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An energy relaxation time model for device simulation

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Abstract

We present an empirical model for the electron energy relaxation time. It is based on Monte-Carlo simulation results and is applicable to all relevant diamond and zinc-blende structure semiconductors. The energy relaxation times are expressed as functions of the carrier and lattice temperatures, and in the case of semiconductor alloys, of the material composition. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

As scaling down of the transistor's gate length is progressing, more appropriate models taking into account nonlocal effects are necessary [1–3]. It is well known that for submicron structures, the classic drift-diffusion transport equations are insufficient to describe properly the physical behaviour. Energy transport equations are necessary to model the increase of the carrier temperature at high electric fields [4]. Nonlocal effects, such as overshoot or real space transfer, must be reproduced.

A constant energy relaxation time (τ_w) [5], or a quadratic dependence on the electron temperature [6], are usually assumed. A precise simulation needs to include the dependence of τ_w on the lattice and carrier temperatures.

In this paper we present a new analytical model for the electron energy relaxation time based on Monte-Carlo simulation results [7]. The dependence on the lattice and electron temperatures has been considered, and also the material composition for the semiconductor alloys. No doping concentration influence is taken into account.

In Section 2 the used methodology is explained. The new model is presented in Section 3. It is applied to Si, Ge and III–V binary materials, and is also extended to semiconductor alloys.

2. Methodology

Depending on the semiconductor under investigation, different results are available from Monte-Carlo simulations. Two methods—direct and indirect—are used to obtain τ_w.

2.1. The direct method

For Si, Ge and GaAs, the dependence of the electron energy relaxation time and the average electron energy, w, on the electric field are available in [7]. The average energy is approximated by the thermal energy with the kinetic term being neglected:

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Table 1
Parameter values for nonalloy materials

Material	$\tau_{w,0}$ [ps]	$\tau_{w,1}$ [ps]	C_0	C_1	C_2	C_3
Si	1.0	−0.538	0	0.0015	−0.09	0.17
Ge	0.26	1.49	0	−0.434	1.322	0
GaAs	0.48	0.025	0	−0.053	0.853	0.5
AlAs	0.17	0.025	61	−0.053	0.853	0.5
InAs	0.08	0.025	3	−0.053	0.853	0.5

$$w = \frac{1}{2}m_n \times v_n^2 + \frac{3}{2}k_B \times T_n \approx \frac{3}{2}k_B \times T_n, \qquad (1)$$

where m_n, v_n, and T_n are the electron mass, velocity and temperature, respectively, and k_B is the Boltzmann constant.

This approximation together with the interpolation of the Monte-Carlo simulation results for different electric fields allows to obtain directly τ_w as a function of the electron temperature at different lattice temperatures. This procedure is called direct method.

2.2. The indirect method

In the case of binary and ternary III–V compounds, such as InAs, AlAs, $In_xGa_{1-x}As$, and $Al_xGa_{1-x}As$, the dependence of τ_w on the electric field is not available. In this case we calculate τ_w in an indirect way, using the dependence of the electron velocity on the electric field from [7]. The local energy balance equation [8] is obtained by neglecting the energy flux

$$\tau_w = \frac{3 \times k_B}{2 \times q} \times \frac{T_n - T_L}{v_n \times E}, \qquad (2)$$

where q is the electron charge, T_L the lattice temperature, and E is the electric field.Using (1) and (2), and the dependences of the average electron energy and the electron velocity on the electric field, τ_w is extracted. The procedure is called indirect method.

3. The relaxation time model

We use the following Gaussian function to model the electron relaxation time as a function of the carrier and lattice temperatures:

$$\tau_w = \tau_{w,0} + \tau_{w,1} \times \exp\left[C_1 \times \left(\frac{T_n}{300\,\mathrm{K}} + C_0\right)^2 + C_2 \times \left(\frac{T_n}{300\,\mathrm{K}} + C_0\right) + C_3 \times \left(\frac{T_L}{300\,\mathrm{K}}\right)\right] \qquad (3)$$

The flexibility of this function allows its easy adaption to all considered materials. For Si, Ge, and III–V binary materials, all parameters in (3) are summarized in Table 1.

Table 2
Parameter values for alloy materials

Material	$\tau^*_{w,0}$ [ps]	$\tau_{w,1}$ [ps]	C^*_0	C_1	C_2	C_3
AlGaAs	−0.35	0.025	−61	−0.053	0.853	0.5
InGaAs	1.8	0.025	−34	−0.053	0.853	0.5

In the case of III–V semiconductor alloys the dependence of τ_w on the material composition (x) is included. $\tau_{w,0}$ and C_0 are modeled as a quadratic function of x. The parameters are summarized in Table 2.

