

19 Juncap2

19.1 JUNCAP2 Model

19.1.1 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 in more concise form (mathematically identical to previous version), see Eq. (19.12).

History of the documentation

April 2005 First release of JUNCAP2, level 200 documentation.

August 2005 Documentation updated for JUNCAP2, level 200.1 release. Section 19.1.6 has been added to document the so-called hyp-functions introduced in level 200.1.

19.1.2 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.semiconductors.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/

19.1.3 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 generation-recombination 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.

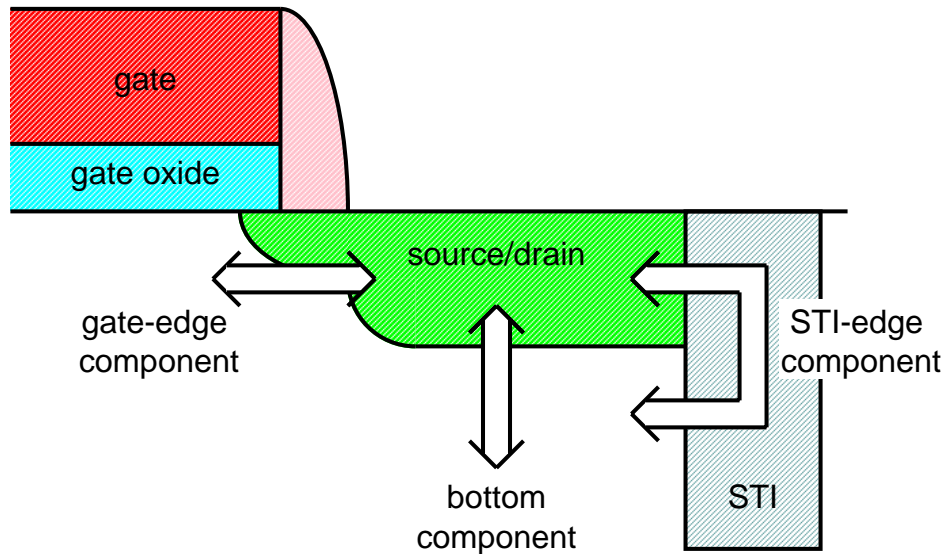


Figure 79: The three contributions to the source/drain junction of a MOSFET

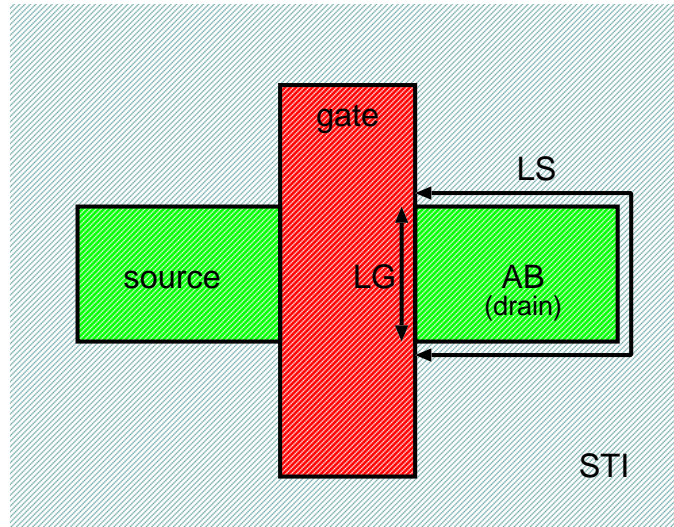


Figure 80: Schematic top view of the MOSFET. The meaning of the instance parameters **AB**, **LS**, and **LG** is indicated in the drain region

19.1.4 Parameters and constants

Physical constants

Symbol	Unit	Value	Description
T_0	K	273.15	Offset between Celcius and Kelvin Temperature scale
k_B	J/K	$1.3806505 \cdot 10^{-23}$	Boltzmann constant
q	C	$1.6021918 \cdot 10^{-19}$	elementary charge
h	Js	$1.05457168 \cdot 10^{-34}$	reduced Planck constant
m_0	kg	$9.1093826 \cdot 10^{-31}$	electron rest mass
ϵ_{Si}	F/m	$1.045 \cdot 10^{-10}$	absolute permittivity of silicon

Other constants

Symbol	Unit	Value	Description
T_{min}	°C	-250	minimum temperature for model equations
$V_{bi,low}$	V	0.050	lower boundary for built-in voltage
a	-	2	sets upper limit of forward capacitance to $a \cdot C_{jo}$
ϵ_{ch}	-	0.1	smoothing constant for charge model
ΔV_{bi}	-	0.050	voltage difference used in band-to-band tunneling model
ϵ_{av}	-	1×10^{-6}	smoothing constant for effective voltage in avalanche model
$V_{br,max}$	V	1×10^3	upper limit for VBR ; for larger values, avalanche model is switched off
α_{av}	-	0.999	below $-\alpha_{av} \cdot \mathbf{VBR}$ avalanche model is linearized

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

Instance parameters

Name	Unit	Default	Min.	Max.	Description
AB	m ²	1×10^{-12}	0	-	junction area
LS	m	1×10^{-6}	0	-	STI-edge part of junction perimeter
LG	m	1×10^{-6}	0	-	gate-edge part of junction perimeter
MULT	-	1	0	-	multiplication factor

Model parameters

Name	Unit	Default	Min.	Max.	Description
LEVEL	-	200	200	200	level must be 200
PARAMCHK	-	0	-	-	Level of clip warnings *)
TYPE ^a	-	1	-1	1	switch (-1 or 1) to select <i>p - n</i> or <i>n - p</i> junction
TRJ	°C	21	T_{min}	-	reference temperature
DTA	°C	0	-	-	temperature offset with respect to ambient temperature
IMAX	A	1000	1×10^{-12}	-	maximum current up to which forward current behaves exponentially

Capacitance parameters

CJORBOT	F/m ²	1×10^{-3}	1×10^{-12}	-	zero-bias capacitance per unit-of-area of bottom component
CJORSTI	F/m	1×10^{-9}	1×10^{-18}	-	zero-bias capacitance per unit-of-length of STI-edge component

CJORGAT	F/m	1×10^{-9}	1×10^{-18}	-	zero-bias capacitance per unit-of-length of gate-edge component
VBIRBOT	V	1	$V_{bi,low}$	-	built-in voltage at the reference temperature of bottom component
VBIRSTI	V	1	$V_{bi,low}$	-	built-in voltage at the reference temperature of STI-edge component
VBIRGAT	V	1	$V_{bi,low}$	-	built-in voltage at the reference temperature of gate-edge component
PBOT	-	0.5	0.05	0.95	grading coefficient of bottom component
PSTI	-	0.5	0.05	0.95	grading coefficient of STI-edge component
PGAT	-	0.5	0.05	0.95	grading coefficient of gate-edge component
Ideal-current parameters					
PHIGBOT	V	1.16	-	-	zero-temperature band-gap voltage of bottom component
PHIGSTI	V	1.16	-	-	zero-temperature band-gap voltage of STI-edge component
PHIGGAT	V	1.16	-	-	zero-temperature band-gap voltage of gate-edge component
IDSATRBOT	A/m ²	1×10^{-12}	0	-	saturation current density at the reference temperature of bottom component
IDSATRSTI	A/m	1×10^{-18}	0	-	saturation current density at the reference temperature of STI-edge component

