Genius

Semiconductor Device Simulator

Version 1.7.4

Genius User's Guide

Cgenda Pte Ltd

Contents

CHAPTER 1

Physics in Genius Device Simulator

Since Gummel's original work, the drift-diffusion model has been widely used in the semiconductor device simulation. It is now the de facto industry standard in this field.

The original DD model can be achieved by following approximation from hydrodynamic model:

- Light speed is much faster than carrier speed.
- All the collision is elastic.
- Bandgap does not change during collision.
- Carrier temperature equals to lattice temperature and keeps equilibrium.
- The gradient of driving force should keep small.
- Carrier degenerate can be neglected.

Some improvements have been applied to DD model for extend its capability. These "patches" of course make things complex, but they can deal with real problems.

This chapter describes the DD model and its variations used by GENIUS code for describing semiconductor device behavior as well as physical based parameters such as mobility, recombination rate and son on.

Some improvements have been applied to DD model for extend its capability. These "patches" of course make things complex, but they can deal with real problems.

$$\nabla \cdot \varepsilon \nabla \psi = -q \left(p - n + {N_D}^+ - {N_A}^- \right) \tag{1.1}$$

where, ψ is the electrostatic potential of the vacuum level. This choice makes the description of metal-oxide-semiconductor contact and heterojunction easier. n and p are the electron and hole concentration, ${N_D}^+$ and ${N_A}^-$ are the ionized impurity concentrations. q is the magnitude of the charge of an electron.

The relationship of conduct band E_c, valence band E_v and vacuum level ψ is:

$$E_c = -q\psi - \chi - \Delta E_c \tag{1.2}$$
$$E_v = E_c - E_g + \Delta E_v. \tag{1.3}$$

Level 1 Drift-Diffusion Equation

Level 1 Drift-Diffusion (DDML1) is the fundamental solver of GENIUS code for lattice temperature keeps constant though out the solve procedure.

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Poisson's Equation

$$\nabla \cdot \varepsilon \nabla \psi = -q \left(p - n + {N_D}^+ - {N_A}^- \right) \tag{1.4}$$

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The relationship of conduct band E_c, valence band E_v and vacuum level ψ is:

$$E_c = -q\psi - \chi - \Delta E_c \tag{1.5a}$$
$$E_v = E_c - E_g + \Delta E_v. \tag{1.5b}$$

Here, χ is the electron affinity. E_g is the bandgap of semiconductor. ΔE_c and ΔE_v are the bandgap shift caused by heavy doping or mechanical strain.

Furthermore, the relationship of vacuum level ψ and intrinsic Fermi potential $\psi_{\text{intrinsic}}$ is:

$$\psi = \psi_{\text{intrinsic}} - \frac{\chi}{q} - \frac{E_g}{2q} - \frac{k_b T}{2q} \ln\left(\frac{N_c}{N_v}\right) \tag{1.6}$$

The reference 0eV of energy is set to intrinsic Fermi level of equilibrium state in GENIUS.

Continuity Equations

The continuity equations for electrons and holes are defined as follows:

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla \cdot \vec{J_n} - (U - G) \tag{1.7a}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla \cdot \vec{J_p} - (U - G) \tag{1.7b}$$

where $\vec{J_n}$ and $\vec{J_p}$ are the electron and hole current densities, U and G are the recombination and generation rates for both electrons and holes.

Drift-Diffusion Current Equations

The current densities $\vec{J_n}$ and $\vec{J_p}$ are expressed in terms of the level 1 drift-diffusion model here.

$$\vec{J_n} = q\mu_n n\vec{E}_n + qD_n\nabla n \tag{1.8a}$$

$$\vec{J_p} = q\mu_p p\vec{E}_p - qD_p\nabla p \tag{1.8b}$$

where μ_n and μ_p are the electron and hole mobilities. $D_n = \frac{k_bT}{q}\mu_n$ and $D_p = \frac{k_bT}{q}\mu_p$ are the electron and hole diffusivities, according to Einstein relationship.

