise-induced excess low-frequency noise in floating-body partially depleted SOI MOSFET's*, IEEE Trans. El. Dev., Vol. 46, No. 6, pp. 1180– 1185, June 1999.

[32] MOSModel 9:
`http://www.semiconductors.philips.com/Philips_Models/`

18.2.3 Physics

The JUNCAP2 model has been developed for the description of source and drain junctions in MOSFETs. The model equations have been developed for symmetrical junctions of arbitrary grading coefficient. The following physical effects have been included:

Geometrical scaling

JUNCAP2 models the capacitances and currents of bottom-, STI-edge, and gate-edge components. This is illustrated in Figs. 79 and 80.

Depletion capacitance

The depletion capacitance model, similar to JUNCAP level=1, is a standard textbook equation. It has been safeguarded against numerical overflow in the forward mode of operation.

Ideal current

The ideal diode current is modelled using the ideal-case Shockley equation. The bandgap has been made a free parameter to be able to tune the temperature dependence. No (unphysical) ideality factor has been included. Non-idealities are modelled with physics-based equations, as outlined below.

Shockley-Read-Hall current

The Shockley-Read-Hall current is calculated by integrating the Shockley-Read-Hall generationrecombination rate over the depletion region. This is done for arbitrary grading coefficient and results in a single-piece expression in forward and reverse mode of operation.

Trap-assisted tunneling current

The trap-assisted tunneling current is calculated in a similar fashion as the Shockley-Read-Hall current. Now also the field-enhancement factor [30] is taken into account in the calculation. In contrast to e.g. Diode Level 500 [29], the calculation is not based on the low-field approximation of this field enhancement factor, but is generally valid for both low and high fields. The calculation results in a single-piece expression which is valid in both the forward and reverse regime, and for arbitrary grading coefficient.

Band-to-band tunneling current

For the band-to-band tunneling current, a physical model similar to the Diode Level 500 [29] equation has been implemented. Some additional freedom in fitting the (small) temperature dependence of this current is provided.

Avalanche breakdown

For avalanche breakdown, an expression has been derived which is a simplified form of the Diode Level 500 [29] equations for this phenomenon. In comparison with Diode Level 500, some additional freedom in fitting the onset to breakdown is provided.

Noise

In partially depleted silicon-on-insulator (PD SOI), the shot noise of the junction current is important because, together with the shot noise of the impact ionization current of the MOSFET, it leads to additional Lorentzian noise in the drain current [31]. Therefore, shot noise has been implemented in JUNCAP2.

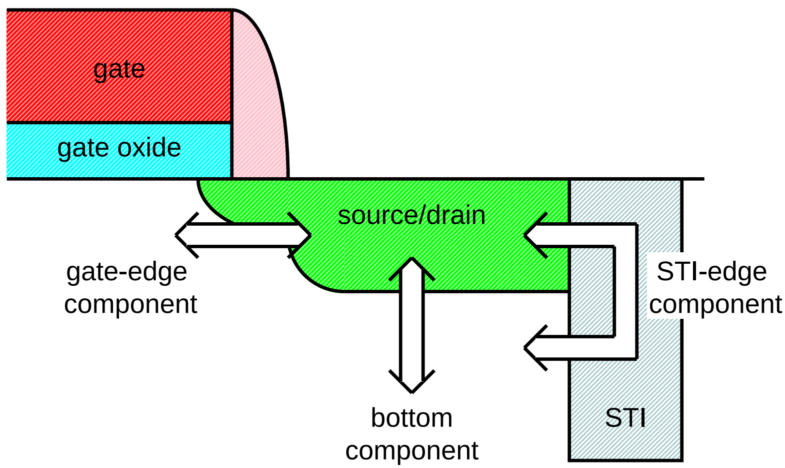


Figure 79: The three contributions to the source/drain junction of a MOSFET

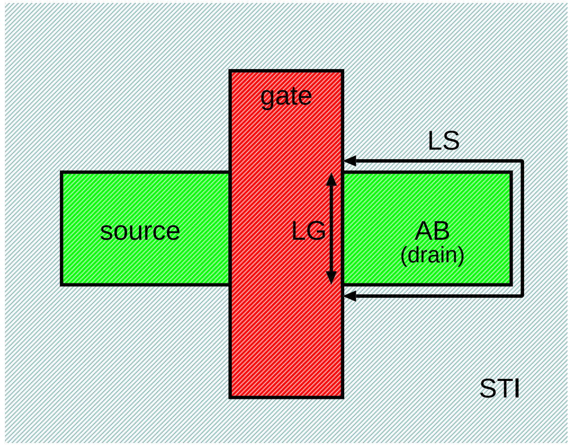


*Figure 80: Schematic top view of the MOSFET. The meaning of the instance parameters **AB**, **LS**, and **LG** is indicated in the drain region*

18.2.4 Parameters and constants

Physical constants

No.	Symbol	Unit	Value	Description
1	T_0	K	273.15	Offset between Celcius and Kelvin Temperature scale
2	k_B	J/K	$1.3806505 \cdot 10^{-23}$	Boltzmann constant
3	q	C	$1.6021918 \cdot 10^{-19}$	elementary charge
4	h	Js	$1.05457168 \cdot 10^{-34}$	reduced Planck constant
5	m_0	kg	$9.1093826 \cdot 10^{-31}$	electron rest mass
6	ε_{Si}	F/m	$1.045 \cdot 10^{-10}$	absolute permittivity of silicon

Other constants

No.	Symbol	Unit	Value	Description
1	T_{min}	^{o}C	-250	minimum temperature for model equations
2	$V_{bi,low}$	V	0.050	lower boundary for built-in voltage
3	a	-	2	sets upper limit of forward capacitance to $a \cdot C_{jo}$
4	ε_{ch}	-	0.1	smoothing constant for charge model
5	ΔV_{bi}	-	0.050	voltage difference used in band-to-band tunneling model
6	ε_{av}	-	1×10^{-6}	smoothing constant for effective voltage in avalanche model
7	$V_{br,max}$	V	1×10^{3}	upper limit for **VBR;** for larger values, avalanche model is switched off
8	α_{av}	-	0.999	below $-\alpha_{av} \cdot \mathbf{VBR}$ avalanche model is linearized

9	$V_{max,large}$	V	1×10^{8}	value assigned to V_{max} when I_{DSAT} is zero
10	a_{erfc}	-	0.29214664	parameter in erfc approximation
11	p_{erfc}	-	$\sqrt{\pi} \cdot a_{erfc}$	parameter in erfc approximation
12	b_{erfc}	-	$\frac{6 - 5 \cdot a_{erfc} - p_{erfc}{}^{-2}}{3}$	parameter in erfc approximation
13	c_{erfc}	-	$1 - a_{erfc} - b_{erfc}$	parameter in erfc approximation

Instance parameters

No.	Name	Unit	Default	Min.	Max.	Description
1	AB	m^2	1×10^{-12}	0	-	junction area
2	LS	m	1×10^{-6}	0	-	STI-edge part of junction perimeter
3	LG	m	1×10^{-6}	0	-	gate-edge part of junction perimeter
4	MULT	-	1	0	-	multiplication factor

Model parameters

No.	Name	Unit	Default	Min.	Max.	Description
0	**LEVEL**	-	200	200	200	level must be 200
1	**TYPE**[a]	-	1	-1	1	switch (-1 or 1) to select *p* - *n* or *n* - *p* junction
2	**TRJ**	^oC	21	T_{min}	-	reference temperature
3	**DTA**	^oC	0	-	-	temperature offset with respect to ambient temperature
4	**IMAX**	A	1000	1×10^{-12}	-	maximum current up to which forward current behaves exponentially
			Capacitance parameters			
5	**CJORBOT**	F/m^2	1×10^{-3}	1×10^{-12}	-	zero-bias capacitance per unit-of-area of bottom component
6	**CJORSTI**	F/m	1×10^{-9}	1×10^{-18}	-	zero-bias capacitance per unit-of-length of STI-edge component
7	**CJORGAT**	F/m	1×10^{-9}	1×10^{-18}	-	zero-bias capacitance per unit-of-length of gate-edge component

8	**VBIRBOT**	V	1	$V_{bi,low}$	-	built-in voltage at the reference temperature of bottom component
9	**VBIRSTI**	V	1	$V_{bi,low}$	-	built-in voltage at the reference temperature of STI-edge component
10	**VBIRGAT**	V	1	$V_{bi,low}$	-	built-in voltage at the reference temperature of gate-edge component
11	**PBOT**	-	0.5	0.05	0.95	grading coefficient of bottom component
12	**PSTI**	-	0.5	0.05	0.95	grading coefficient of STI-edge component
13	**PGAT**	-	0.5	0.05	0.95	grading coefficient of gate-edge component
			Ideal-current parameters			
14	**PHIGBOT**	V	1.16	-	-	zero-temperature band-gap voltage of bottom component
15	**PHIGSTI**	V	1.16	-	-	zero-temperature band-gap voltage of STI-edge component
16	**PHIGGAT**	V	1.16	-	-	zero-temperature band-gap voltage of gate-edge component
17	**IDSATRBOT**	A/m^2	1×10^{-12}	0	-	saturation current density at the reference temperature of bottom component
18	**IDSATRSTI**	A/m	1×10^{-18}	0	-	saturation current density at the reference temperature of STI-edge component