IDSATRGAT	A/m	1×10^{-18}	0	-	saturation current density at the reference temperature of gate-edge component
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Shockley-Read-Hall parameters

CSRHBOT	A/m ³	1×10^2	0	-	Shockley-Read-Hall prefactor of bottom component
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CSRHSTI	A/m ²	1×10^{-4}	0	-	Shockley-Read-Hall prefactor of STI-edge component
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CSRHGAT	A/m ²	1×10^{-4}	0	-	Shockley-Read-Hall prefactor of gate-edge component
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XJUNSTI	m	1×10^{-7}	1×10^{-9}	-	junction depth of STI-edge component
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XJUNGAT	m	1×10^{-7}	1×10^{-9}	-	junction depth of gate-edge component
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Trap-assisted tunneling parameters

CTATBOT	A/m ³	1×10^2	0	-	trap-assisted tunneling prefactor of bottom component
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CTATSTI	A/m ³	1×10^{-4}	0	-	trap-assisted tunneling prefactor of STI-edge component
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CTATGAT	A/m ³	1×10^{-4}	0	-	trap-assisted tunneling prefactor of gate-edge component
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MEFFTATBOT	-	0.25	0.01	-	effective mass (in units of m_0) for trap-assisted tunneling of bottom component
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MEFFTATSTI	-	0.25	0.01	-	effective mass (in units of m_0) for trap-assisted tunneling of STI-edge component
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

CBBTBOT	AV^{-3}	1×10^{-12}	0	-	band-to-band tunneling prefactor of bottom component
CBBTSTI	$AV^{-3}m$	1×10^{-18}	0	-	band-to-band tunneling prefactor of STI-edge component
CBBTGAT	$AV^{-3}m$	1×10^{-18}	0	-	band-to-band tunneling prefactor of gate-edge component
FBBTRBOT	Vm^{-1}	1×10^9	-	-	normalization field at the reference temperature for band-to-band tunneling of bottom component
FBBTRSTI	Vm^{-1}	1×10^9	-	-	normalization field at the reference temperature for band-to-band tunneling of STI-edge component
FBBTRGAT	Vm^{-1}	1×10^9	-	-	normalization field at the reference temperature for band-to-band tunneling of gate-edge component
STFBBTBOT	K^{-1}	-1×10^{-3}	-	-	temperature scaling parameter for band-to-band tunneling of bottom component

STFBBTSTI	K ⁻¹	-1 × 10 ⁻³	-	-	temperature scaling parameter for band-to-band tunneling of STI-edge component
STFBBTGAT	K ⁻¹	-1 × 10 ⁻³	-	-	temperature scaling parameter for band-to-band tunneling of gateedge component

Avalanche and breakdown parameters

VBRBOT	V	10	0.1	-	breakdown voltage of bottom component
VBRSTI	V	10	0.1	-	breakdown voltage of STI-edge component
VBRGAT	V	10	0.1	-	breakdown voltage of gate-edge component
PBRBOT	V	4	0.1	-	breakdown onset tuning parameter of bottom component
PBRSTI	V	4	0.1	-	breakdown onset tuning parameter of STI-edge component
PBIGAT	V	4	0.1	-	breakdown onset tuning parameter of gate-edge component

a. For more details on the **TYPE** parameter, see section 19.1.8, titled “*Simulator specific items*”, on page 1149.

*) See Appendix B for the definition of PARAMCHK.

19.1.5 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 separately in section 19.1.6.

Input parameters of the juncap function

Name	Description
V_{AK}	in case TYPE = 1: voltage between anode (<i>p</i> -side) and cathode (<i>n</i> -side); in case TYPE = -1: voltage between cathode and anode
T_{KR}	reference temperature in Kelvin
T_{KD}	device temperature in Kelvin
ϕ_{TD}	thermal voltage at device temperature
ϕ_{GD}	bandgap voltage at device temperature
F_{TD}	intrinsic carrier concentration at device temperature, divided by that at reference temperature
I_{DSAT}	saturation current density of ideal current
V_{bi}	built-in voltage at the device temperature
$V_{bi,min}$	minimum V_{bi} of bottom, STI-edge, and gate-edge contribution
$V_{F,min}$	limiting voltage for charge model
V_{ch}	smoothing constant for transition $V_{F,min} \rightarrow V_{ch}$ in charge model
VMAX	maximum voltage up to which forward current behaves exponentially
CJOR	zero-bias capacitance per unit-of-area
VBIR	built-in voltage at the reference temperature
P	grading coefficient
CSRH	Shockley-Read-Hall prefactor

XJUN	junction depth
CTAT	trap-assisted tunneling prefactor
MEFFTAT	effective mass (in units of m_0) for trap-assisted tunneling
CBBT	band-to-band tunneling prefactor
FBTTR	normalization field at the reference temperature for band-to-band tunneling
STFBBT	temperature scaling parameter for band-to-band tunneling
VBR	breakdown voltage
PBR	breakdown onset tuning parameter

Outputs of the juncap function

Name	Description
I'_j	junction current per unit of area or length
Q'_j	junction charge per unit of area or length

Junction charge

$$C_{jo} = \mathbf{CJOR} \cdot \left(\frac{\mathbf{VBIR}}{V_{bi}} \right)^{\mathbf{P}} \quad (19.1)$$

$$V_j = \text{hyp}_5(V_{AK}; V_{F,min}, V_{ch}) \quad (19.2)$$

$$Q'_j = \left\{ \frac{C_{jo} \cdot V_{bi}}{1 - \mathbf{P}} \cdot \left[1 - \left(1 - \frac{V_j}{V_{bi}} \right)^{1 - \mathbf{P}} \right] + a \cdot C_{jo} \cdot (V_{AK} - V_j) \right\} \quad (19.3)$$

Ideal current

$$M_{ID} = \begin{cases} \exp\left(\frac{V_{AK}}{\phi_{TD}}\right) & \text{if } V_{AK} < V_{max} \\ \left(1 + \frac{V_{AK} - \mathbf{VMAX}}{\phi_{TD}}\right) \cdot \exp\left(\frac{\mathbf{VMAX}}{\phi_{TD}}\right) & \text{if } V_{AK} \geq V_{max} \end{cases} \quad (19.4)$$

$$I'_D = (M_{ID} - 1) \cdot I_{DSAT} \quad (19.5)$$

Shockley-Read-Hall current

Note: if **CSRH** = **CTAT** = 0, Eqs. (19.6)... (19.15) should be skipped and $I'_{SRH} = 0$.