Effective Electrical Field

$\vec{E}_n$ and $\vec{E}_p$ are the effective driving electrical field to electrons and holes, which related to local band diagram. The band structure of heterojunction has been taken into account here [**?**].

$$\vec{E}_n = \frac{1}{q}\nabla E_c - \frac{k_bT}{q}\nabla\left(\ln(N_c) - \ln(T^{3/2})\right) \tag{1.9a}$$

$$\vec{E}_p = \frac{1}{q}\nabla E_v + \frac{k_bT}{q}\nabla\left(\ln(N_v) - \ln(T^{3/2})\right) \tag{1.9b}$$

The lattice temperature keeps uniform throughout DDML1, the above temperature gradient item takes no effect in fact.

By substituting drift-diffusion model into the current density expressions, and combining with Poisson's equation, the following basic equations for DDML1 are obtained:

$$\frac{\partial n}{\partial t} = \nabla \cdot \left(\mu_n n\vec{E}_n + \mu_n\frac{k_bT}{q}\nabla n\right) - (U - G) \tag{1.10a}$$

$$\frac{\partial p}{\partial t} = -\nabla \cdot \left(\mu_p p\vec{E}_p - \mu_p\frac{k_bT}{q}\nabla p\right) - (U - G) \tag{1.10b}$$

$$\nabla \cdot \varepsilon\nabla\psi = -q(p - n + {N_D}^+ - {N_A}^-) \tag{1.10c}$$

DDML1 is suitable for PN diode, BJT transistor and long gate MOSFET simulation. It is robust, and runs pretty fast for real work. The detailed discretization scheme can be found at [[TODO]].

Level 2 Drift-Diffusion Equation

The Level 2 DD model considers the influence of lattice temperature by solving the extra thermal equation simultaneously with the electrical equations. Also, the formula of drift-diffusion equation should be modified according to [**?**].

The electron diffusion current in DDML1 can be written as:

$$\vec{J}_{n,\text{diff}} = \frac{k_b T}{q}\mu_n q \nabla n = k_b T \mu_n \nabla n \tag{1.11}$$

Temperature Gradient Correction

But for DDML2, it has the form of

$$\vec{J}_{n,\text{diff}} = \mu_n k_b (T\nabla n + n\nabla T) \tag{1.12}$$

The hole diffusion current should be modified in the same manner.

$$\vec{J}_{p,\text{diff}} = -\mu_p k_b (T\nabla p + p\nabla T) \tag{1.13}$$

Heat Flow Equation

The following heat flow equation is used:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot \kappa \nabla T + \vec{J} \cdot \vec{E} + (E_g + 3k_b T) \cdot (U - G) \tag{1.14}$$

where ρ is the mass density of semiconductor material. c_p is the heat capacity. κ is the thermal conductivity of the material. $\vec{J} \cdot \vec{E}$ is the joule heating of current. $(E_g + 3k_b T) \cdot (U - G)$ is lattice heating due to carrier recombination and generation.

From above discussion, the governing equations for DDML2 are as follows:

$$\frac{\partial n}{\partial t} = \nabla \cdot \left(\mu_n n \vec{E}_n + \mu_n \frac{k_b T}{q} \nabla n + \mu_n \frac{k_b \nabla T}{q} n \right) - (U - G) \tag{1.15a}$$

$$\frac{\partial p}{\partial t} = -\nabla \cdot \left(\mu_p p \vec{E}_p - \mu_p \frac{k_b T}{q} \nabla p - \mu_p \frac{k_b \nabla T}{q} p \right) - (U - G) \tag{1.15b}$$

$$\nabla \cdot \varepsilon \nabla \psi = -q \left(p - n + {N_D}^+ - {N_A}^- \right) \tag{1.15c}$$

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot \kappa \nabla T + \vec{J} \cdot \vec{E} + (E_g + 3k_b T) \cdot (U - G) \tag{1.15d}$$

This model can be used as power transistor simulation as well as breakdown simulation. Unfortunately, nearly all the physical parameters are related with temperature. They should be considered during self consistent simulation, which greatly slows down the speed. The DDML2 solver runs $50-70\,\%$ slower than DDML1. However, it seems no convergence degradation happens in most of the case. The discretization scheme can be found at [[TODO]].