19	**IDSATRGAT**	A/m	1×10^{-18}	0	-	saturation current density at the reference temperature of gate-edge component
			Shockley-Read-Hall parameters			
20	**CSRHBOT**	A/m^3	1×10^{2}	0	-	Shockley-Read-Hall prefactor of bottom component
21	**CSRHSTI**	A/m^2	1×10^{-4}	0	-	Shockley-Read-Hall prefactor of STI-edge component
22	**CSRHGAT**	A/m^2	1×10^{-4}	0	-	Shockley-Read-Hall prefactor of gate-edge component
23	**XJUNSTI**	m	1×10^{-7}	1×10^{-9}	-	junction depth of STI-edge component
24	**XJUNGAT**	m	1×10^{-7}	1×10^{-9}	-	junction depth of gate-edge component
			Trap-assisted tunneling parameters			
25	**CTATBOT**	A/m^3	1×10^{2}	0	-	trap-assisted tunneling prefactor of bottom component
26	**CTATSTI**	A/m^3	1×10^{-4}	0	-	trap-assisted tunneling prefactor of STI-edge component
27	**CTATGAT**	A/m^3	1×10^{-4}	0	-	trap-assisted tunneling prefactor of gate-edge component
28	**MEFFTATBOT**	-	0.25	0.01	-	effective mass (in units of m_0) for trap-assisted tunneling of bottom component

29	**MEFFTATSTI**	-	0.25	0.01	-	effective mass (in units of m_0) for trap-assisted tunneling of STI-edge component
30	**MEFFTATGAT**	-	0.25	0.01	-	effective mass (in units of m_0) for trap-assisted tunneling of gate-edge component
			Band-to-band tunneling parameters			
31	**CBBTBOT**	AV^{-3}	1×10^{-12}	0	-	band-to-band tunneling prefactor of bottom component
32	**CBBTSTI**	$AV^{-3}m$	1×10^{-18}	0	-	band-to-band tunneling prefactor of STI-edge component
33	**CBBTGAT**	$AV^{-3}m$	1×10^{-18}	0	-	band-to-band tunneling prefactor of gate-edge component
34	**FBBTRBOT**	Vm^{-1}	1×10^{9}	-	-	normalization field at the reference temperature for band-to-band tunneling of bottom component
35	**FBBTRSTI**	Vm^{-1}	1×10^{9}	-	-	normalization field at the reference temperature for band-to-band tunneling of STI-edge component
36	**FBBTRGAT**	Vm^{-1}	1×10^{9}	-	-	normalization field at the reference temperature for band-to-band tunneling of gate-edge component
37	**STFBBTBOT**	K^{-1}	-1×10^{-3}	-	-	temperature scaling parameter for band-to-band tunneling of bottom component

38	**STFBBTSTI**	K^{-1}	-1×10^{-3}	-	-	temperature scaling parameter for band-to-band tunneling of STI-edge component
39	**STFBBTGAT**	K^{-1}	-1×10^{-3}	-	-	temperature scaling parameter for band-to-band tunneling of gateedge component
		Avalanche and breakdown parameters				
40	**VBRBOT**	V	10	0.1	-	breakdown voltage of bottom component
41	**VBRSTI**	V	10	0.1	-	breakdown voltage of STI-edge component
42	**VBRGAT**	V	10	0.1	-	breakdown voltage of gate-edge component
43	**PBRBOT**	V	4	0.1	-	breakdown onset tuning parameter of bottom component
44	**PBRSTI**	V	4	0.1	-	breakdown onset tuning parameter of STI-edge component
45	**PBIGAT**	V	4	0.1	-	breakdown onset tuning parameter of gate-edge component

a. For more details on the **TYPE** parameter, see section 18.2.8, titled *“Simulator specific items”,* on page 1230.

18.2.5 Model equations

The JUNCAP function

This section describes a function which contains the full characteristics of the JUNCAP2 model. In the actual model it will be called three times: for the bottom, STI-edge, and gate-edge components of the model. It uses the so-called hyp-functions, which are described seperately in section 18.2.6.

Input parameters of the juncap function

No.	Name	Description
0	V_{AK}	in case **TYPE** = 1: voltage between anode (*p*-side) and cathode (*n*-side); in case **TYPE** = -1: voltage between cathode and anode
1	T_{KR}	reference temperature in Kelvin
2	T_{KD}	device temperature in Kelvin
3	ϕ_{TD}	thermal voltage at device temperature
4	ϕ_{GD}	bandgap voltage at device temperature
5	F_{TD}	intrinsic carrier concentration at device temperature, divided by that at reference temperature
6	I_{DSAT}	saturation current density of ideal current
7	V_{bi}	built-in voltage at the device temperature
8	$V_{bi,min}$	minimum V_{bi} of bottom, STI-edge, and gate-edge contribution
9	$V_{F,min}$	limiting voltage for charge model
10	V_{ch}	smoothing constant for transition $V_{F,min} \rightarrow V_{ch}$ in charge model
11	**VMAX**	maximum voltage up to which forward current behaves exponentially
12	**CJOR**	zero-bias capacitance per unit-of-area
13	**VBIR**	built-in voltage at the reference temperature
14	**P**	grading coefficient
15	**CSRH**	Shockley-Read-Hall prefactor

16	**XJUN**	junction depth
17	**CTAT**	trap-assisted tunneling prefactor
18	**MEFFTAT**	effective mass (in units of m_0) for trap-assisted tunneling
19	**CBBT**	band-to-band tunneling prefactor
20	**FBBTR**	normalization field at the reference temperature for band-to-band tunneling
21	**STFBBT**	temperature scaling parameter for band-to-band tunneling
22	**VBR**	breakdown voltage
23	**PBR**	breakdown onset tuning parameter

Outputs of the juncap function

No.	**Name**	**Description**
0	I'_j	junction current per unit of area or length
1	Q'_j	junction charge per unit of area or length

Junction charge

$$C_{jo} = \mathbf{CJOR} \cdot \left(\frac{\mathbf{VBIR}}{V_{bi}}\right)^{\mathbf{P}} \tag{18.40}$$

$$V_j = \text{hyp}_5(V_{AK}; V_{F,min}, V_{ch}) \tag{18.41}$$

$$Q'_j = \left\{\frac{C_{jo} \cdot V_{bi}}{1 - \mathbf{P}} \cdot \left[1 - \left(1 - \frac{V_j}{V_{bi}}\right)^{1 - \mathbf{P}}\right] + a \cdot C_{jo} \cdot (V_{AK} - V_j)\right\} \tag{18.42}$$

Ideal current

$$M_{ID} = \begin{cases} \exp\left(\frac{V_{AK}}{\phi_{TD}}\right) & \text{if } V_{AK} < V_{max} \\ \left(1 + \frac{V_{AK} - \mathbf{VMAX}}{\phi_{TD}}\right) \cdot \exp\left(\frac{\mathbf{VMAX}}{\phi_{TD}}\right) & \text{if } V_{AK} \geq V_{max} \end{cases} \quad (18.43)$$

$$I'_D = (M_{ID} - 1) \cdot I_{DSAT} \quad (18.44)$$

Shockley-Read-Hall current

Note: if **CSRH** = **CTAT** = 0, Eqs. (18.45)... (18.54) should be skipped and $I'_{SRH} = 0$.

$$z_{inv} = \sqrt{M_{ID}} \quad (18.45)$$

$$z = \frac{1}{z_{inv}} \quad (18.46)$$

$$\psi^* = \begin{cases} \phi_{TD} \cdot \ln[z + 2 + \sqrt{(z+1) \cdot (z+3)}] & \text{if } V_{AK} > 0 \\ \frac{-V_{AK}}{2} + \phi_{TD} \cdot \ln[1 + 2 \cdot z_{inv} + \sqrt{(1 + z_{inv}) \cdot (1 + 3 \cdot z_{inv})}] & \text{if } V_{AK} \leq 0 \end{cases} \quad (18.47)$$

$$V_{j,lim} = V_{bi,min} - 2 \cdot \psi^* \quad (18.48)$$

$$V_{j,SRH} = hyp_2(V_{AK}; V_{j,lim}, \phi_{TD}) \quad (18.49)$$

$$w_{SRH,step} = 1 - \sqrt{1 - \frac{2 \cdot \psi^*}{V_{bi} - V_{j,SRH}}} \tag{18.50}$$

$$\Delta w_{SRH} = \left(\frac{w_{SRH,step}^{\;2} \cdot \ln w_{SRH,step}}{1 - w_{SRH,step}} + w_{SRH,step} \right) \cdot (1 - 2 \cdot \mathbf{P}) \tag{18.51}$$

$$w_{SRH} = w_{SRH,step} + \Delta w_{SRH} \tag{18.52}$$

$$W_{dep} = \frac{\mathbf{XJUN} \cdot \varepsilon_{Si}}{\mathbf{CJOR}} \cdot \left(\frac{V_{bi} - V_{j,SRH}}{\mathbf{VBIR}} \right)^{\mathbf{P}} \tag{18.53}$$

$$I'_{SRH} = \mathbf{CSRH} \cdot F_{TD} \cdot (z_{inv} - 1) \cdot w_{SRH} \cdot W_{dep} \tag{18.54}$$