$$z_{inv} = \sqrt{M_{ID}} \quad (19.6)$$

$$z = \frac{1}{z_{inv}} \quad (19.7)$$

$$\Psi^* = \begin{cases} \phi_{TD} \cdot \ln[z + 2 + \sqrt{(z + 1) \cdot (z + 3)}] & \text{if } V_{AK} > 0 \\ \frac{-V_{AK}}{2} + \phi_{TD} \cdot \ln[1 + 2 \cdot z_{inv} + \sqrt{(1 + z_{inv}) \cdot (1 + 3 \cdot z_{inv})}] & \text{if } V_{AK} \leq 0 \end{cases} \quad (19.8)$$

$$V_{j,lim} = V_{bi,min} - 2 \cdot \Psi^* \quad (19.9)$$

$$V_{j,SRH} = hyp_2(V_{AK}; V_{j,lim}, \phi_{TD}) \quad (19.10)$$

$$w_{SRH,step} = 1 - \sqrt{1 - \frac{2 \cdot \Psi^*}{V_{bi} - V_{j,SRH}}} \quad (19.11)$$

$$\Delta w_{SRH} = \left(\frac{w_{SRH,step}^2 \cdot \ln w_{SRH,step}}{1 - w_{SRH,step}} + w_{SRH,step} \right) \cdot (1 - 2 \cdot \mathbf{P}) \quad (19.12)$$

$$w_{SRH} = w_{SRH,step} + \Delta w_{SRH} \quad (19.13)$$

$$W_{dep} = \frac{\mathbf{XJUN} \cdot \epsilon_{Si}}{\mathbf{CJOR}} \cdot \left(\frac{V_{bi} - V_{j,SRH}}{\mathbf{VBIR}} \right)^{\mathbf{P}} \quad (19.14)$$

$$I'_{SRH} = \mathbf{CSRH} \cdot F_{TD} \cdot (z_{inv} - 1) \cdot w_{SRH} \cdot W_{dep} \quad (19.15)$$

Trap-assisted-tunelling current

Note: if $\mathbf{CTAT} = 0$, Eqs. (19.16)... (19.30) should be skipped and $I'_{TAT} = 0$.

$$F_{max} = \frac{V_{bi} - V_{j,SRH}}{W_{dep} \cdot (1 - \mathbf{P})} \quad (19.16)$$

$$m_{eff} = \mathbf{MEFFTAT} \cdot m_0 \quad (19.17)$$

$$\Delta E = \max\left(\frac{\phi_{GD}}{2}, \phi_{TD}\right) \quad (19.18)$$

$$a_{TAT} = \frac{\Delta E}{\phi_{TD}} \quad (19.19)$$

$$b_{TAT} = \sqrt{\frac{32 \cdot m_{eff} \cdot q \cdot \Delta E^3}{3 \cdot h \cdot F_{max}}} \quad (19.20)$$

$$u'_{max} = \left(\frac{2 \cdot a_{TAT}}{3 \cdot b_{TAT}} \right)^2 \quad (19.21)$$

$$u_{max} = \sqrt{\frac{u'_{max}{}^2}{u'_{max}{}^2 + 1}} \quad (19.22)$$

$$w_{\Gamma} = (1 + b_{TAT} \cdot u_{max}^{3/2})^{\frac{P}{P-1}} \quad (19.23)$$

$$w_{TAT} = \frac{w_{SRH} \cdot w_{\Gamma}}{w_{SRH} + w_{\Gamma}} \quad (19.24)$$

$$k_{TAT} = \sqrt{\frac{3 \cdot b_{TAT}}{8 \cdot \sqrt{u_{max}}}} \quad (19.25)$$

$$l_{TAT} = \frac{4 \cdot a_{TAT}}{3 \cdot b_{TAT}} \cdot \sqrt{u_{max}} - u_{max} \quad (19.26)$$

$$m_{TAT} = \frac{2 \cdot a_{TAT}{}^2}{3 \cdot b_{TAT}} \cdot \sqrt{u_{max}} - a_{TAT} \cdot u_{max} + \frac{b_{TAT}}{2} \cdot u_{max}^{3/2} \quad (19.27)$$

$$\text{erfcapprox}(y) = \begin{cases} t_{erfc} = \begin{cases} \frac{1}{1 + p_{erfc} \cdot y} & \text{if } y > 0 \\ \frac{1}{1 - p_{erfc} \cdot y} & \text{if } y \leq 0 \end{cases} \\ \text{erfcapprox}^+ = (a_{erfc} \cdot t_{erfc} + b_{erfc} \cdot t_{erfc}^2 + c_{erfc} \cdot t_{erfc}^3) \cdot \exp(-y^2) \\ \text{erfcapprox}(y) = \begin{cases} \text{erfcapprox}^+ & \text{if } y > 0 \\ 2 - \text{erfcapprox}^+ & \text{if } y \leq 0 \end{cases} \end{cases} \quad (19.28)$$

$$\Gamma_{max} = \frac{a_{TAT} \cdot \exp(m_{TAT}) \cdot \text{erfcapprox}[k_{TAT} \cdot (l_{TAT} - 1)] \cdot \sqrt{\pi}}{2 \cdot k_{TAT}} \quad (19.29)$$

$$I'_{TAT} = \mathbf{CTAT} \cdot F_{TD} \cdot (z_{inv} - 1) \cdot \Gamma_{max} \cdot w_{TAT} \cdot W_{dep} \quad (19.30)$$

Band-to-band tunnelling current

Note: if $\mathbf{CBBT} = 0$, Eqs. (19.33)... (19.36) should be skipped and $I'_{BBT} = 0$.

$$V_{BBT,lim} = \min(\mathbf{VBIRBOT}, \mathbf{VBIRSTI}, \mathbf{VBIRGAT}) - \Delta V_{bi} \quad (19.31)$$

$$V_{BBT} = \text{hyp}_2(V_{AK}, V_{BBT,lim}, \phi_{TR}) \quad (19.32)$$

$$W_{dep,r} = \frac{\mathbf{XJUN} \cdot \epsilon_{Si}}{\mathbf{CJOR}} \cdot \left(\frac{\mathbf{VBIR} - V_{BBT}}{\mathbf{VBIR}} \right)^P \quad (19.33)$$

$$F_{max,r} = \frac{\mathbf{VBIR} - V_{BBT}}{W_{dep,r} \cdot (1 - P)} \quad (19.34)$$

$$F_{BBT} = \mathbf{FBBTR} \cdot [1 + \mathbf{STFBBT} \cdot (T_{KD} - T_{KR})] \quad (19.35)$$

$$I'_{BBT} = \mathbf{CBBT} \cdot V_{AK} \cdot F_{max,r}^2 \cdot \exp\left(-\frac{F_{BBT}}{F_{max,r}}\right) \quad (19.36)$$

Avalanche and breakdown

Note: if $\mathbf{VBR} > V_{br,max}$, Eqs. (19.37)... (19.40) should be skipped and $f_{breakdown} = 1$.

$$V_{av} = \text{hyp}_2(V_{AK}; 0, \epsilon_{av}) \quad (19.37)$$

$$f_{stop} = \frac{1}{1 - \alpha_{av}^{\mathbf{PBR}}} \quad (19.38)$$

$$s_f = -f_{stop}^2 \cdot \alpha_{av}^{\mathbf{PBR}-1} \cdot \frac{\mathbf{PBR}}{\mathbf{VBR}} \quad (19.39)$$

$$f_{breakdown} = \begin{cases} \frac{1}{1 - \left| \frac{-V_{av}}{\mathbf{VBR}} \right|^{\mathbf{PBR}}} & \text{if } V_{av} > -\alpha_{av} \cdot \mathbf{VBR} \\ f_{stop} + (V_{av} + \alpha_{av} \cdot \mathbf{VBR}) \cdot s_f & \text{if } V_{av} \leq -\alpha_{av} \cdot \mathbf{VBR} \end{cases} \quad (19.40)$$

Total current

$$I'_j = (I'_D + I'_{SRH} + I'_{TAT} + I'_{BBT}) \cdot f_{breakdown} \quad (19.41)$$