Level 3 Energy Balance Equation

Energy Balance Model [**?**] is introduced into GENIUS code for simulating short channel MOSFET. This is a simplification of full hydrodynamic (HD) model [**?**]. The current density expressions from the drift-diffusion model are modified to include additional coupling to the carrier temperature. Also, reduced carrier energy conservation equations, which derived from second order moment of Boltzmann Transport Equation, are solved consistently with drift-diffusion model. The simplification from HD to EB makes sophisticated Scharfetter-Gummel discretization still can be used in the numerical solution, which ensures the stability.

Current Equation for EBM

The current density $\vec{J}_n$ and $\vec{J}_p$ are then expressed as:

$$\vec{J}_n = q\mu_n n\vec{E}_n + k_b\mu_n\left(n\nabla T_n + T_n\nabla n\right) \tag{1.16a}$$

$$\vec{J}_p = q\mu_p p\vec{E}_p - k_b\mu_p\left(p\nabla T_p + T_p\nabla p\right) \tag{1.16b}$$

where, T_n and T_p are electron and hole temperature, respectively. The difference between above equations and carrier density equations in DDML2 is lattice temperature replaced by carrier temperature.

Energy Balance Equations

In addition, the energy balance model includes the following electron and hole energy balance equations:

$$\frac{\partial\left(n\omega_n\right)}{\partial t} + \nabla\cdot\vec{S}_n = \vec{E}_n\cdot\vec{J}_n + H_n \tag{1.17a}$$

$$\frac{\partial\left(p\omega_p\right)}{\partial t} + \nabla\cdot\vec{S}_p = \vec{E}_p\cdot\vec{J}_p + H_p \tag{1.17b}$$

where, ω_n and ω_p are electron and hole energy. For HD model, the carrier energy includes thermal and kinetic terms $\omega_c = \frac{3}{2}k_bT_c + \frac{1}{2}m^*v_c^2$, but only thermal energy for EB model $\omega_c = \frac{3}{2}k_bT_c$. Here c stands for n or p. $\omega_0 = \frac{3}{2}k_bT$ is the carrier equilibrium energy, for carrier temperature equals to lattice temperature.

$\vec{S}_n$ and $\vec{S}_p$ are the flux of energy:

$$\vec{S}_n = -\kappa_n \nabla T_n - (\omega_n + k_b T_n)\frac{\vec{J}_n}{q} \tag{1.18a}$$

$$\vec{S}_p = -\kappa_p \nabla T_p + (\omega_p + k_b T_p)\frac{\vec{J}_p}{q} \tag{1.18b}$$

The heat conductivity parameter for carriers can be expressed as:

$$\kappa_c = (\frac{2}{5} + \gamma)\frac{{k_b}^2}{q} T_c \mu_c c \tag{1.19}$$

where c stands for n and p, respectively. The constant parameter γ equals -0.7 in the GENIUS software.

The H_n and H_p are the rate of net loss of carrier kinetic energy:

$$H_n = (R_{\text{Aug}} - G)\cdot\left(E_g + \frac{3k_bT_p}{2}\right) - \frac{3k_bT_n}{2}(R_{\text{SHR}} + R_{\text{dir}} - G) - \frac{n(\omega_n - \omega_0)}{\tau_n} \tag{1.20a}$$

$$H_p = (R_{\text{Aug}} - G)\cdot\left(E_g + \frac{3k_bT_n}{2}\right) - \frac{3k_bT_p}{2}(R_{\text{SHR}} + R_{\text{dir}} - G) - \frac{p(\omega_p - \omega_0)}{\tau_p} \tag{1.20b}$$

Lattice Heat Equation for EBM

At last, the lattice heat flow equation should be rewritten as:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot \kappa \nabla T + H \tag{1.21}$$

where

$$H = R_{\text{SHR}} \cdot \left(E_g + \frac{3k_bT_p}{2} + \frac{3k_bT_n}{2}\right) + \frac{n(\omega_n - \omega_0)}{\tau_n} + \frac{p(\omega_p - \omega_0)}{\tau_p} \tag{1.22}$$

The carrier energy is mainly contributed by joule heating term $\vec{E}_c \cdot \vec{J}_c$, and heating (cooling) due to carrier generation (recombination) term. The carriers exchange energy with lattice by collision, which described by energy relaxation term τ_{ω_c}. This model is suitable for sub-micron MOS (channel length $1 \sim 0.1$ μm) and advanced BJT simulation. However, the computation burden of EB method is much higher than DD. And the convergence of EB solver is difficult to achieve, which requires more strict initial value and more powerful inner linear solver. The discretization scheme can be found at [[TODO]].