Trap-assisted-tunelling current

Note: if **CTAT** = 0, Eqs. (18.55)... (18.69) should be skipped and $I'_{TAT} = 0$.

$$F_{max} = \frac{V_{bi} - V_{j,SRH}}{W_{dep} \cdot (1 - \mathbf{P})} \tag{18.55}$$

$$m_{eff} = \mathbf{MEFFTAT} \cdot m_0 \tag{18.56}$$

$$\Delta E = \max\left(\frac{\phi_{GD}}{2}, \phi_{TD} \right) \tag{18.57}$$

$$a_{TAT} = \frac{\Delta E}{\phi_{TD}} \tag{18.58}$$

$$b_{TAT} = \sqrt{\frac{32 \cdot m_{eff} \cdot q \cdot \Delta E^3}{3 \cdot h \cdot F_{max}}} \tag{18.59}$$

$$u'_{max} = \left(\frac{2 \cdot a_{TAT}}{3 \cdot b_{TAT}}\right)^2 \tag{18.60}$$

$$u_{max} = \sqrt{\frac{u'_{max}{}^2}{u'_{max}{}^2 + 1}} \tag{18.61}$$

$$w_{\Gamma} = (1 + b_{TAT} \cdot u_{max}{}^{3/2})^{\frac{\mathbf{P}}{\mathbf{P} - 1}} \tag{18.62}$$

$$w_{TAT} = \frac{w_{SRH} \cdot w_{\Gamma}}{w_{SRH} + w_{\Gamma}} \tag{18.63}$$

$$k_{TAT} = \sqrt{\frac{3 \cdot b_{TAT}}{8 \cdot \sqrt{u_{max}}}} \tag{18.64}$$

$$l_{TAT} = \frac{4 \cdot a_{TAT}}{3 \cdot b_{TAT}} \cdot \sqrt{u_{max}} - u_{max} \tag{18.65}$$

$$m_{TAT} = \frac{2 \cdot a_{TAT}{}^2}{3 \cdot b_{TAT}} \cdot \sqrt{u_{max}} - a_{TAT} \cdot u_{max} + \frac{b_{TAT}}{2} \cdot u_{max}{}^{3/2} \tag{18.66}$$

$$\text{erfcapprox(y)} = \begin{cases} t_{erfc} = \begin{cases} \dfrac{1}{1 + p_{erfc} \cdot y} & \text{if } y > 0 \\ \dfrac{1}{1 - p_{erfc} \cdot y} & \text{if } y \le 0 \end{cases} \\ \text{erfcapprox}^{+} = (a_{erfc} \cdot t_{erfc} + b_{erfc} \cdot t^{2}{}_{erfc} + c_{erfc} \cdot t^{3}{}_{erfc}) \cdot \exp(-y^{2}) \\ \text{erfcapprox(y)} = \begin{cases} \text{erfcapprox}^{+} & \text{if } y > 0 \\ 2 - \text{erfcapprox}^{+} & \text{if } y \le 0 \end{cases} \end{cases} \tag{18.67}$$

$$\Gamma_{max} = \frac{a_{TAT} \cdot \exp(m_{TAT}) \cdot \text{erfcapprox}[k_{TAT} \cdot (l_{TAT} - 1)] \cdot \sqrt{\pi}}{2 \cdot k_{TAT}} \tag{18.68}$$

$$I'_{TAT} = \mathbf{CTAT} \cdot F_{TD} \cdot (z_{inv} - 1) \cdot \Gamma_{max} \cdot w_{TAT} \cdot W_{dep} \tag{18.69}$$

Band-to-band tunelling current

Note: if **CBBT** = 0, Eqs. (18.72)... (18.75) should be skipped and $I'_{BBT} = 0$.

$$V_{BBT,lim} = \min(\mathbf{VBIRBOT},\ \mathbf{VBIRSTI},\ \mathbf{VBIRGAT}) - \Delta V_{bi} \tag{18.70}$$

$$V_{BBT} = \text{hyp}_2(V_{AK},\ V_{BBT,lim},\ \phi_{TR}) \tag{18.71}$$

$$W_{dep,r} = \frac{\mathbf{XJUN} \cdot \varepsilon_{Si}}{\mathbf{CJOR}} \cdot \left(\frac{\mathbf{VBIR} - V_{BBT}}{\mathbf{VBIR}}\right)^{\mathbf{P}} \tag{18.72}$$

$$F_{max,r} = \frac{\mathbf{VBIR} - V_{BBT}}{W_{dep,r} \cdot (1 - \mathbf{P})} \tag{18.73}$$

$$F_{BBT} = \mathbf{FBBTR} \cdot [1 + \mathbf{STFBBT} \cdot (T_{KD} - T_{KR})] \tag{18.74}$$

$$I'_{BBT} = \mathbf{CBBT} \cdot V_{AK} \cdot F_{max,r}{}^{2} \cdot \exp\left(-\frac{F_{BBT}}{F_{max,r}}\right) \quad (18.75)$$

Avalanche and breakdown

Note: if **VBR** > $V_{br,max}$, Eqs. (18.76)... (18.79) should be skipped and $f_{breakdown} = 1$.

$$V_{av} = \mathrm{hyp}_2(V_{AK}; 0, \varepsilon_{av}) \quad (18.76)$$

$$f_{stop} = \frac{1}{1 - \alpha_{av}{}^{\mathbf{PBR}}} \quad (18.77)$$

$$s_f = -f_{stop}{}^{2} \cdot \alpha_{av}{}^{\mathbf{PBR}-1} \cdot \frac{\mathbf{PBR}}{\mathbf{VBR}} \quad (18.78)$$

$$f_{breakdown} = \begin{cases} \dfrac{1}{1 - \left|\dfrac{-V_{av}}{\mathbf{VBR}}\right|^{\mathbf{PBR}}} & \text{if } V_{av} > -\alpha_{av} \cdot \mathbf{VBR} \\ f_{stop} + (V_{av} + \alpha_{av} \cdot \mathbf{VBR}) \cdot s_f & \text{if } V_{av} \le -\alpha_{av} \cdot \mathbf{VBR} \end{cases}$$

(18.79)

Total current

$$I'_j = (I'_D + I'_{SRH} + I'_{TAT} + I'_{BBT}) \cdot f_{breakdown} \quad (18.80)$$

The JUNCAP model

Thermal voltage

$$T_{KR} = T_0 + \mathbf{TJR} \tag{18.81}$$

$$T_{KD} = \max(T_0 + T_A + \mathbf{DTA}, T_0 + T_{min}) \tag{18.82}$$

$$\phi_{TR} = \frac{k_B \cdot T_{KR}}{q} \tag{18.83}$$

$$\phi_{TD} = \frac{k_B \cdot T_{KD}}{q} \tag{18.84}$$

Band gap

$$\Delta\phi_{GR} = -\frac{7.02 \cdot 10^{-4} \cdot T_{KR}^2}{1108.0 + T_{KR}} \tag{18.85}$$

$$\phi_{GR,bot} = \mathbf{PHIGBOT} + \Delta\phi_{GR} \tag{18.86}$$

$$\phi_{GR,sti} = \mathbf{PHIGSTI} + \Delta\phi_{GR} \tag{18.87}$$

$$\phi_{GR,gat} = \mathbf{PHIGGAT} + \Delta\phi_{GR} \tag{18.88}$$

$$\Delta\phi_{GD} = -\frac{7.02 \cdot 10^{-4} \cdot T_{KD}^2}{1108.0 + T_{KD}} \tag{18.89}$$

$$\phi_{GD,bot} = \mathbf{PHIGBOT} + \Delta\phi_{GD} \tag{18.90}$$

$$\phi_{GD,sti} = \mathbf{PHIGSTI} + \Delta\phi_{GD} \tag{18.91}$$

$$\phi_{GD,gat} = \mathbf{PHIGGAT} + \Delta\phi_{GD} \tag{18.92}$$

Intrinsic carrier concentration

$$F_{TD,bot} = \left(\frac{T_{KD}}{T_{KR}}\right)^{1.5} \cdot \exp\left(\frac{\phi_{GR,bot}}{2 \cdot \phi_{TR}} - \frac{\phi_{GD,bot}}{2 \cdot \phi_{TD}}\right) \tag{18.93}$$

$$F_{TD,sti} = \left(\frac{T_{KD}}{T_{KR}}\right)^{1.5} \cdot \exp\left(\frac{\phi_{GR,sti}}{2 \cdot \phi_{TR}} - \frac{\phi_{GD,sti}}{2 \cdot \phi_{TD}}\right) \tag{18.94}$$

$$F_{TD,gat} = \left(\frac{T_{KD}}{T_{KR}}\right)^{1.5} \cdot \exp\left(\frac{\phi_{GR,gat}}{2 \cdot \phi_{TR}} - \frac{\phi_{GD,gat}}{2 \cdot \phi_{TD}}\right) \tag{18.95}$$