The JUNCAP model

Thermal voltage

$$T_{KR} = T_0 + \mathbf{TJR} \quad (19.42)$$

$$T_{KD} = \max(T_0 + T_A + \mathbf{DTA}, T_0 + T_{min}) \quad (19.43)$$

$$\phi_{TR} = \frac{k_B \cdot T_{KR}}{q} \quad (19.44)$$

$$\phi_{TD} = \frac{k_B \cdot T_{KD}}{q} \quad (19.45)$$

Band gap

$$\Delta\phi_{GR} = -\frac{7.02 \cdot 10^{-4} \cdot T_{KR}^2}{1108.0 + T_{KR}} \quad (19.46)$$

$$\phi_{GR,bot} = \mathbf{PHIGBOT} + \Delta\phi_{GR} \quad (19.47)$$

$$\phi_{GR,sti} = \mathbf{PHIGSTI} + \Delta\phi_{GR} \quad (19.48)$$

$$\phi_{GR,gat} = \mathbf{PHIGGAT} + \Delta\phi_{GR} \quad (19.49)$$

$$\Delta\phi_{GD} = -\frac{7.02 \cdot 10^{-4} \cdot T_{KD}^2}{1108.0 + T_{KD}} \quad (19.50)$$

$$\phi_{GD,bot} = \mathbf{PHIGBOT} + \Delta\phi_{GD} \quad (19.51)$$

$$\phi_{GD,sti} = \mathbf{PHIGSTI} + \Delta\phi_{GD} \quad (19.52)$$

$$\phi_{GD,gat} = \mathbf{PHIGGAT} + \Delta\phi_{GD} \quad (19.53)$$

Intrinsic carrier concentration

$$F_{TD,bot} = \left(\frac{T_{KD}}{T_{KR}}\right)^{1.5} \cdot \exp\left(\frac{\phi_{GR,bot}}{2 \cdot \phi_{TR}} - \frac{\phi_{GD,bot}}{2 \cdot \phi_{TD}}\right) \quad (19.54)$$

$$F_{TD,sti} = \left(\frac{T_{KD}}{T_{KR}}\right)^{1.5} \cdot \exp\left(\frac{\phi_{GR,sti}}{2 \cdot \phi_{TR}} - \frac{\phi_{GD,sti}}{2 \cdot \phi_{TD}}\right) \quad (19.55)$$

$$F_{TD,gat} = \left(\frac{T_{KD}}{T_{KR}}\right)^{1.5} \cdot \exp\left(\frac{\phi_{GR,gat}}{2 \cdot \phi_{TR}} - \frac{\phi_{GD,gat}}{2 \cdot \phi_{TD}}\right) \quad (19.56)$$

Saturation current density at device temperature

$$I_{DSAT,bot} = \mathbf{IDSATRBOT} \cdot F_{TD,bot}^2 \quad (19.57)$$

$$I_{DSAT,sti} = \mathbf{IDSATRSTI} \cdot F_{TD,sti}^2 \quad (19.58)$$

$$I_{DSAT,gat} = \mathbf{IDSATRGAT} \cdot F_{TD,gat}^2 \quad (19.59)$$

Determination of V_{max}

$$V_{max,bot} = \begin{cases} V_{max,large} & \text{if } I_{DSAT,bot} \cdot \mathbf{AB} = 0 \\ \phi_{TD} \cdot \ln\left(\frac{\mathbf{IMAX}}{I_{DSAT,bot} \cdot \mathbf{AB}} + 1\right) & \text{if } I_{DSAT,bot} \cdot \mathbf{AB} \neq 0 \end{cases} \quad (19.60)$$

$$V_{max,sti} = \begin{cases} V_{max,large} & \text{if } I_{DSAT,sti} \cdot \mathbf{LS} = 0 \\ \phi_{TD} \cdot \ln\left(\frac{\mathbf{IMAX}}{I_{DSAT,sti} \cdot \mathbf{LS}} + 1\right) & \text{if } I_{DSAT,sti} \cdot \mathbf{LS} \neq 0 \end{cases} \quad (19.61)$$

$$V_{max,gat} = \begin{cases} V_{max,large} & \text{if } I_{DSAT,gat} \cdot \mathbf{LG} = 0 \\ \phi_{TD} \cdot \ln\left(\frac{\mathbf{IMAX}}{I_{DSAT,gat} \cdot \mathbf{LG}} + 1\right) & \text{if } I_{DSAT,gat} \cdot \mathbf{LG} \neq 0 \end{cases} \quad (19.62)$$

$$V_{max} = \min(V_{max,bot}, V_{max,sti}, V_{max,gat}) \quad (19.63)$$

Built-in voltages

$$U_{bi,bot} = \mathbf{VBIRBOT} \cdot \frac{T_{KD}}{T_{KR}} - 2 \cdot \phi_{TD} \cdot \ln F_{TD,bot} \quad (19.64)$$

$$V_{bi,bot} = U_{bi,bot} + \phi_{TD} \cdot \ln\left[1 + \exp\left(\frac{V_{bi,low} - U_{bi,bot}}{\phi_{TD}}\right)\right] \quad (19.65)$$

$$U_{bi,sti} = \mathbf{VBIRSTI} \cdot \frac{T_{KD}}{T_{KR}} - 2 \cdot \phi_{TD} \cdot \ln F_{TD,sti} \quad (19.66)$$

$$V_{bi,sti} = U_{bi,sti} + \phi_{TD} \cdot \ln \left[1 + \exp \left(\frac{V_{bi,low} - U_{bi,sti}}{\phi_{TD}} \right) \right] \quad (19.67)$$

$$U_{bi,gat} = \mathbf{VBIRGAT} \cdot \frac{T_{KD}}{T_{KR}} - 2 \cdot \phi_{TD} \cdot \ln F_{TD,gat} \quad (19.68)$$

$$V_{bi,gat} = U_{bi,gat} + \phi_{TD} \cdot \ln \left[1 + \exp \left(\frac{V_{bi,low} - U_{bi,gat}}{\phi_{TD}} \right) \right] \quad (19.69)$$

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

$$V_{bi,min} = \min(V_{bi,bot}, V_{bi,sti}, V_{bi,gat}) \quad (19.70)$$

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

$$V_{F,min} = \begin{cases} V_{bi,min} \cdot (1 - a^{-1/\mathbf{PBOT}}) & \text{if } V_{bi,min} = V_{bi,bot} \\ V_{bi,min} \cdot (1 - a^{-1/\mathbf{PSTI}}) & \text{if } V_{bi,min} = V_{bi,sti} \\ V_{bi,min} \cdot (1 - a^{-1/\mathbf{PGAT}}) & \text{if } V_{bi,min} = V_{bi,gat} \end{cases} \quad (19.71)$$