From above discussion, all the governing equations of DD/EB method is elliptical or parabolic. From mathematic point of view, does not like hyperbolic system[1],

[1] One have to face discontinuous problem, i.e. shock wave.

the solution of elliptical or parabolic system is always smooth. The required numerical technique is simple and mature for these systems. As a result, the DD and EB method is preferred against full hydrodynamic method.

Band Structure Model

The band structure parameters, including bandgap E_g, effective density of states in the conduction band N_c and valence band N_v, and intrinsic carrier concentration n_{ie}, are the most important and fundamental physical parameters for semiconductor material [**?**].

Effective Density of States

Effective density of states in the conduction and valence band are defined as follows:

$$N_c \equiv 2\left(\frac{{m_n}^* k_b T}{2\pi\hbar^2}\right)^{3/2} \tag{1.23a}$$

$$N_v \equiv 2\left(\frac{{m_p}^* k_b T}{2\pi\hbar^2}\right)^{3/2} \tag{1.23b}$$

The temperature dependencies of effective density of states is fairly simple:

$$N_c\left(T\right) = N_c\left(300\mathrm{K}\right)\left(\frac{T}{300\mathrm{K}}\right)^{1.5} \tag{1.24a}$$

$$N_v\left(T\right) = N_v\left(300\mathrm{K}\right)\left(\frac{T}{300\mathrm{K}}\right)^{1.5} \tag{1.24b}$$

Bandgap

The bandgap in GENIUS is expressed as follows:

$$\begin{aligned} E_g(T) &= E_g(0) - \frac{\alpha T^2}{T+\beta} \\ &= E_g(300) + \alpha\left[\frac{300^2}{300+\beta} - \frac{T^2}{T+\beta}\right] \end{aligned} \tag{1.25a}$$

Bandgap Narrowing due to Heavy Doping

When bandgap narrowing effects due to heavy doping takes place [**?**], the band edge shifts:

$$\Delta E_g = \frac{E_{\mathrm{bgn}}}{2k_bT}\left[\ln\frac{N_{\mathrm{total}}}{N_{\mathrm{ref}}} + \sqrt{\left(\ln\frac{N_{\mathrm{total}}}{N_{\mathrm{ref}}}\right)^2 + C_{\mathrm{bgn}}}\right]. \tag{1.26}$$

Symbol	Parameter	Unit	Silicon	GaAs
$E_g(300)$	EG300	eV	1.1241	1.424
α	EGALPH	eV/K	2.73×10^{-4}	5.405×10^{-4}
β	EGBETA	K	0	204
E_{bgn}	V0.BGN	eV	6.92×10^{-3}	0
N_{ref}	N0.BGN	cm^3	1.30×10^{17}	1×10^{17}
C_{bgn}	CON.BGN	-	0.5	0.5
m_n	ELECMASS	m_0	1.0903	0.067
m_p	HOLEMASS	m_0	1.1525	0.6415
$N_c(300)$	NC300	cm^3	2.86×10^{19}	4.7×10^{17}
$N_v(300)$	NV300	cm^3	3.10×10^{19}	7.0×10^{18}

Table 1.1: Parameters of the Default band structure model

The intrinsic concentration should be modified:

$$n_{ie} = \sqrt{N_c N_v} \exp\left(-\frac{E_g}{2k_b T}\right) \cdot \exp(\Delta E_g) \tag{1.27}$$

Since the carrier current Equation (1.9),

XXXXXXXXXXXXXXXXXXXXXXXXXX

involves the energy level of conduction band N_c and valence band N_v, the bandgap shift should be attributed to them. The bandgap narrowing is attributed half to the conduction band and another half to the valence band as default:

$$E_c' = E_c - \frac{1}{2}\Delta E_g \tag{1.28a}$$

$$E_v' = E_v + \frac{1}{2}\Delta E_g \tag{1.28b}$$

The parameters used in the default band structure model is listed in Table ,

Band structure of compound semiconductors

[[TODO]]