Saturation current density at device temperature

$$I_{DSAT,bot} = \mathbf{IDSATRBOT} \cdot {F_{TD,bot}}^{2} \tag{18.96}$$

$$I_{DSAT,sti} = \mathbf{IDSATRSTI} \cdot {F_{TD,sti}}^{2} \tag{18.97}$$

$$I_{DSAT,gat} = \mathbf{IDSATRGAT} \cdot {F_{TD,gat}}^{2} \tag{18.98}$$

Determination of V_{max}

$$V_{max,bot} = \begin{cases} V_{max,large} & \text{if } I_{DSAT,bot} \cdot \mathbf{AB} = 0 \\ \phi_{TD} \cdot \ln\left(\dfrac{\mathbf{IMAX}}{I_{DSAT,bot} \cdot \mathbf{AB}} + 1\right) & \text{if } I_{DSAT,bot} \cdot \mathbf{AB} \neq 0 \end{cases} \tag{18.99}$$

$$V_{max,sti} = \begin{cases} V_{max,large} & \text{if } I_{DSAT,sti} \cdot \mathbf{LS} = 0 \\ \phi_{TD} \cdot \ln\left(\dfrac{\mathbf{IMAX}}{I_{DSAT,sti} \cdot \mathbf{LS}} + 1\right) & \text{if } I_{DSAT,sti} \cdot \mathbf{LS} \neq 0 \end{cases} \tag{18.100}$$

$$V_{max,gat} = \begin{cases} V_{max,large} & \text{if } I_{DSAT,gat} \cdot \mathbf{LG} = 0 \\ \phi_{TD} \cdot \ln\left(\dfrac{\mathbf{IMAX}}{I_{DSAT,gat} \cdot \mathbf{LG}} + 1\right) & \text{if } I_{DSAT,gat} \cdot \mathbf{LG} \neq 0 \end{cases} \tag{18.101}$$

$$V_{max} = \min(V_{max,bot}, V_{max,sti}, V_{max,gat}) \tag{18.102}$$

Built-in voltages

$$U_{bi,bot} = \mathbf{VBIRBOT} \cdot \frac{T_{KD}}{T_{KR}} - 2 \cdot \phi_{TD} \cdot \ln F_{TD,bot} \tag{18.103}$$

$$V_{bi,bot} = U_{bi,bot} + \phi_{TD} \cdot \ln\left[1 + \exp\left(\frac{V_{bi,low} - U_{bi,bot}}{\phi_{TD}}\right)\right] \tag{18.104}$$

$$U_{bi,sti} = \mathbf{VBIRSTI} \cdot \frac{T_{KD}}{T_{KR}} - 2 \cdot \phi_{TD} \cdot \ln F_{TD,sti} \tag{18.105}$$

$$V_{bi,sti} = U_{bi,sti} + \phi_{TD} \cdot \ln\left[1 + \exp\left(\frac{V_{bi,low} - U_{bi,sti}}{\phi_{TD}}\right)\right] \tag{18.106}$$

$$U_{bi,gat} = \mathbf{VBIRGAT} \cdot \frac{T_{KD}}{T_{KR}} - 2 \cdot \phi_{TD} \cdot \ln F_{TD,gat} \tag{18.107}$$

$$V_{bi,gat} = U_{bi,gat} + \phi_{TD} \cdot \ln\left[1 + \exp\left(\frac{V_{bi,low} - U_{bi,gat}}{\phi_{TD}}\right)\right] \tag{18.108}$$

Determination of $V_{F,min}$ and V_{ch}

$$V_{bi,min} = \min(V_{bi,bot}, V_{bi,sti}, V_{bi,gat}) \tag{18.109}$$

Note: in taking this minimum, only Vbi of the relevant contributions are taken into account. For example, when **AB** = 0, $V_{bi,bot}$ is not taken into account.

$$V_{F,min} = \begin{cases} V_{bi,min} \cdot (1 - a^{-1/\mathbf{PBOT}}) & \text{if } V_{bi,min} = V_{bi,bot} \\ V_{bi,min} \cdot (1 - a^{-1/\mathbf{PSTI}}) & \text{if } V_{bi,min} = V_{bi,sti} \\ V_{bi,min} \cdot (1 - a^{-1/\mathbf{PGAT}}) & \text{if } V_{bi,min} = V_{bi,gat} \end{cases} \tag{18.110}$$

$$V_{ch} = \varepsilon_{ch} \cdot V_{bi,min} \tag{18.111}$$

Voltage difference V_{AK}

$$V_{AK} = \mathbf{TYPE} \cdot (V_A - V_K) \tag{18.112}$$

Junction charge

$$
\begin{aligned}
Q'_{j,bot} = Q'_j(&V_{AK} = V_{AK},\ T_{KR} = T_{KR},\ T_{KD} = T_{KD},\ \phi_{TD} = \phi_{TD},\\
&\phi_{GR} = \phi_{GR,bot},\ \phi_{GD} = \phi_{GD,bot},\ F_{TD} = F_{TD,bot},\\
&I_{DSAT} = I_{DSAT,bot},\ V_{bi} = V_{bi,bot},\ V_{bi,min} = V_{bi,min},\ V_{F,min} = V_{F,min},\\
&V_{ch} = V_{ch},\ \mathbf{VMAX} = \mathbf{VMAX},\ \mathbf{CJOR} = \mathbf{CJORBOT},\\
&\mathbf{VBIR} = \mathbf{VBIRBOT},\ \mathbf{P} = \mathbf{PBOT},\ \mathbf{CSRH} = \mathbf{CSRHBOT},\\
&\mathbf{XJUN} = 1,\ \mathbf{CTAT} = \mathbf{CTATBOT},\\
&\mathbf{MEFFTAT} = \mathbf{MEFFTATBOT},\ \mathbf{CBBT} = \mathbf{CBBTBOT},\\
&\mathbf{FBBTR} = \mathbf{FBBTRBOT},\ \mathbf{STFBBT} = \mathbf{STFBBTBOT},\\
&\mathbf{VBR} = \mathbf{VBRBOT},\ \mathbf{PBR} = \mathbf{PBRBOT}\ )
\end{aligned}
\tag{18.113}
$$

$$
\begin{aligned}
Q'_{j,sti} = Q'_j(&V_{AK} = V_{AK},\ T_{KR} = T_{KR},\ T_{KD} = T_{KD},\ \phi_{TD} = \phi_{TD},\\
&\phi_{GR} = \phi_{GR,sti},\ \phi_{GD} = \phi_{GD,sti},\ F_{TD} = F_{TD,sti},\\
&I_{DSAT} = I_{DSAT,sti},\ V_{bi} = V_{bi,sti},\ V_{bi,min} = V_{bi,min},\ V_{F,min} = V_{F,min},\\
&V_{ch} = V_{ch},\ \mathbf{VMAX} = \mathbf{VMAX},\ \mathbf{CJOR} = \mathbf{CJORSTI},\\
&\mathbf{VBIR} = \mathbf{VBIRSTI},\ \mathbf{P} = \mathbf{PSTI},\ \mathbf{CSRH} = \mathbf{CSRHSTI},\\
&\mathbf{XJUN} = \mathbf{XJUNSTI},\ \mathbf{CTAT} = \mathbf{CTATSTI},\\
&\mathbf{MEFFTAT} = \mathbf{MEFFTATSTI},\ \mathbf{CBBT} = \mathbf{CBBTSTI},\\
&\mathbf{FBBTR} = \mathbf{FBBTRSTI},\ \mathbf{STFBBT} = \mathbf{STFBBTSTI},\\
&\mathbf{VBR} = \mathbf{VBRSTI},\ \mathbf{PBR} = \mathbf{PBRSTI}\ )
\end{aligned}
\tag{18.114}
$$