$$V_{ch} = \varepsilon_{ch} \cdot V_{bi,min} \quad (19.72)$$

Voltage difference V_{AK}

$$V_{AK} = \mathbf{TYPE} \cdot (V_A - V_K) \quad (19.73)$$

Junction charge

$$\begin{aligned}
Q'_{j,bot} = Q'_j & (V_{AK} = V_{AK}, T_{KR} = T_{KR}, T_{KD} = T_{KD}, \phi_{TD} = \phi_{TD}, \\
& \phi_{GR} = \phi_{GR,bot}, \phi_{GD} = \phi_{GD,bot}, F_{TD} = F_{TD,bot}, \\
I_{DSAT} = I_{DSAT,bot}, V_{bi} = V_{bi,bot}, V_{bi,min} = V_{bi,min}, V_{F,min} = V_{F,min}, \\
V_{ch} = V_{ch}, \mathbf{VMAX} = \mathbf{VMAX}, \mathbf{CJOR} = \mathbf{CJORBOT}, \\
\mathbf{VBIR} = \mathbf{VBIRBOT}, \mathbf{P} = \mathbf{PBOT}, \mathbf{CSRH} = \mathbf{CSRHBOT}, \\
\mathbf{XJUN} = 1, \mathbf{CTAT} = \mathbf{CTATBOT}, \\
\mathbf{MEFFTAT} = \mathbf{MEFFTATBOT}, \mathbf{CBBT} = \mathbf{CBBTBOT}, \\
\mathbf{FBBTR} = \mathbf{FBBTRBOT}, \mathbf{STFBBT} = \mathbf{STFBBTBOT}, \\
\mathbf{VBR} = \mathbf{VBRBOT}, \mathbf{PBR} = \mathbf{PBRBOT})
\end{aligned}
\tag{19.74}$$

$$\begin{aligned}
Q'_{j,sti} = Q'_j & (V_{AK} = V_{AK}, T_{KR} = T_{KR}, T_{KD} = T_{KD}, \phi_{TD} = \phi_{TD}, \\
& \phi_{GR} = \phi_{GR,sti}, \phi_{GD} = \phi_{GD,sti}, F_{TD} = F_{TD,sti}, \\
I_{DSAT} = I_{DSAT,sti}, V_{bi} = V_{bi,sti}, V_{bi,min} = V_{bi,min}, V_{F,min} = V_{F,min}, \\
V_{ch} = V_{ch}, \mathbf{VMAX} = \mathbf{VMAX}, \mathbf{CJOR} = \mathbf{CJORSTI}, \\
\mathbf{VBIR} = \mathbf{VBIRSTI}, \mathbf{P} = \mathbf{PSTI}, \mathbf{CSRH} = \mathbf{CSRHSTI}, \\
\mathbf{XJUN} = \mathbf{XJUNSTI}, \mathbf{CTAT} = \mathbf{CTATSTI}, \\
\mathbf{MEFFTAT} = \mathbf{MEFFTATSTI}, \mathbf{CBBT} = \mathbf{CBBTSTI}, \\
\mathbf{FBBTR} = \mathbf{FBBTRSTI}, \mathbf{STFBBT} = \mathbf{STFBBTSTI}, \\
\mathbf{VBR} = \mathbf{VBRSTI}, \mathbf{PBR} = \mathbf{PBRSTI})
\end{aligned}
\tag{19.75}$$

$$\begin{aligned}
Q'_{j,gat} = Q'_j & (V_{AK} = V_{AK}, T_{KR} = T_{KR}, T_{KD} = T_{KD}, \phi_{TD} = \phi_{TD}, \\
& \phi_{GR} = \phi_{GR,gat}, \phi_{GD} = \phi_{GD,gat}, F_{TD} = F_{TD,gat}, \\
& I_{DSAT} = I_{DSAT,gat}, V_{bi} = V_{bi,gat}, V_{bi,min} = V_{bi,min}, V_{F,min} = V_{F,min}, \\
& V_{ch} = V_{ch}, \mathbf{VMAX} = \mathbf{VMAX}, \mathbf{CJOR} = \mathbf{CJORGAT}, \\
& \mathbf{VBIR} = \mathbf{VBIRGAT}, \mathbf{P} = \mathbf{PGAT}, \mathbf{CSRH} = \mathbf{CSRHGAT}, \\
& \mathbf{XJUN} = \mathbf{XJUNGAT}, \mathbf{CTAT} = \mathbf{CTATGAT}, \\
& \mathbf{MEFFTAT} = \mathbf{MEFFTATGAT}, \mathbf{CBBT} = \mathbf{CBBTGAT}, \\
& \mathbf{FBBTR} = \mathbf{FBBTRGAT}, \mathbf{STFBBT} = \mathbf{STFBBTGAT}, \\
& \mathbf{VBR} = \mathbf{VBRGAT}, \mathbf{PBR} = \mathbf{PBRGAT})
\end{aligned} \tag{19.76}$$

$$Q_j = \mathbf{TYPE} \cdot \mathbf{MULT} \cdot (\mathbf{AB} \cdot Q'_{j,bot} + \mathbf{LS} \cdot Q'_{j,sti} + \mathbf{LG} \cdot Q'_{j,gat}) \tag{19.77}$$

Junction current

$$\begin{aligned}
I'_{j,bot} = I'_j & (V_{AK} = V_{AK}, T_{KR} = T_{KR}, T_{KD} = T_{KD}, \phi_{TD} = \phi_{TD}, \\
& \phi_{GR} = \phi_{GR,bot}, \phi_{GD} = \phi_{GD,bot}, F_{TD} = F_{TD,bot}, \\
& I_{DSAT} = I_{DSAT,bot}, V_{bi} = V_{bi,bot}, V_{bi,min} = V_{bi,min}, V_{F,min} = V_{F,min}, \\
& V_{ch} = V_{ch}, \mathbf{VMAX} = \mathbf{VMAX}, \mathbf{CJOR} = \mathbf{CJORBOT}, \\
& \mathbf{VBIR} = \mathbf{VBIRBOT}, \mathbf{P} = \mathbf{PBOT}, \mathbf{CSRH} = \mathbf{CSRHBOT}, \\
& \mathbf{XJUN} = 1, \mathbf{CTAT} = \mathbf{CTATBOT}, \\
& \mathbf{MEFFTAT} = \mathbf{MEFFTATBOT}, \mathbf{CBBT} = \mathbf{CBBTBOT}, \\
& \mathbf{FBBTR} = \mathbf{FBBTRBOT}, \mathbf{STFBBT} = \mathbf{STFBBTBOT}, \\
& \mathbf{VBR} = \mathbf{VBRBOT}, \mathbf{PBR} = \mathbf{PBRBOT})
\end{aligned} \tag{19.78}$$

$$\begin{aligned}
I'_{j,sti} &= I'_j(V_{AK} = V_{AK}, T_{KR} = T_{KR}, T_{KD} = T_{KD}, \phi_{TD} = \phi_{TD}, \\
&\phi_{GR} = \phi_{GR,sti}, \phi_{GD} = \phi_{GD,sti}, F_{TD} = F_{TD,sti}, \\
I_{DSAT} &= I_{DSAT,sti}, V_{bi} = V_{bi,sti}, V_{bi,min} = V_{bi,min}, V_{F,min} = V_{F,min}, \\
V_{ch} &= V_{ch}, \mathbf{VMAX} = \mathbf{VMAX}, \mathbf{CJOR} = \mathbf{CJORSTI}, \\
\mathbf{VBIR} &= \mathbf{VBIRSTI}, \mathbf{P} = \mathbf{PSTI}, \mathbf{CSRH} = \mathbf{CSRHSTI}, \\
\mathbf{XJUN} &= \mathbf{XJUNSTI}, \mathbf{CTAT} = \mathbf{CTATSTI}, \\
\mathbf{MEFFTAT} &= \mathbf{MEFFTATSTI}, \mathbf{CBBT} = \mathbf{CBBTSTI}, \\
\mathbf{FBBTR} &= \mathbf{FBBTRSTI}, \mathbf{STFBBT} = \mathbf{STFBBTSTI}, \\
\mathbf{VBR} &= \mathbf{VBRSTI}, \mathbf{PBR} = \mathbf{PBRSTI})
\end{aligned}
\tag{19.79}$$