Band Structure of SiGe

[[TODO]]

Band Structure of Tertiary Compound Semiconductor

[[TODO]]

Bandgap

[[TODO]]

Electron Affinity

[[TODO]]

Effective Mass

[[TODO]]

Density of States

[[TODO]]

Schenk's Bandgap Narrowing Model

[[TODO]] Equations of Schenk's model

The Schenk's bandgap narrowing model is available for silicon, and can be loaded with the option Schenk in the PMI command.

Carrier Recombination

Three recombination mechanisms are considered in GENIUS at present, including Shockley-Read-Hall, Auger, and direct (or radiative) recombination. The total recombination is considered as the sum of all:

$$U = U_n = U_p = U_{\text{SRH}} + U_{\text{dir}} + U_{\text{Auger}} \tag{1.29}$$

where U_{SRH}, U_{dir} and U_{Auger} are SRH recombination, direct recombination and Auger recombination, respectively.

SRH Recombination

Shockley-Read-Hall (SRH) recombinationrate is determined by the following formula:

$$U_{\text{SRH}} = \frac{pn - {n_{ie}}^2}{\tau_p \left[n + n_{ie} \exp\left(\frac{\mathbf{ETRAP}}{kT_L} \right) \right] + \tau_n \left[p + n_{ie} \exp\left(\frac{-\mathbf{ETRAP}}{kT_L} \right) \right]} \tag{1.30}$$

where τ_n and τ_p are carrier life time, which dependent on impurity concentration [**?**].

$$\tau_n = \frac{\mathbf{TAUN0}}{1 + N_{\text{total}}/\mathbf{NSRHN}} \tag{1.31a}$$

$$\tau_p = \frac{\mathbf{TAUP0}}{1 + N_{\text{total}}/\mathbf{NSRHP}} \tag{1.31b}$$

Parameter	Unit	Silicon	GaAs	Ge
ETRAP	eV	0	0	0
DIRECT	cm^3s^{-1}	1.1e-14	7.2e-10	6.41e-14
AUGN	cm^6s^{-1}	1.1e-30	1e-30	1e-30
AUGP	cm^6s^{-1}	0.3e-30	1e-29	1e-30
TAUN0	s	1e-7	5e-9	1e-7
TAUP0	s	1e-7	3e-6	1e-7
NSRHN	cm^{-3}	5e16	5e17	5e16
NSRHP	cm^{-3}	5e16	5e17	5e16

Table 1.2: Default values of recombination parameters

Auger Recombination

The Auger recombination is a three-carrier recombination process, involving either two electrons and one hole or two holes and one electron. This mechanism becomes important when carrier concentration is large.

$$U_{\text{Auger}} = \mathbf{AUGN}\left(pn^2 - n{n_{ie}}^2\right) + \mathbf{AUGP}(np^2 - p{n_{ie}}^2) \tag{1.32}$$

where AUGN and AUGP are Auger coefficient for electrons and holes. The value of Auger recombination U_{Auger} can be negative some times, which refers to Auger generation.

Direct Recombination

The direct recombination model expresses the recombination rate as a function of the carrier concentrations n and p, and the effective intrinsic density n_{ie}:

$$U_{\text{dir}} = \mathbf{DIRECT}(np - {n_{ie}}^2) \tag{1.33}$$

The default value of the recombination parameters are listed in Table 1.2,

Surface Recombination

At semiconductor-insulator interfaces, additional SRH recombination can be introduced. The surface recombination rate has the unit with

$$U_{\text{Surf}} = \frac{pn - {n_{ie}}^2}{\dfrac{1}{\mathbf{STAUN}}(n + n_{ie}) + \dfrac{1}{\mathbf{STAUP}}(p + n_{ie})}. \tag{1.34}$$

The surface recombination velocities, STAUN and STAUP, have the unit of cm/s, and the default value of 0.

Mobility Models

Carrier mobility is one of the most important parameters in the carrier transport model. The DD model itself, developed at early 1980s, is still being used today due to advanced mobility model enlarged its ability to sub-micron device.