$$Q'_{j,gat} = Q'_j(V_{AK} = V_{AK},\ \ T_{KR} = T_{KR},\ \ T_{KD} = T_{KD},\ \ \phi_{TD} = \phi_{TD},\ \ \phi_{GR} = \phi_{GR,gat},\ \ \phi_{GD} = \phi_{GD,gat},\ \ F_{TD} = F_{TD,gat},\ \ I_{DSAT} = I_{DSAT,gat},\ \ V_{bi} = V_{bi,gat},\ \ V_{bi,min} = V_{bi,min},\ \ V_{F,min} = V_{F,min},\ \ V_{ch} = V_{ch},\ \ \mathbf{VMAX} = \mathbf{VMAX},\ \ \mathbf{CJOR} = \mathbf{CJORGAT},\ \ \mathbf{VBIR} = \mathbf{VBIRGAT},\ \ \mathbf{P} = \mathbf{PGAT},\ \ \mathbf{CSRH} = \mathbf{CSRHGAT},\ \ \mathbf{XJUN} = \mathbf{XJUNGAT},\ \ \mathbf{CTAT} = \mathbf{CTATGAT},\ \ \mathbf{MEFFTAT} = \mathbf{MEFFTATGAT},\ \ \mathbf{CBBT} = \mathbf{CBBTGAT},\ \ \mathbf{FBBTR} = \mathbf{FBBTRGAT},\ \ \mathbf{STFBBT} = \mathbf{STFBBTGAT},\ \ \mathbf{VBR} = \mathbf{VBRGAT},\ \ \mathbf{PBR} = \mathbf{PBRGAT}\ ) \tag{18.115}$$

$$Q_j = \mathbf{TYPE} \cdot \mathbf{MULT} \cdot (\mathbf{AB} \cdot Q'_{j,bot} + \mathbf{LS} \cdot Q'_{j,sti} + \mathbf{LG} \cdot Q'_{j,gat}) \tag{18.116}$$

Junction current

$$I'_{j,bot} = I'_j(V_{AK} = V_{AK},\ \ T_{KR} = T_{KR},\ \ T_{KD} = T_{KD},\ \ \phi_{TD} = \phi_{TD},\ \ \phi_{GR} = \phi_{GR,bot},\ \ \phi_{GD} = \phi_{GD,bot},\ \ F_{TD} = F_{TD,bot},\ \ I_{DSAT} = I_{DSAT,bot},\ \ V_{bi} = V_{bi,bot},\ \ V_{bi,min} = V_{bi,min},\ \ V_{F,min} = V_{F,min},\ \ V_{ch} = V_{ch},\ \ \mathbf{VMAX} = \mathbf{VMAX},\ \ \mathbf{CJOR} = \mathbf{CJORBOT},\ \ \mathbf{VBIR} = \mathbf{VBIRBOT},\ \ \mathbf{P} = \mathbf{PBOT},\ \ \mathbf{CSRH} = \mathbf{CSRHBOT},\ \ \mathbf{XJUN} = 1,\ \ \mathbf{CTAT} = \mathbf{CTATBOT},\ \ \mathbf{MEFFTAT} = \mathbf{MEFFTATBOT},\ \ \mathbf{CBBT} = \mathbf{CBBTBOT},\ \ \mathbf{FBBTR} = \mathbf{FBBTRBOT},\ \ \mathbf{STFBBT} = \mathbf{STFBBTBOT},\ \ \mathbf{VBR} = \mathbf{VBRBOT},\ \ \mathbf{PBR} = \mathbf{PBRBOT}\ ) \tag{18.117}$$

$$I'_{j,sti} = I'_j(V_{AK} = V_{AK},\ T_{KR} = T_{KR}, T_{KD} = T_{KD},\ \phi_{TD} = \phi_{TD},$$
$$\phi_{GR} = \phi_{GR,sti},\ \phi_{GD} = \phi_{GD,sti},\ F_{TD} = F_{TD,sti},$$
$$I_{DSAT} = I_{DSAT,sti},\ V_{bi} = V_{bi,sti},\ V_{bi,min} = V_{bi,min},\ V_{F,min} = V_{F,min},$$
$$V_{ch} = V_{ch},\ \mathbf{VMAX} = \mathbf{VMAX},\ \mathbf{CJOR} = \mathbf{CJORSTI},$$
$$\mathbf{VBIR} = \mathbf{VBIRSTI},\ \mathbf{P} = \mathbf{PSTI},\ \mathbf{CSRH} = \mathbf{CSRHSTI},$$
$$\mathbf{XJUN} = \mathbf{XJUNSTI},\ \mathbf{CTAT} = \mathbf{CTATSTI},$$
$$\mathbf{MEFFTAT} = \mathbf{MEFFTATSTI},\ \mathbf{CBBT} = \mathbf{CBBTSTI},$$
$$\mathbf{FBBTR} = \mathbf{FBBTRSTI},\ \mathbf{STFBBT} = \mathbf{STFBBTSTI},$$
$$\mathbf{VBR} = \mathbf{VBRSTI},\ \mathbf{PBR} = \mathbf{PBRSTI}\ ) \tag{18.118}$$

$$I'_{j,gat} = I'_j(V_{AK} = V_{AK},\ T_{KR} = T_{KR},\ T_{KD} = T_{KD},\ \phi_{TD} = \phi_{TD},$$
$$\phi_{GR} = \phi_{GR,gat},\ \phi_{GD} = \phi_{GD,gat},\ F_{TD} = F_{TD,gat},$$
$$I_{DSAT} = I_{DSAT,gat},\ V_{bi} = V_{bi,gat},\ V_{bi,min} = V_{bi,min},\ V_{F,min} = V_{F,min},$$
$$V_{ch} = V_{ch},\ \mathbf{VMAX} = \mathbf{VMAX},\ \mathbf{CJOR} = \mathbf{CJORGAT},$$
$$\mathbf{VBIR} = \mathbf{VBIRGAT},\ \mathbf{P} = \mathbf{PGAT},\ \mathbf{CSRH} = \mathbf{CSRHGAT},$$
$$\mathbf{XJUN} = \mathbf{XJUNGAT},\ \mathbf{CTAT} = \mathbf{CTATGAT},$$
$$\mathbf{MEFFTAT} = \mathbf{MEFFTATGAT},\ \mathbf{CBBT} = \mathbf{CBBTGAT},$$
$$\mathbf{FBBTR} = \mathbf{FBBTRGAT},\ \mathbf{STFBBT} = \mathbf{STFBBTGAT},$$
$$\mathbf{VBR} = \mathbf{VBRGAT},\ \mathbf{PBR} = \mathbf{PBRGAT}\ ) \tag{18.119}$$

$$I_j = \mathbf{TYPE} \cdot \mathbf{MULT} \cdot (\mathbf{AB} \cdot I'_{j,bot} + \mathbf{LS} \cdot I'_{j,sti} + \mathbf{LG} \cdot I'_{j,gat}) \tag{18.120}$$

Junction noise

$$S_I = 2 \cdot q \cdot |I_j| \tag{18.121}$$

18.2.6 Auxiliary equations

In this section, the hyp-functions that are used in the JUNCAP model equations are defined. These functions have been adopted from MOS Model 9, and their naming is consistent with the MOS Model 9 description [32]. The functions hyp1, hyp2, and hyp5 are given by Eqs. (18.122), (18.123), and (18.124), respectively, and illustrated in Figs. 81, 82, and 83, respectively.

$$\mathrm{hyp}_1(x;\varepsilon) = \frac{1}{2}\cdot\left(x+\sqrt{x^2+4\cdot\varepsilon^2}\right) \tag{18.122}$$

$$\mathrm{hyp}_2(x;x_0,\varepsilon) = x-\mathrm{hyp}_1(x-x_0;\varepsilon) \tag{18.123}$$

$$\mathrm{hyp}_5(x;x_0,\varepsilon) = x_0-\mathrm{hyp}_1\left(x_0-x-\frac{\varepsilon^2}{x_0};\varepsilon\right) \tag{18.124}$$