$$\begin{aligned}
I'_{j,gat} &= I'_j(V_{AK} = V_{AK}, T_{KR} = T_{KR}, T_{KD} = T_{KD}, \phi_{TD} = \phi_{TD}, \\
&\phi_{GR} = \phi_{GR,gat}, \phi_{GD} = \phi_{GD,gat}, F_{TD} = F_{TD,gat}, \\
I_{DSAT} &= I_{DSAT,gat}, V_{bi} = V_{bi,gat}, V_{bi,min} = V_{bi,min}, V_{F,min} = V_{F,min}, \\
V_{ch} &= V_{ch}, \mathbf{VMAX} = \mathbf{VMAX}, \mathbf{CJOR} = \mathbf{CJORGAT}, \\
\mathbf{VBIR} &= \mathbf{VBIRGAT}, \mathbf{P} = \mathbf{PGAT}, \mathbf{CSRH} = \mathbf{CSRHGAT}, \\
\mathbf{XJUN} &= \mathbf{XJUNGAT}, \mathbf{CTAT} = \mathbf{CTATGAT}, \\
\mathbf{MEFFTAT} &= \mathbf{MEFFTATGAT}, \mathbf{CBBT} = \mathbf{CBBTGAT}, \\
\mathbf{FBBTR} &= \mathbf{FBBTRGAT}, \mathbf{STFBBT} = \mathbf{STFBBTGAT}, \\
\mathbf{VBR} &= \mathbf{VBRGAT}, \mathbf{PBR} = \mathbf{PBRGAT})
\end{aligned}
\tag{19.80}$$

$$I_j = \mathbf{TYPE} \cdot \mathbf{MULT} \cdot (\mathbf{AB} \cdot I'_{j,bot} + \mathbf{LS} \cdot I'_{j,sti} + \mathbf{LG} \cdot I'_{j,gat}) \tag{19.81}$$

Junction noise

$$S_I = 2 \cdot q \cdot |I_j| \tag{19.82}$$

19.1.6 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. (19.83), (19.84), and (19.85), respectively, and illustrated in Figs. 81, 82, and 83, respectively.

$$\text{hyp}_1(x; \varepsilon) = \frac{1}{2} \cdot (x + \sqrt{x^2 + 4 \cdot \varepsilon^2}) \quad (19.83)$$

$$\text{hyp}_2(x; x_0, \varepsilon) = x - \text{hyp}_1(x - x_0; \varepsilon) \quad (19.84)$$

$$\text{hyp}_5(x; x_0, \varepsilon) = x_0 - \text{hyp}_1\left(x_0 - x - \frac{\varepsilon^2}{x_0}; \varepsilon\right) \quad (19.85)$$