Mobility modeling is normally divided into: low field behavior, high field behavior and mobility in the (MOS) inversion layer.

The low electric field behavior has carriers almost in equilibrium with the lattice. The low-field mobility is commonly denoted by the symbol μ_{n0}, μ_{p0}. The value of this mobility is dependent upon phonon and impurity scattering. Both of which act to decrease the low field mobility. Since scattering mechanism is depended on lattice temperature, the low-field mobility is also a function of lattice temperature.

The high electric field behavior shows that the carrier mobility declines with electric field because the carriers that gain energy can take part in a wider range of scattering processes. The mean drift velocity no longer increases linearly with increasing electric field, but rises more slowly. Eventually, the velocity doesn't increase any more with increasing field but saturates at a constant velocity. This constant velocity is commonly denoted by the symbol v_{sat}. Impurity scattering is relatively insignificant for energetic carriers, and so v_{sat} is primarily a function of the lattice temperature.

Modeling carrier mobilities in inversion layers introduces additional complications. Carriers in inversion layers are subject to surface scattering, carrier-carrier scattering, velocity overshoot and quantum mechanical size quantization effects. These effects must be accounted for in order to perform accurate simulation of MOS devices. The transverse electric field is often used as a parameter that indicates the strength of inversion layer phenomena.

It can be seen that some physical mechanisms such as velocity overshoot and quantum effect which can't be described by DD method at all, can be taken into account by comprehensive mobility model. The comprehensive mobility model extends the application range of DD method. However, when the EB method (which accounts for velocity overshoot) and QDD method (including quantum effect) are used, more calibrations are needed to existing mobility models.

Bulk Mobility Models

The first family of mobility models were designed to model the carrier transport at low electric fields. They usually focus on the temperature and doping concentration dependence of the carrier mobilities. The surface-related or transverse E-field effects are *not* included in these models. On the other hand, in GENIUS, these low-field mobilities models are coupled to a velocity saturation model to account for the carrier velocity saturation effect. This family of mobility models are suitable for bulk device, such as bipolar transistors.

Symbol	Parameter	Unit	Si:n	Si:p	GaAs:n	GaAs:p
μ_{min}	MUN.MIN / MUP.MIN	$\text{cm}^2\text{V}^{-1}\text{s}^{-1}$	55.24	49.70	0.0	0.0
μ_{max}	MUN.MAX / MUP.MAX	$\text{cm}^2\text{V}^{-1}\text{s}^{-1}$	1429.23	479.37	8500.0	400.0
ν	NUN / NUP	-	-2.3	-2.2	-1.0	-2.1
ξ	XIN / XIP	-	-3.8	-3.7	0.0	0.0
α	ALPHAN / ALPHAP	-	0.73	0.70	0.436	0.395
N_{ref}	NREFN / NREFP	cm^{-3}	1.072e17	1.606e17	1.69e17	2.75e17

Table 1.3: Default parameter values of the analytic mobility model

In brief, the low field carrier mobility is first computed, then a velocity saturation formula is applied to yield the corrected mobility value. Three choices are available for the low-field mobility calculation, each described in one of the following sub-sections. The choices of velocity saturation is described in the last sub-section.

Analytic Mobility Model

In the GENIUS code, the Analytic Mobility model [**?**] is the default low field mobility model for all the material. It is an concentration and temperature dependent empirical mobility model expressed as:

$$\mu_0 = \mu_{\text{min}} + \frac{\mu_{\text{max}} \left(\frac{T}{300}\right)^{\nu} - \mu_{\text{min}}}{1 + \left(\frac{T}{300}\right)^{\xi} \left(\frac{N_{\text{total}}}{N_{\text{ref}}}\right)^{\alpha}} \tag{1.35}$$

where $N_{\text{total}} = N_A + N_D$ is the total impurity concentration.

Default parameters for Si, GaAs and Ge are listed below:

In GENIUS, the analytic model is the simplest mobility model, and is available for a wide range of materials. For some materials, such as silicon, some more advanced mobility models are available.