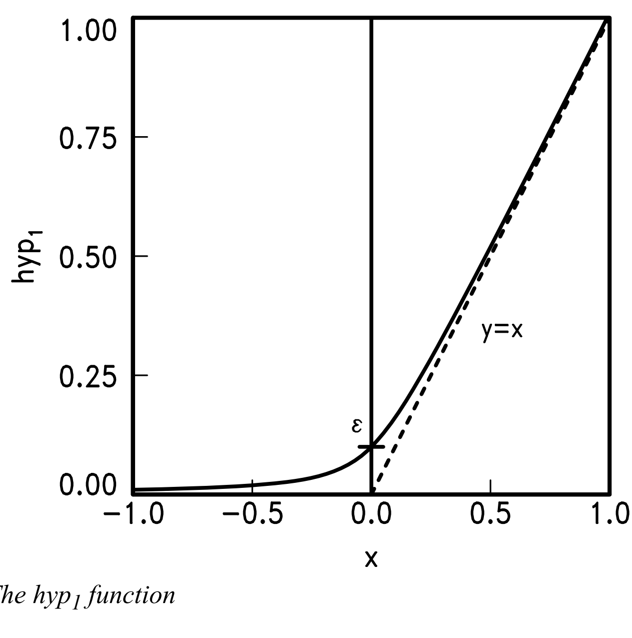


Figure 81: The hyp_1 function

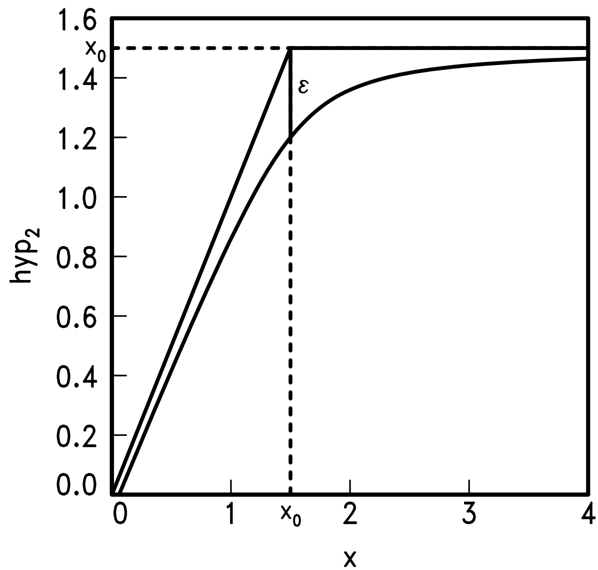


Figure 82: The hyp_2 function

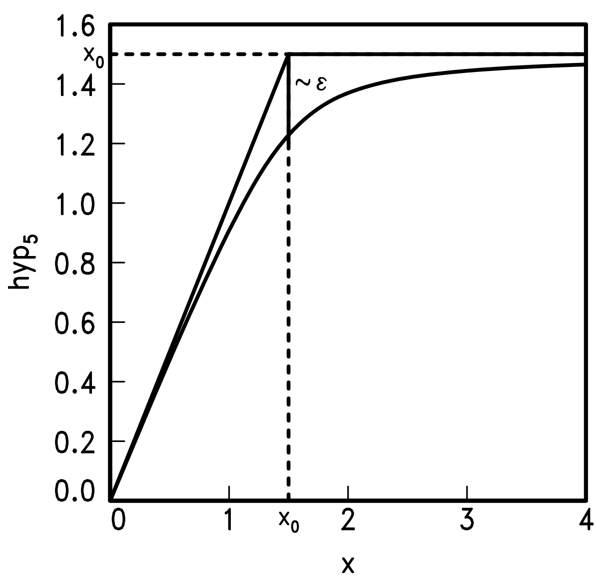


Figure 83: The hyp_5 function

18.2.7 DC operating point output

The DC operating point output facility gives information on the state of a device at its operating point.

No.	Name	Unit	Value	Description
0	**VAK**	V	$\mathbf{TYPE} \cdot V_{AK}$	voltage between anode and cathode
1	**CJ**	F	$\frac{\partial Q_j}{\partial V_{AK}}$	total junction capacitance
2	**CJBOT**	F	$\mathbf{TYPE} \cdot \mathbf{MULT} \cdot \mathbf{AB} \cdot \frac{\partial Q'_{j,bot}}{\partial V_{AK}}$	bottom component of the junction capacitance
3	**CJSTI**	F	$\mathbf{TYPE} \cdot \mathbf{MULT} \cdot \mathbf{LS} \cdot \frac{\partial Q'_{j,sti}}{\partial V_{AK}}$	STI-edge component of the junction capacitance
4	**CJGAT**	F	$\mathbf{TYPE} \cdot \mathbf{MULT} \cdot \mathbf{LG} \cdot \frac{\partial Q'_{j,gat}}{\partial V_{AK}}$	gate-edge component of the junction capacitance
5	**IJ**	A	I_j	total junction current
6	**IJBOT**	A	$\mathbf{TYPE} \cdot \mathbf{MULT} \cdot \mathbf{AB} \cdot I'_{j,bot}$	bottom component of the junction current
7	**IJSTI**	A	$\mathbf{TYPE} \cdot \mathbf{MULT} \cdot \mathbf{LS} \cdot I'_{j,sti}$	STI-edge component of the junction current
8	**IJGAT**	A	$\mathbf{TYPE} \cdot \mathbf{MULT} \cdot \mathbf{LG} \cdot I'_{j,gat}$	gate-edge component of the junction current
9	**SI**	A^2/Hz	S_I	total junction current noise spectral density

18.2.8 Simulator specific items

Pstar syntax

juncap_n (a,k) level=200, type=1, <parameters>
juncap_n (a,k) level=200, type=-1, <parameters>

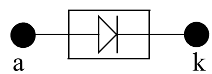
n	:	occurrence indicator
<parameters>	:	list of model parameters

a and k are anode and cathode terminals respectively.

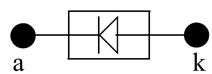
3 Note

The type parameter indicates the position of the diode.

When type = 1:



When type = -1:



The default type for Juncap level 200 is 1.

Spectre syntax

model modelname juncap200 type=n <modpar>
componentname a k modelname <inpar>
model modelname juncap200 type=p <modpar>
componentname a k modelname <inpar>

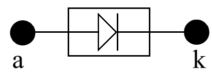
modelname	:	name of model, user defined
componentname	:	occurrence indicator
<modpar>	:	list of model parameters
<inpar>	:	list of instance parameters

a and k are anode and cathode terminals respectively.

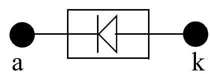
3 Note

The type parameter indicates the position of the diode.

When type = n:



When type = p:



The default type for Juncap level 200 is n.

Warning! In Spectre, use only the parameter statements type=`n` or type=`p`. Using any other string and/or numbers will result in unpredictable and possibly erroneous results.

ADS syntax

model modelname juncap200 gender=1 <modpar>
modelname: componentname a k <instpar>
model modelname juncap200 gender=-1 <modpar>
modelname: componentname a k <instpar>

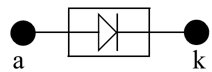
modelname	:	name of model, user defined
componentname	:	occurrence indicator
<modpar>	:	list of model parameters
<instpar>	:	list of instance parameters

a and k are anode and cathode terminals respectively.

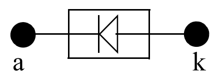
3 Note

The gender parameter indicates the position of the diode.

When gender = 1:



When gender = 0:



The default gender for Juncap level 200 is 1, which is n-type.

The ON/OFF condition for Pstar

The solution for a circuit involves a process of successive calculations. The calculations are started from a set of 'initial guesses' for the electrical quantities of the nonlinear elements. A simplified DCAPPROX mechanism for devices using ON/OFF keywords is given in [9]. By default the devices start in the off state.

JUNCAP2			
	Default	ON	OFF
V_{AK}	-0.1	0.7	-0.1

The ON/OFF condition for Spectre

JUNCAP2			
	Default	ON	OFF
V_{AK}	0.0	0.7	0.0

The ON/OFF condition for ADS

JUNCAP2			
	Default	ON	OFF
V_{AK}	0.0	0.0	0.0

18.2.9 Parameter extraction

Test structures

For extraction of JUNCAP2 parameters, one needs three different test structures, depicted schematically in Figure 84. The first structure is a simple, square diode, which has a large bottom component, a relatively small STI-edge component, and no gate-edge component. The second structure is a finger diode, which has a much larger STI-edge component, and no gate-edge component. The third structure is a Miller diode, which is nothing else than a multi-fingered MOSFET with source and drains tied together. It has a relatively small STI-edge component, and a significant gate-edge component. Besides the three test structures described here, which are needed for parameter extraction, one can optionally use additional geometries for verification purposes. The test structures should be sufficiently large so that currents and capacitances are easily measurable.

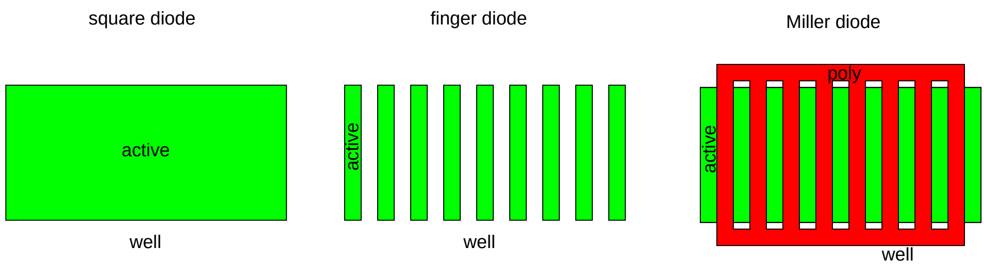


Figure 84: Schematic representation of three test structures needed for parameter extraction

Measurements

For extraction of JUNCAP2 parameters, one needs both *CV* and *IV* measurements. The *IV* data should be taken over a large range of temperatures, ranging from -40^{o}C to at least 125^{o}C. If available, even higher temperatures can be very helpful in the extraction because the junction current tends more and more to ideal behavior at higher temperatures.