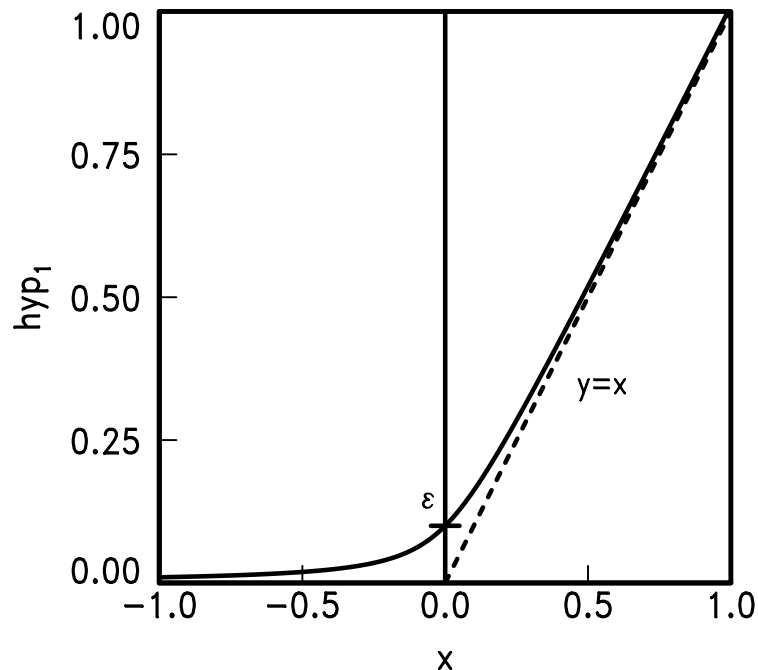


Figure 81: The hyp₁ function

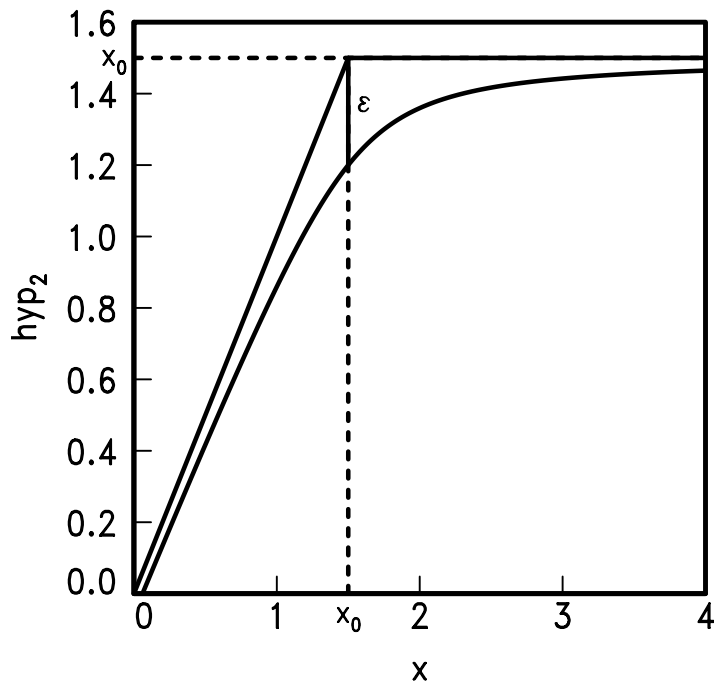


Figure 82: The hyp_2 function

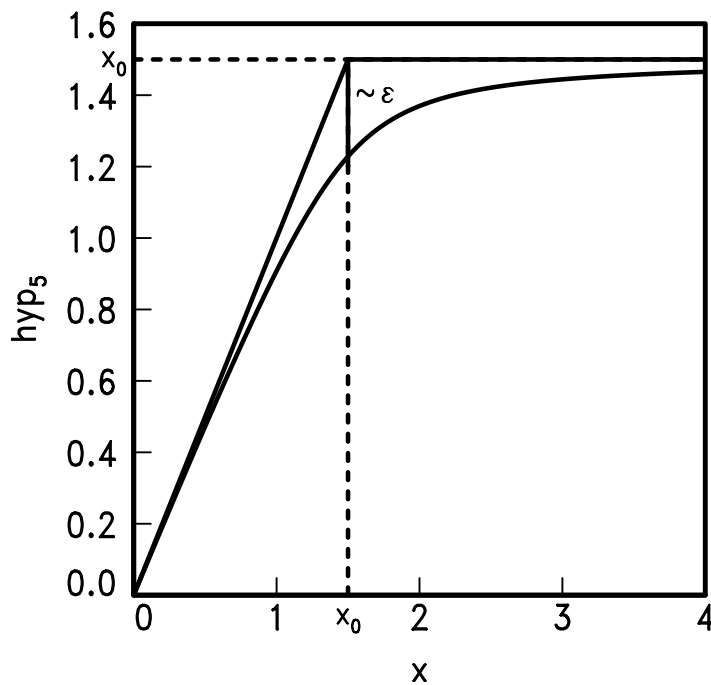


Figure 83: The hyp_5 function

19.1.7 DC operating point output

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

Name	Unit	Value	Description
VAK	V	$\text{TYPE} \cdot V_{AK}$	voltage between anode and cathode
CJ	F	$\frac{\partial Q_j}{\partial V_{AK}}$	total junction capacitance
CJBOT	F	$\text{TYPE} \cdot \text{MULT} \cdot \text{AB} \cdot \frac{\partial Q'_{j,bot}}{\partial V_{AK}}$	bottom component of the junction capacitance
CJSTI	F	$\text{TYPE} \cdot \text{MULT} \cdot \text{LS} \cdot \frac{\partial Q'_{j,sti}}{\partial V_{AK}}$	STI-edge component of the junction capacitance
CJGAT	F	$\text{TYPE} \cdot \text{MULT} \cdot \text{LG} \cdot \frac{\partial Q'_{j,gat}}{\partial V_{AK}}$	gate-edge component of the junction capacitance
IJ	A	I_j	total junction current
IJBOT	A	$\text{TYPE} \cdot \text{MULT} \cdot \text{AB} \cdot I'_{j,bot}$	bottom component of the junction current
IJSTI	A	$\text{TYPE} \cdot \text{MULT} \cdot \text{LS} \cdot I'_{j,sti}$	STI-edge component of the junction current
IJGAT	A	$\text{TYPE} \cdot \text{MULT} \cdot \text{LG} \cdot I'_{j,gat}$	gate-edge component of the junction current
SI	A ² / Hz	S_I	total junction current noise spectral density
IDSATSBOT	A	$\text{MULT} \cdot \text{AB} \cdot I_{DSAT,bot}$	total bottom saturation current at device temperature
IDSATSSTI	A	$\text{MULT} \cdot \text{LS} \cdot I_{DSAT,sti}$	total STI-edge saturation current at device temperature
IDSATSGAT	A	$\text{MULT} \cdot \text{LG} \cdot I_{DSAT,gat}$	total gate-edge saturation current at device temperature

CJOSBOT	F	$\text{MULT} \cdot \text{AB} \cdot C_{jo, bot}$	total bottom capacity at device temperature
CJOSSTI	F	$\text{MULT} \cdot \text{AB} \cdot C_{jo, sti}$	total STI-edge capacity at device temperature
CJOSGAT	F	$\text{MULT} \cdot \text{AB} \cdot C_{jo, gat}$	total gate-edge capacity at device temperature
VBISBOT	V	$V_{bi, bot}$	built-in voltage at device temperature
VBISSTI	V	$V_{bi, sti}$	built-in voltage at device temperature
VBISGAT	V	$V_{bi, gat}$	built-in voltage at device temperature

19.1.8 Simulator specific items

Pstar syntax

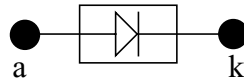
```
juncap_n (a,k) level=200, type=1, <parameters>
juncap_n (a,k) level=200, type=-1, <parameters>
```

n : occurrence indicator
 <parameters> : list of model parameters
 a and k are anode and cathode terminals respectively.

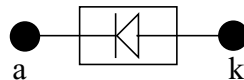
3 Note

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>
```

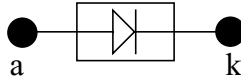
modelname : name of model, user defined
 componentname : occurrence indicator
 <modpar> : list of model parameters
 <inpar> : list of instance parameters

a and k are anode and cathode terminals respectively.

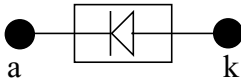
3 Note

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>
```

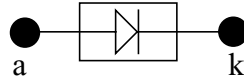
modelname	:	name of model, user defined
componentname	:	occurrence indicator
<modpar>	:	list of model parameters
<instpar>	:	list of instance parameters

a and k are anode and cathode terminals respectively.

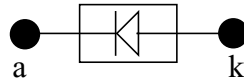
3 Note

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

19.1.9 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.

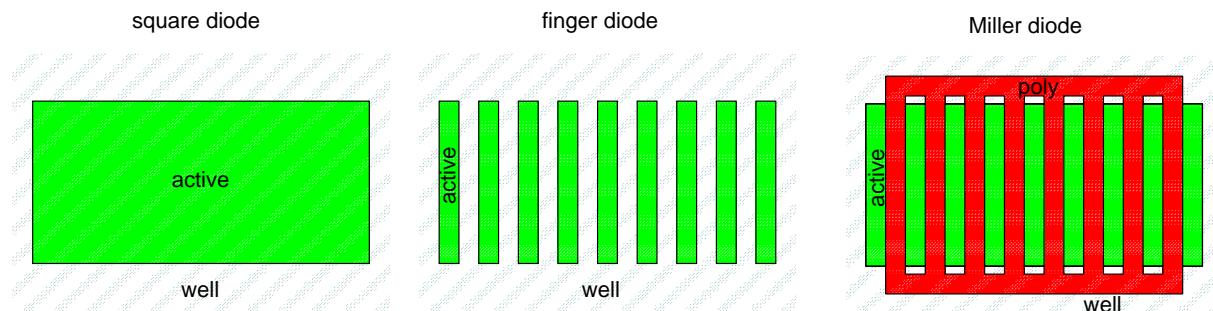


Figure 84: Schematic representation of three test structures needed for parameter extraction

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°C to at least 125°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° 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:

$$C_{j,square} = \mathbf{AB}_{square} \cdot C'_{j,bot} + \mathbf{LS}_{square} \cdot C'_{j,sti} \quad (19.86)$$

$$C_{j,finger} = \mathbf{AB}_{finger} \cdot C'_{j,bot} + \mathbf{LS}_{finger} \cdot C'_{j,sti} \quad (19.87)$$

For the Miller diode, we write:

$$C_{j,Miller} = \mathbf{AB}_{Miller} \cdot C'_{j,bot} + \mathbf{LS}_{Miller} \cdot C'_{j,sti} + \mathbf{LG}_{Miller} \cdot C'_{j,gat} \quad (19.88)$$

From eqs. (19.86) and (19.87) we straightforwardly solve the two unknowns $C'_{j,bot}$ and $C'_{j,sti}$:

$$C'_{j,bot} = \frac{\mathbf{LS}_{finger} \cdot C_{j,square} - \mathbf{LS}_{square} \cdot C_{j,finger}}{\mathbf{LS}_{finger} \cdot \mathbf{AB}_{square} - \mathbf{LS}_{square} \cdot \mathbf{AB}_{finger}} \quad (19.89)$$

$$C'_{j,sti} = \frac{\mathbf{AB}_{square} \cdot C_{j,finger} - \mathbf{AB}_{finger} \cdot C_{j,square}}{\mathbf{LS}_{finger} \cdot \mathbf{AB}_{square} - \mathbf{LS}_{square} \cdot \mathbf{AB}_{finger}} \quad (19.90)$$

And now we can derive the final unknown quantity $C'_{j,gat}$ from Eq. (19.88).

$$C'_{j,gat} = \frac{C_{j,Miller} - \mathbf{AB}_{Miller} \cdot C'_{j,bot} - \mathbf{LS}_{Miller} \cdot C'_{j,sti}}{\mathbf{LG}_{Miller}} \quad (19.91)$$

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:

$$n_{bot} = \phi_{TD} \cdot \frac{\partial I'_{j,bot}}{\partial V_{AK}} \quad (19.92)$$

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:

$$E_{act} = \frac{\partial \ln(I'_{j,bot})}{\partial \phi_{TD}^{-1}} \quad (19.93)$$

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 $0.3 \text{ V} < E_{act} < 0.7 \text{ V}$.