Masetti Analytic Model

The doping-dependent low-field mobility model proposed by Masetti et al.[**?**] is an alternative to the default analytic model. The general expression for the low-field mobility is

$$\mu_{\text{dop}} = \mu_{\text{min1}} \exp\left(-\frac{P_c}{N_{\text{tot}}}\right) + \frac{\mu_{\text{const}} - \mu_{\text{min2}}}{1 + (N_{\text{tot}}/C_r)^{\alpha}} - \frac{\mu_1}{1 + (C_s/N_{\text{tot}})^{\beta}} \tag{1.36}$$

where N_{tot} is the total doping concentration. The term μ_{const} is the temperature-dependent, phonon-limited mobility

Symbol	Parameter	Unit	4H-SiC:n	4H-SiC:p
μ_{max}	MUN.MAX / MUP.MAX	$\text{cm}^2\text{V}^{-1}\text{s}^{-1}$	947.0	124.0
ζ	MUN.ZETA / MUP.ZETA	-	1.962	1.424
μ_{min1}	MUN.MIN1 / MUP.MIN1	$\text{cm}^2\text{V}^{-1}\text{s}^{-1}$	0	15.9
μ_{min2}	MUN.MIN2 / MUP.MIN2	$\text{cm}^2\text{V}^{-1}\text{s}^{-1}$	0	15.9
μ_1	MUN1 / MUP1	$\text{cm}^2\text{V}^{-1}\text{s}^{-1}$	0	0
P_c	PCN / PCP	cm^3	0	0
C_r	CRN / CRP	cm^3	1.94×10^{17}	1.76×10^{19}
C_s	CSN / CSP	cm^3	0	0
α	MUN.ALPHA / MUP.ALPHA	-	0.61	0.34
β	MUN.BETA / MUP.BETA	-	0	0

Table 1.4: Parameters of the Masetti mobility model

$$\mu_{\text{const}} = \mu_{\text{max}} \left(\frac{T}{300} \right)^{\zeta} \tag{1.37}$$

where T is the lattice temperature.

The parameters of the Masetti model is listed in Table ,

Philips Mobility Model

Another low field mobility model implemented into GENIUS is the Philips Unified Mobility model [**?**, **?**]. This model takes into account the distinct acceptor and donor scattering, carrier-carrier scattering and carrier screening, which is recommended for bipolar devices simulation.

The electron mobility is described by the following expressions:

$$\mu_{0,n}{}^{-1} = \mu_{\text{Lattice},n}{}^{-1} + \mu_{D+A+p}{}^{-1} \tag{1.38}$$

where $\mu_{0,n}$ is the total low field electron mobilities, $\mu_{\text{Lattice},n}$ is the electron mobilities due to lattice scattering, μ_{D+A+p} is the electron and hole mobilities due to donor (D), acceptor (A), screening (P) and carrier-carrier scattering.

$$\mu_{\text{Lattice},n} = \mu_{\text{max}} \left(\frac{T}{300} \right)^{-2.285} \tag{1.39}$$

$$\mu_{D+A+p} = \mu_{1,n} \left(\frac{N_{\text{sc},n}}{N_{\text{sc,eff},n}} \right) \left(\frac{N_{\text{ref}}}{N_{\text{sc},n}} \right)^{\alpha} + \mu_{2,n} \left(\frac{n+p}{N_{\text{sc,eff},n}} \right) \tag{1.40}$$

The parameters $\mu_{1,n}$ and $\mu_{2,n}$ are given as:

$$\mu_{1,n} = \frac{\mu_{\text{max}}^2}{\mu_{\text{max}} - \mu_{\text{min}}} \left(\frac{T}{300} \right)^{3\alpha - 1.5} \tag{1.41a}$$

$$\mu_{2,n} = \frac{\mu_{\text{max}} \cdot \mu_{\text{min}}}{\mu_{\text{max}} - \mu_{\text{min}}} \left(\frac{300}{T} \right)^{1.5} \tag{1.41b}$$

where $N_{\text{sc},n}$ and $N_{\text{sc,eff},n}$ is the impurity-carrier scattering concentration and effect impurity-carrier scattering concentration given by:

$$N_{\text{sc},n} = {N_D}^* + N_A^* + p \tag{1.42a}$$

$$N_{\text{sc,eff},n} = {N_D}^* + {N_A}^* G\left(P_n\right) + \frac{p}{F\left(P_n\right)} \tag{1.42b}$$

where N_D^* and N_A^* take ultra-high doping effects into account and are defined by:

$${N_D}^* = N_D \left(1 + \frac{1}{C_D + \left(\frac{N_{D,\text{ref}}}{N_D} \right)^2} \right) \tag{1.43a}$$

$${N_A}^* = N_A \left(1 + \frac{1}{C_A + \left(\frac{N_{A,\text{ref}}}{N_A} \right)^2} \right) \tag{1.43b}$$