3.1. Elementary and binary semiconductors

The direct method is used for Si, Ge and GaAs, and the indirect one for AlAs and InAs. For Si we can see in Fig. 1 the values for τ_w obtained from the model (lines) and Monte-Carlo results (circles and triangles) at different lattice temperatures. The energy relaxation time slightly decreases with the increase of the lattice temperature. It is also observed that for high electron temperatures, τ_w tends to saturate.

At very low electron temperature τ_w starts to increase. This effect is not reproduced by the model. When the electron temperature is close to the lattice temperature, the term $(T_n - T_L)/\tau_w$ appearing in the energy balance tends to zero [5]. Thus, the influence of τ_w is negligible, and its increase can be neglected.

In GaAs and Ge similar behaviour was observed at very low electron temperature, and the same assumptions as for Si were made.

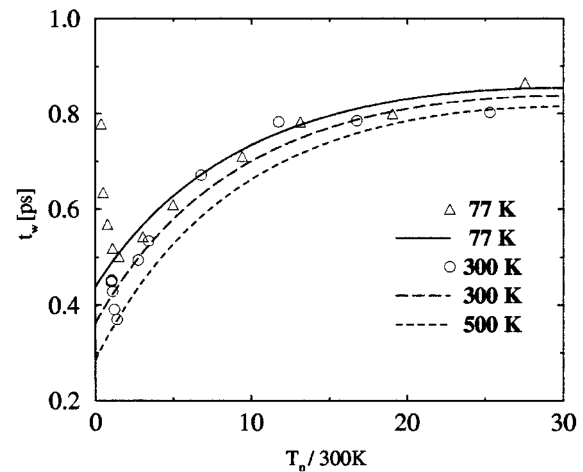

Fig. 1. Energy relaxation time as a function of electron temperature. Comparison of the model and MC data for Si at several lattice temperatures.

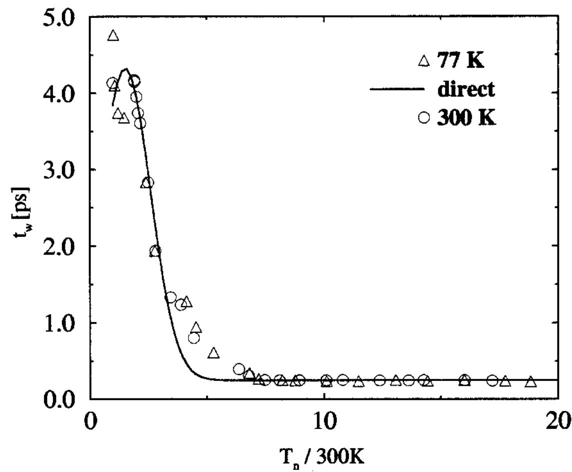

Fig. 2. Energy relaxation time as a function of electron temperature. Comparison of the model and MC data for Ge.

In the case of Ge Fig. 2 shows that τ_w is nearly independent of the lattice temperature, except for very low electron temperature. Therefore, any lattice temperature dependence is neglected ($C_3 = 0$ in (3)). The sharp initial fall is attributed to the increase of optical and intervalley scattering as the electrons are heated by the field [9].

The results for GaAs are shown in Fig. 3. At high electron temperatures τ_w tends to some saturated value and becomes independent of the lattice temperature. For low and intermediate electron temperatures, the behaviour can be attributed to the transition of electrons from the Γ to the L valleys. The electron temperature for which τ_w reaches the peak value is

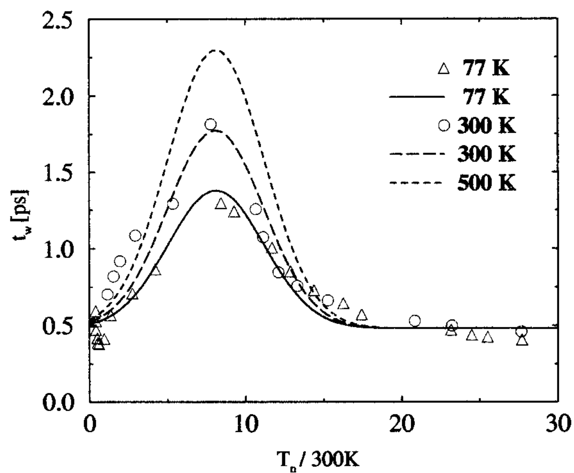

Fig. 3. Energy relaxation time as a function of electron temperature. Comparison of the model and MC data for GaAs at several lattice temperatures.