Because the temperature dependence of capacitance is fairly low, it is possible (but not recommended) to restrict oneself to room-temperature *CV* measurements only. For optimal accuracy of the capacitance model however, measurements at different temperature are needed. Therefore it is recommended to take the *CV* data at the same temperatures as the *IV* data.

All *IV* measurements should be done from reverse bias $(-2 \cdot V_{supply})$ up to small forward bias (e.g. 0.5 V). If avalanche breakdown parameters need to be extracted, one needs to do additional measurements with a reverse bias much larger than the supply voltage. Because the JUNCAP2 model has no parameters to model temperature dependence of the breakdown, it suffices to do this breakdown characterization at room temperature. In the *IV* measurements, it is recommended to apply a current compliance (e.g. 10 mA) to avoid damaging the test structures when they are biased in the forward regime or in the avalanche breakdown regime.

The *CV* measurements should be done from reverse bias $(-2 \cdot V_{supply})$ up to zero bias. *CV* measurements in the forward mode of operation rapidly become unreliable because the phase angle starts to deviate from 90^o quickly. When the junction capacitance is measured on a Miller diode, the gate should be grounded.

Extraction of bottom, STI-edge, and gate-edge components

All measurements are carried out on three test structures. The measurements on these three structures are used to extract the three components (bottom, STI-edge, and gate-edge components) of either current or capacitance. For the capacitance, the extraction procedure will be outlined below.

For the capacitance of the square diode and finger diode, both having zero gate edge, we can write:

$$C_{j,square} = \mathbf{AB}_{square} \cdot C'_{j,bot} + \mathbf{LS}_{square} \cdot C'_{j,sti} \tag{18.125}$$

$$C_{j,finger} = \mathbf{AB}_{finger} \cdot C'_{j,bot} + \mathbf{LS}_{finger} \cdot C'_{j,sti} \tag{18.126}$$

For the Miller diode, we write:

$$C_{j,Miller} = \mathbf{AB}_{Miller} \cdot C'_{j,bot} + \mathbf{LS}_{Miller} \cdot C'_{j,sti} + \mathbf{LG}_{Miller} \cdot C'_{j,gat} \tag{18.127}$$

From eqs. (18.125) and (18.126) we straightforwardly solve the two unknowns $C'_{j,bot}$ and $C'_{j,sti}$:

$$C'_{j,bot} = \frac{\mathbf{LS}_{finger} \cdot C_{j,square} - \mathbf{LS}_{square} \cdot C_{j,finger}}{\mathbf{LS}_{finger} \cdot \mathbf{AB}_{square} - \mathbf{LS}_{square} \cdot \mathbf{AB}_{finger}} \tag{18.128}$$

$$C'_{j,sti} = \frac{\mathbf{AB}_{square} \cdot C_{j,finger} - \mathbf{AB}_{finger} \cdot C_{j,square}}{\mathbf{LS}_{finger} \cdot \mathbf{AB}_{square} - \mathbf{LS}_{square} \cdot \mathbf{AB}_{finger}} \qquad (18.129)$$

And now we can derive the final unknown quantity $C'_{j,gat}$ from Eq. (18.127).

$$C'_{j,gat} = \frac{C_{j,Miller} - \mathbf{AB}_{Miller} \cdot C'_{j,bot} - \mathbf{LS}_{Miller} \cdot C'_{j,sti}}{\mathbf{LG}_{Miller}} \qquad (18.130)$$

The procedure as outlined above is also applied to the junction currents, resulting in the current components $I'_{j,bot}$, $I'_{j,sti}$ and $I'_{j,gat}$.

Extraction of CV parameters

Having extracted the current and capacitance components as explained above, we are ready for the actual parameter extraction.

First, one has to set some general parameters:
– **LEVEL** is equal to 200 for the first release of the JUNCAP2 model. Possible successors will be 201, 202, etc.
– **TYPE** should be set properly to select either *n - p* or *p - n* junction.
– **DTA** should be set to zero
– **IMAX** should be set to a value which is large enough (e.g. larger than the highest forward current measured) so that it does not affect the extraction procedure.

Before *IV* parameter extraction is started, it is mandatory to perform the *CV* extraction first, because the *CV* parameters are used throughout the *IV* model. In other words, changing *CV* parameters after *IV* parameter extraction will change not only the *CV* curves, but also the *IV* curves.

The *CV* parameter extraction is basically the same for the three components. Therefore we will restrict the description to the bottom component. The **PHIGBOT** has to be initialized to a reasonable value, e.g. 1.16 V. (It will be fitted later on to the forward *IV* curves, but this usually has a negligible effect on the *CV* curves). From the *CV* curves one extracts three parameters per component:
– **CJORBOT**, i.e. the zero-bias capacitance per unit of area at the reference temperature. Its initial value is directly taken from the $C'_{j,bot}$ curves. One should select the curve $C'_{j,bot}$ measured at the temperature closest to the reference temperature, and use the zero-bias $C'_{j,bot}$ value of that curves as starting value for **CJORBOT**.
– **PBOT**, i.e. the grading coefficient. As starting value one can take **PBOT** = 0.5.

– **VBIRBOT**, i.e. the junction built-in voltage at the reference temperature. As starting value one can take **VBIRBOT** = 1.

Using the starting values specified above, one can perform a least-square fit of these three parameters to the measured *CV* curves. Typical values for the grading coefficient are between 0.3 and 0.6. Typical values for the built-in voltage are between 0.5 V and 1.2 V (from physics, we know that this quantity may exceed the band gap voltage only slightly).

Extraction of IV parameters

Ideal-current parameters

The *IV* parameter extraction starts with the extraction of the ideal-current parameters, which are **IDSATRBOT** and **PHIGBOT** (we restrict ourselves again to the bottom component). The parameter **IDSATRBOT** has effect on the ideal current only. The parameter **PHIGBOT** is used throughout the model. The ideal-current parameters are extracted on those parts of the forward *IV* curves which shown nearly ideal behavior. These parts are selected using the ideality factor n_{bot} which can be determined from the forward *IV* measurements as follows:

$$n_{bot} = \phi_{TD} \cdot \frac{\partial I'_{j,bot}}{\partial V_{AK}} \tag{18.131}$$

For the fitting of the ideal-current parameters we select those measurement points, for which the ideality factor is reasonably close to 1. For instance, the criterion $n_{bot} > 0.9$ works well for this purpose. Because the parameter **PHIGBOT** has already been initialized to 1.16, we only need to worry about a starting value for **IDSATRBOT**. This starting value can be found by setting **IDSATRBOT** to 1, and calculate the average ratio of measured and modelled current in the region selected by the ideality-factor method. (Note: this can only be done successfully when **IMAX** is temporarily set to a huge value.) After this initialization, modelled and measured curves should be reasonably close and one can further optimize the parameters **IDSATRBOT** and **PHIGBOT** using a least-square fit of the model to the measurement points selected by the ideality-factor method.

Please note once more that this ideality factor is only a quantity directly derived from measurements. It is not a model parameter as in many other junction models.

Identification of leakage mechanisms

The next step is the extraction of the remaining leakage current parameters. First, one needs to get an idea which effects need to be included. Sometimes, only Shockley-Read-Hall and trap-assisted tunneling are relevant, sometimes only band-to-band-tunneling, sometimes both. To this purpose one may investigate the temperature dependence by inspection of the activation energy of the leakage currents, which is calculated (in eV) as follows:

$$E_{act} = \frac{\partial \ln(I'_{j,bot})}{\partial \phi_{TD}^{-1}} \quad (18.132)$$

An activation energy close to the bandgap (1.16 eV) is an indication that the current is ideal. An activation energy around half the bandgap is an indication that the current is dominated by Shockley-Read-Hall and trap-assisted tunneling. An activation energy well below half the bandgap is an indication that the current is dominated by band-to-band-tunneling.

Not only the temperature dependence (as expressed in terms of activation energy), but also the bias dependence is indicative for the mechanisms behind the observed reverse junction current. The ideal current has no bias dependence (for reverse biases in excess of a few times the thermal voltage). Shockley-Read-Hall and trap-assisted tunneling have much more significant bias dependence. For Shockley-Read-Hall, the bias dependence goes approximately as the square root of the voltage. For trap-assisted tunneling, due to the field-enhancement, the bias dependence is larger. The largest bias dependence however is seen in case of band-to-band tunneling.

In conclusion, inspection of both temperature and bias dependence of the reverse current helps to identify the relevant leakage mechanism(s) in the junction component under investigation.