The screening factor functions $G\left(P_n\right)$ and $F\left(P_n\right)$ take the repulsive potential for acceptors and the finite mass of scattering holes into account.

$$G\left(P_n\right) = 1 - \frac{0.89233}{\left[0.41372 + P_n \left(\frac{m_0}{m_e} \frac{T}{300} \right)^{0.28227} \right]^{0.19778}} + \frac{0.005978}{\left[P_n \left(\frac{m_e}{m_0} \frac{T}{300} \right)^{0.72169} \right]^{1.80618}} \tag{1.44}$$

$$F\left(P_n\right) = \frac{0.7643 {P_n}^{0.6478} + 2.2999 + 6.5502 \frac{m_e}{m_h}}{{P_n}^{0.6478} + 2.3670 - 0.8552 \frac{m_e}{m_h}} \tag{1.45}$$

The P_n parameter that takes screening effects into account is given by:

$$P_n = \left[\frac{f_{cw}}{N_{\text{sc,ref}} \cdot {N_{\text{sc},n}}^{-2/3}} + \frac{f_{BH}}{\frac{N_{\text{c,ref}}}{n+p} \left(\frac{m_e}{m_0} \right)} \right]^{-1} \left(\frac{T}{300} \right)^2 \tag{1.46}$$

Similar expressions hold for holes. The default parameters for Philips model are listed in Table

In the actual code, Philips model is corrected by Caughey-Thomas expression for taking high field velocity saturation effects into account. This model can be loaded by Philips keyword in the PMI statements.

Velocity Saturation

Silicon-like materials

For silicon-like materials, the Caughey-Thomas expression [**?**], is used:

$$\mu = \frac{\mu_0}{\left[1 + \left(\frac{\mu_0 E_{\|}}{v_{\text{sat}}} \right)^{\beta} \right]^{1/\beta}} \tag{1.47}$$

Symbol	Parameter	Unit	Si:n	Si:p
μ_{min}	MMNN.UM / MMNP.UM	$\text{cm}^2\text{V}^{-1}\text{s}^{-1}$	55.24	49.70
μ_{max}	MMXN.UM / MMXP.UM	$\text{cm}^2\text{V}^{-1}\text{s}^{-1}$	1417.0	470.5
α	ALPN.UM / ALPP.UM	-	0.68	0.719
N_{ref}	NRFN.UM / NRFP.UM	cm^{-3}	9.68e16	2.23e17
C_D	CRFD.UM	-	0.21	0.21
C_A	CRFA.UM	-	0.5	0.5
$N_{\text{D,ref}}$	NRFD.UM	cm^{-3}	4.0e20	4.0e20
$N_{\text{A,ref}}$	NRFA.UM	cm^{-3}	7.2e20	7.2e20
m_e	me_over_m0	m_0	1.0	-
m_h	mh_over_m0	m_0	-	1.258
f_{cw}	-	2.459	2.459	
f_{BH}	-	3.828	3.828	
$N_{\text{sc,ref}}$	NSC.REF	cm^{-2}	3.97e13	3.97e13
$N_{\text{c,ref}}$	CAR.REF	cm^{-3}	1.36e20	1.36e20

Table 1.5: Default values of Philips mobility model parameters

where $E_{\|}$ is the electric field parallel to current flow. v_{sat} is the saturation velocities for electrons or holes. They are computed by default from the expression:

$$v_{\text{sat}}(T) = \frac{v_{\text{sat0}}}{1 + \alpha \cdot \exp\left(\frac{T}{600}\right)} \tag{1.48}$$

CHAPTER 2

The Second Chapter Style