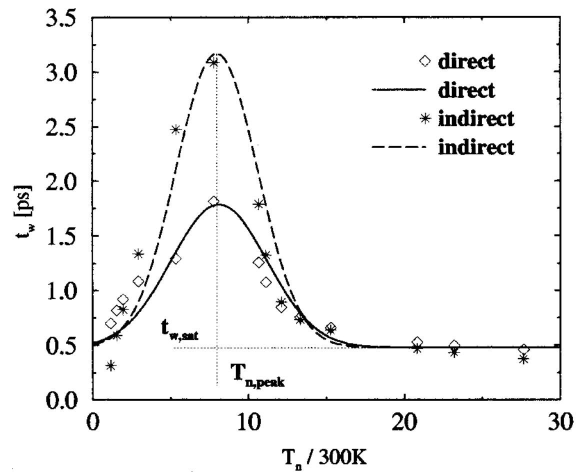

Fig. 4. Energy relaxation time as a function of electron temperature. Results from direct and indirect method for GaAs. $T_L = 300$ K.

independent of the lattice temperature. Its associated average energy (1), 0.31 eV, is close to the energy difference between the two valleys, 0.27 eV.

The lattice temperature dependence of τ_w in GaAs is reverse to that observed in Si.

3.2. Semiconductor alloys

For all semiconductor alloys the indirect method is used. It turns out, that by using (2), τ_w is overestimated compared with the direct method. The following criteria were assumed for compensation. In Fig. 4 τ_w for GaAs is shown as a function of the electron temperature at 300 K as it results from both the direct and indirect methods. We can see that the saturation value of τ_w at high electron temperatures, $\tau_{w,sat}$, and the location of the peak, $T_{n,peak}$, are independent of the methodology used. The energy relaxation time in $In_xGa_{1-x}As$ and $Al_xGa_{1-x}As$ τ_w behaves similarly to GaAs (see Figs. 5 and 6). Thus, we model τ_w for the III–V semiconductor alloys by preserving the standard deviation and the amplitude of the Gaussian function obtained for GaAs with the direct method and by adjusting then the position with the material composition dependence of $\tau_{w,sat}$ and $T_{n,peak}$.

For III–V semiconductor alloys, $A_xB_{1-x}C$, a quadratic interpolation between the values from Table 1 for the binary compounds, AC and BC, is used to calculate $\tau_{w,0}$ and C_0. Thus we have:

$$\tau_{w,0}^{ABC} = \tau_{w,0}^{AC} \times x + \tau_{w,0}^{BC} \times (1-x) + \tau_{w,0}^{*} \times (1-x) \times x \quad (4)$$

$$C_0^{ABC} = C_0^{AC} \times x + C_0^{BC} \times (1-x) + C_0^{*} \times (1-x) \times x \quad (5)$$

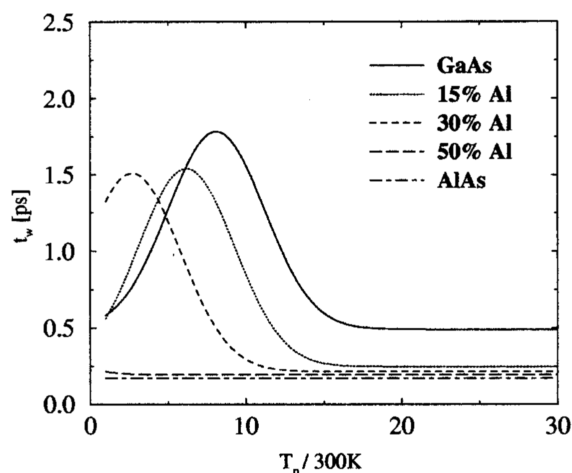

Fig. 5. Energy relaxation time as a function of electron temperature for different Al contents in AlGaAs at room temperature.