Extraction Shockley-Read-Hall and trap-assisted tunneling parameters

The fitting of Shockley-Read-Hall and trap-assisted tunneling parameters goes as follows. First, one needs to initialize the relevant parameters:

1. **MEFFTATBOT** should be initialized to 0.25. It will be fitted to the data later and affects the bias dependence of the trap-assisted tunneling current.
2. **XJUNSTI** or **XJUNGAT** should be initialized to a physically reasonable value (between 10 and 100 nm for modern CMOS). There is obviously no **XJUN** for the bottom component.
3. **CTATBOT** = **CSRHBOT**. A good starting value is found as follows. First, set **CTATBOT** and **CSRHBOT** equal to 1 and calculate the junction current. The required starting value is now found by averaging the ratio of measured and modelled currents for those reverse-bias points which are selected using the activation-energy method. A suitable criterion to select those bias points is
   0.3 V < E_{act} < 0.7 V.

After this initialization the parameters **CTATBOT** = **CSRHBOT**, **MEFFTATBOT** are optimized by a least-square fit of the parameters to the measured data. For the STI-edge and gate-edge components also the parameters **XJUNSTI** resp. **XJUNGAT** may be optimized. Usually a good fit can be achieved while retaining the identity **CTATBOT** = **CSRHBOT**. The parameter **MEFFTATBOT** is sometimes seen to deviate from the value of 0.25 expected theoretically. One should be able to retain a physically reasonable value for the **XJUN** parameter, in case of STI-edge and gate-edge components, although it is difficult to retain the expected identity
XJUNSTI = **XJUNGAT**.

Extraction band-to-band tunneling parameters

If band-to-band tunneling is of importance, one needs to initialize the relevant parameters:

1. **FBBTRBOT** should be initialized to 1×10^{9} V/m. It will be fitted to the data later, and affects the bias dependence of the band-to-band tunneling current.
2. **STFBBTBOT** should be initialized to -1×10^{-3} . It will be fitted to the data later, and affects the temperature dependence dependence of the band-to-band tunneling current.
3. **CBBTBOT**. A good starting value is found as follows. First, set **CBBTBOT** to 1 and calculate the junction current. The required starting value is now found by averaging the ratio of measured and modelled currents for those reverse-bias points which are selected using the activation-energy method. A suitable criterion to select those bias points is $E_{act} < 0.2$ V.

After this initialization the parameters are optimized by a least-square fit of the parameters to the measured data.

Extraction avalanche breakdown parameters

The breakdown voltage **VBRBOT** is easily found by inspection of the breakdown measurement curves: at V = -**VBRBOT** a sharp increase in the current is observed. The parameter **PBRBOT** can be used to tune the onset to breakdown. Again, a least-squares curve fit can be used to get a good fit. It is important to check that the Shockley-Read-Hall, trap-assisted-tunneling, and band-to-band tunneling model extrapolate well to the regime of avalanche breakdown. Sometimes, one needs to tune the corresponding parameters slightly to accomplish this.

General extraction scheme

Here we list a general extraction scheme which should work for most junctions. But please be aware that parameter extraction can never be a “push-button” exercise. The parameter extraction may have to be adapted to specific cases.

1. Fit *CV* parameters;
2. Fit ideal current parameters;

3. Fit Shockley-Read-Hall and trap-assisted tunneling parameters;
4. Fit band-to-band tunneling parameters;
5. Fit full *IV* curves, except avalanche curve, once more with all relevant parameters;
6. Fit avalanche breakdown parameters;
7. Re-fit *CV* parameters (because bandgap voltage may have changed);
8. Re-fit full *IV* curves, except avalanche curve, once more with all relevant parameters, except the bandgap voltage: this is needed because the capacitance may have changed, which affects the current;
9. Calculate all model curves once more.

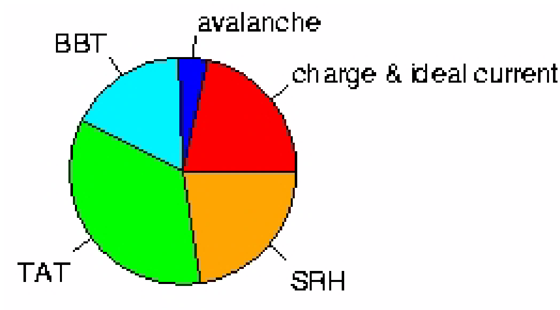
18.2.10Simulation time considerations

MOSFET junction models are computationally expensive by their very nature: every MOS-FEThas at least *two* junctions (source, drain); each junction has *three* components (bottom, STI-edge, gate-edge); each current component, in turn, can have as many as *five* different conduction mechanisms (ideal, SRH, TAT, BBT, avalanche). Moreover, the physics of junctions is ruled by computationally expensive functionssuch as powers and exponents.

JUNCAP2 has been constructed in such a way that calculations are skipped when junction components and/or current mechanisms are set to zero. For instance, when **BBT** is not needed in the bottom component of a junction, one can set **CBBTBOT** to zero, and the corresponding calculation is entirely skipped.

A considerable amount of simulation time can be saved when negligible current contributions are completely switched off in a parameter set that is being extracted. Thus, in the above-mentioned example, instead of leaving **CBBTBOT** at a small, negligible non-zero value, one should set **CBBTBOT** to exactly zero in order to avoid unnecessary function evaluations when the model is used by circuit designers.

Fig. 85, shows a typical result for the contribution of the various parts of the JUNCAP2 model to the total JUNCAP2 simulation time. (Note that the results may be different for different simulators or operating systems). It is observed that **SRH**, **TAT**, and **BBT** are very significant contributors to the overall JUNCAP2 simulation time. Therefore it is useful to check for each junction component (bottom, STI-edge, gate edge), whether it is possible to switch off one or more of these physical effects without affecting the model accuracy too much. It should be noted that switching off the **SRH** effect only decreases the simulation time when the corresponding **TAT** parameter is also switched off. The reason for this is that the **TAT** equations make use of quantities calculated in the **SRH** equations. Therefore the **SRH** part of the equations is also calculated when **SRH** is switched off and **TAT** is switched on. Switching off **TAT**, on the other hand, always decreases the simulation time, irrespective of the value of the corresponding **SRH** parameter.



charge model & ideal current	21.5 %
Shockley-Read-Hall	22.5 %
trap-assisted tunneling	34.9 %
band-to-band tunneling	17.0 %
avalanche breakdown	4.1 %

Figure 85: Typical distribution of simulation times over the various parts of the model. Results were obtained for JUNCAP2, level 200.1 using the Spectre circuit simulator and SiMKit 2.3.2 on a LINUX platform. Note that switching off the ideal current does not lead to significant CPU time savings.

Table 26 contains the JUNCAP2 features that are needed for a typical case. Typically, the number of current components needed is only half of the totally available current components. Often, the **BBT** component of the gate-edge component dominates the reverse leakage, in which case additional CPU time savings can be achieved by switching off **SRH** and **TAT** for this junction component.

Table 26: Guideline for which JUNCAP2 features to take into account in JUNCAP2 parameter extraction.

JUNCAP2 feature	geometrical components		
	gate-edge	STI-edge	bottom
capacitance	◦	◦	◦

ideal current	∘	∘	∘
SRH current	∘		∘
TAT current	∘		∘
BBT current	∘		
breakdown current	∘		

Table 27: How to switch off JUNCAP2 features.

JUNCAP2 feature	parameter value needed to switch off feature		
	gate-edge	STI-edge	bottom
ideal current	**IDSATRBOT** = 0	**IDSATRSTI** = 0	**IDSATRGAT** = 0
SRH current	**CSRHBOT** = 0	**CSRHSTI** = 0	**CSRHGAT** = 0
TAT current	**CTATBOT** = 0	**CTATSTI** = 0	**CTATGAT** = 0
BBT current	**CBBTBOT** = 0	**CBBTSTI** = 0	**CBBTGAT** = 0
breakdown current	**VBRBOT** > 1000	**VBRSTI** > 1000	**VBRGAT** > 1000

For completeness, we recapitulate here once more how to switch off the different current components (see also Table 27): for the bottom component, the ideal current, **SRH** current, **TAT** current, and **BBT** current are switched off by setting the **IDSATRBOT**, **CSRHBOT**, **CTATBOT** and **CBBTBOT** to zero, respectively. The breakdown model is skipped by setting **VBRBOT** to a value larger than 1000. The procedure for STI-edge and gate-edge currents is, *mutatis mutandis*, the same. Note that it is *not* possible to switch off junction capacitances, because in JUNCAP2 the junction capacitances are used internally to calculate electric fields, and thus influence the junction currents.

Finally, when a geometrical component is not needed, the corresponding instance parameter **AB**, **LS** or **LG** can be set to zero and the calculation for that component is completely skipped. An example is the well diode of a p-channel MOSFET which has no gate-edge contribution (**LG**=0).