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. **FBTTRBOT** 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. **STFBTTRBOT** 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. **CBTTRBOT**. A good starting value is found as follows. First, set **CBTTRBOT** 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.

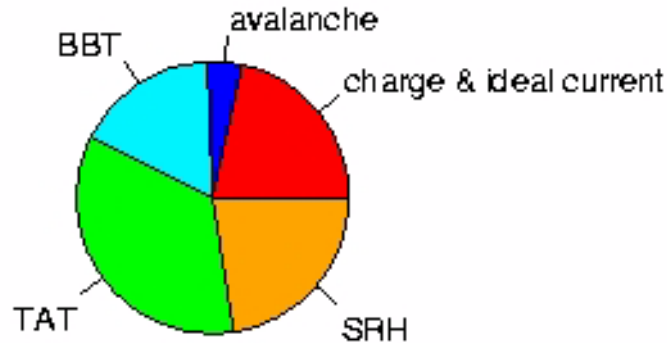
19.1.10 Simulation time considerations

MOSFET junction models are computationally expensive by their very nature: every MOSFET has 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 functions such 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).

A Spectre Specific Information

Imax, Imelt, Jmelt parameters

Introduction

Imax, Imelt and Jmelt are Spectre-specific parameters used to help convergence and to prevent numerical problems. We refer in this text only to the use of Imax model parameter in Spectre with SiMKit devices since the other two parameters, Imelt and Jmelt, are not part of the SiMKit code. For information on Imelt and Jmelt refer to Cadence documentation.

Imax model parameter

Imax is a model parameter present in the following SiMKit models:

- juncap and juncap2
- psp and pspnqs (since they contain juncap models)

In Mextram 504 (bjt504) and Modella (bjt500) SiMKit models, Imax is an internal parameter and its value is set through the adapter via the Spectre-specific parameter Imax.

The default value of the Imax model parameter is 1000A. Imax should be set to a value which is large enough so it does not affect the extraction procedure.

In models that contain junctions, the junction current can be expressed as:

$$I = I_s \exp\left(\frac{V}{N \cdot \phi_{TD}} - 1\right) \quad (19.94)$$

The exponential formula is used until the junction current reaches a maximum (explosion) current Imax.

$$I_{max} = I_s \exp\left(\frac{V_{expl}}{N \cdot \phi_{TD}} - 1\right) \quad (19.95)$$

The corresponding voltage for which this happens is called Vexpl (explosion voltage). The voltage explosion expression can be derived from (1):

$$V_{expl} = N \cdot \phi_{TD} \log\left(\frac{I_{max}}{I_s}\right) + 1 \quad (19.96)$$

For $V > V_{expl}$ the following linear expression is used for the junction current:

$$I = I_{max} + (V - V_{expl}) \frac{I_s}{N \cdot \phi_{TD}} \exp\left(\frac{V_{expl}}{N \cdot \phi_{TD}}\right) \quad (19.97)$$

Region parameter

Region is an Spectre-specific model parameter used as a convergence aid and gives an estimated DC operating region. The possible values of region depend on the model:

- For Bipolar models:
 - subth: Cut-off or sub-threshold mode
 - fwd: Forward
 - rev: Reverse
 - sat: Saturation.
 - off¹
 -
- For MOS models:
 - subth: Cut-off or sub-threshold mode;
 - triode: Triode or linear region;
 - sat: Saturation
 - off¹

For PSP and PSPNQS all regions are allowed, as the PSP(NQS) models both have a MOS part and a juncap (diode). Not all regions are valid for each part, but when e.g. region=forward is set, the initial guesses for the MOS will be set to zero. The same holds for setting a region that is not valid for the JUNCAP.

- For diode models:
 - fwd: Forward
 - rev: Reverse
 - brk: Breakdown
 - off¹

Model parameters for device reference temperature in Spectre

This text describes the use of the tnom, tref and tr model parameters in Spectre with SiMKit devices to set the device reference temperature.

¹.Off is not an electrical region, it just states that the user does not know in what state the device is operating

A Simkit device in Spectre has three model parameter aliases for the model reference temperature, `tnom`, `tref` and `tr`. These three parameters can only be used in a model definition, not as instance parameters.

There is no difference in setting `tnom`, `tref` or `tr`. All three parameters have exactly the same effect. The following three lines are therefore completely equivalent:

```
model nmos11020 mos11020 type=n tnom=30
model nmos11020 mos11020 type=n tref=30
model nmos11020 mos11020 type=n tr=30
```

All three lines set the reference temperature for the `mos11020` device to 30 C.

Specifying combinations of `tnom`, `tref` and `tr` in the model definition has no use, only the value of the last parameter in the model definition will be used. E.g.:

```
model nmos11020 mos11020 type=n tnom=30 tref=34
```

will result in the reference temperature for the `mos11020` device being set to 34 C, `tnom=30` will be overridden by `tref=34` which comes after it.

When there is no reference temperature set in the model definition (so no `tnom`, `tref` or `tr` is set), the reference temperature of the model will be set to the value of `tnom` in the options statement in the Spectre input file. So setting:

```
options1 options tnom=23 gmin=1e-15 reltol=1e-12 \
  vabstol=1e-12 iabstol=1e-16
model nmos11020 mos11020 type=n
```

will set the reference temperature of the `mos11020` device to 23 C.

When no `tnom` is specified in the options statement and no reference temperature is set in the model definition, the default reference temperature is set to 27 C.

So the lines:

```
options1 options gmin=1e-15 reltol=1e-12 vabstol=1e-12 \
  iabstol=1e-16
model nmos11020 mos11020 type=n
```

will set the reference temperature of the `mos11020` device to 27 C.

The default reference temperature set in the SiMKit device itself is in the Spectre simulator never used. It will always be overwritten by either the default "options tnom", an explicitly set option tnom or by a tnom, tref or tr parameter in the model definition.

B Parameter PARAMCHK

Parameter PARAMCHK

Introduction

All models have the parameter PARAMCHK. It is not related to the model behavior, but has been introduced control the clip warning messages. Various situations may call for various levels of warnings. This is made possible by setting this parameter.

PARAMCHK model parameter

This model parameter has been added to control the amount of clip warnings.

PARAMCHK	<	0	No clip warnings
PARAMCHK	≥	0	Clip warnings for instance parameters (default)
PARAMCHK	≥	1	Clip warnings for model parameters
PARAMCHK	≥	2	Clip warnings for electrical parameters at initialisation
PARAMCHK	≥	3	Clip warnings for electrical parameters during evaluation. This highest level is of interest only for selfheating jobs, where electrical parameters may change dependent on temperature.