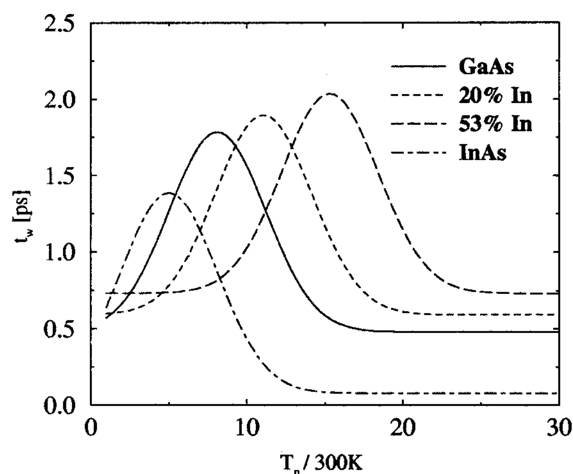

Fig. 6. Energy relaxation time as a function of electron temperature for different In contents in InGaAs at room temperature.

where $\tau^{*}_{w,0}$ and C^{*}_{0} are referred to as nonlinear or bowing parameters. The parameters used in this model are summarized in Table 2.

The lattice temperature dependence of τ_w of GaAs is preserved for both semiconductor alloys considered, $Al_xGa_{1-x}As$ and $In_xGa_{1-x}As$. This approximation is more accurate for low material composition, which is more frequently used ($x < 0.3$).

In Fig. 5 the results of the model for $Al_xGa_{1-x}As$ at 300 K, for different material compositions x, are shown. Note the shift of the electron temperature, at which τ_w reaches its maximum, to lower values with the increase of x. For high values ($x > 0.4$) no peak value of τ_w is observed. This behaviour can be attributed to the x dependence of the Γ, L and X valley minima. When the Al fraction changes from 0 to 0.3, the energy difference between the Γ and L valleys varies between 0.27 and 0.1 eV. The corresponding change of the electron energy associated to the peak of τ_w, varies between 0.31 to 0.1 eV. Furthermore, for Al contents $x > 0.4$ the X valleys are the lowest ones, and the band gap becomes indirect. This explains the absence of a peak of τ_w for $x > 0.4$.

For $In_xGa_{1-x}As$ similar results are obtained in Fig. 6. There is a shift of the maximum τ_w to higher values with the increase of the indium composition up to $x = 0.53$. This can be explained with the electron population change due to Γ–L transitions. For InAs a quick shift to lower values is observed, not explained by the dependence of the energy valleys on x. Monte-Carlo simulation results show that at very high indium contents the average electron energy decreases and the saturation drift velocity increases quickly with x, but no clear results are available in this case.

4. Conclusions

A new electron energy relaxation time model for device simulation is presented. It is applied to the most widely used semiconductors, and takes into account the electron and lattice temperatures, and the material composition in the case of alloys.

The good agreement with the Monte-Carlo simulation results and its simple analytical structure make it attractive for device simulation.

References

[1] Grasser T, Palankovski V, Schrom G, Selberherr S. Hydrodynamic mixed-mode simulation. In: De Meyer K, Biesemans S, editors. Simulation of semiconductor processes and devices. Wien, New York: Springer, 1998. p. 247–50.

[2] Spinelli AS, Benvenuti A, Pacelli A. Self-consistent 2-D model for quantum effects in n-MOS transistors. IEEE Trans Electron Devices 1998;45(6):1342–9.

[3] Shawki T, Salmer G, El-Sayed O. MODFET 2-D hydrodynamic energy modeling: optimization of subquarter-micron-gate structures. IEEE Trans Electron Devices 1990;37(1):21–30.

[4] Kosina H, Langer E, Selberherr S. Device modelling for the 1990s. Microelectronics Journal 1995;26(2/3):217–33.

[5] Brech H. Optimization of GaAs based high electron mobility transistors by numerical simulation. Dissertation, Technische Universität, Wien, 1998.

[6] Agostinelli VM, Bordelon TJ, Wang XL, Yeap CF, Maziar CM, Tasch AF. An energy-dependent two-dimensional substrate current model for the simulation of submicrometer MOSFETs. IEEE Electron Device Lett 1992;13(11):554–6.

[7] Fischetti MV, Laux SE. Monte-Carlo simulation of transport in technologically significant semiconductors of the diamond and zinc-blende structurespart II: submicrometer MOSFETs. IEEE Trans Electron Devices 1991;38(3):650–60.

[8] Sze SM. Physics of semiconductor devices, 2nd ed. New York: Wiley, 1981.

[9] Jacoboni C, Nava F, Canali C, Ottaviani G. Electron drift velocity and diffusivity in germanium. Phys Rev B 1981;24(2):1014–26.