Temperature Dependence of the Transport Properties of InN

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Acknowledgments
This work is supported by the Austrian Science Funds FWF, START Project No.Y247-N13.

Keywords
Indium Nitride, mobility model, temperature dependence, Gunn diode, device simulation

Abstract
In this work, we employ a Monte Carlo (MC) approach to investigate the temperature dependence of the electron transport in wurtzite InN. The velocity-field characteristics of this material show a pronounced negative differential resistance, which is a requirement for the realization of transferred-electron devices. Based on the Monte Carlo simulation results we derive a hydrodynamic mobility model suited for use in device simulation tools. As a particular example, we evaluate the performance of InN Gunn diodes using our two-dimensional device simulator MINIMOS-NT.

Introduction

The research on InN is being boosted by its considerable potential for electronic and optoelectronic device applications. This material exhibits superior electron transport characteristics when compared to those of GaN [1, 2]. Theoretical studies [3, 4, 5] of InN predict a negative differential resistance (NDR) at high electric fields, which is a requirement for the occurrence of the Gunn effect. In addition, the electron mobility in InN is much higher than in GaN. This makes InN a strong candidate for use in the next generation transferred-electron devices, especially Gunn diodes for high-frequency applications. In this work we use a Monte Carlo approach to investigate the electron transport in InN at different temperatures, considering the band structure and scattering model parameters as described in [3]. In addition, we consider temperature-dependent lattice and elastic constants [6]. We rely on the obtained Monte Carlo results to construct an appropriate macroscopic model and implement it in our two dimensional device simulator MINIMOS-NT [7], which is used to evaluate the electrical and thermal performance of an InN-based Gunn diode.

The Monte Carlo Approach

The Monte Carlo method is a powerful technique to establish a consistent link between theory and experiments. It helps to gain understanding of the transport properties, and it provides macroscopic parameters which are necessary for the description of electron devices. We employ a single-particle Monte Carlo technique to investigate stationary electron transport in InN [8, 9]. Our calculations include the three lowest valleys of the conduction band and account for non-parabolicity effects. Several stochastic mechanisms such as acoustic phonon, polar optical phonon, inter-valley phonon, Coulomb, and piezoelectric scattering are considered and their impact is assessed [3]. Temperature-dependent lattice and elastic constants [6] and the corresponding sound velocities in lateral and transversal direction are accounted for. The particular advantage of the Monte Carlo approach is that it provides a transport formulation on microscopic level, limited only by the extent to which the underlying physics of the system is included. Since the InN material system is yet not so well explored, several important input parameters are still missing or just not well known.

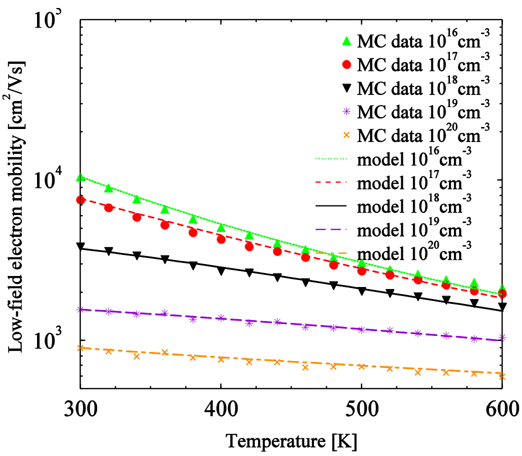

Fig. 1: Low-field electron mobility as a function of lattice temperature in InN for different carrier concentrations.

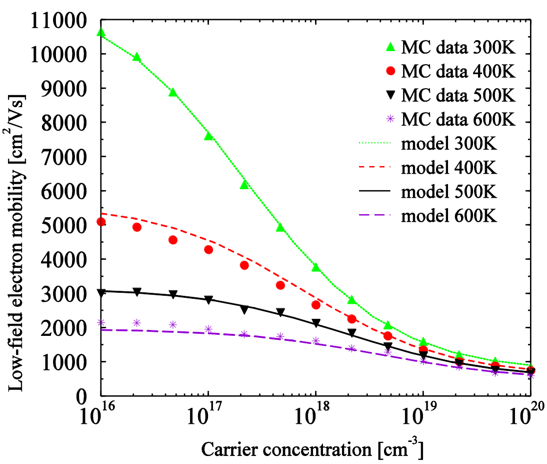

Fig. 2: Low-field electron mobility as a function of carrier concentration in InN for different lattice temperatures.

Monte Carlo Simulation Results

In Fig. 1 the temperature dependence of the low-field electron mobility for different doping concentrations is shown. A mobility value of above 10000 cm^2/Vs for a doping level of 10^{16} cm^{-3} at 300 K is achieved. This value decreases to 2000 cm^2/Vs at 600 K. For the technologically relevant concentration of 10^{17} cm^{-3}, the low-field electron mobility is found to decrease from 8000 cm^2/Vs at 300 K to about 2000 cm^2/Vs at 600 K. In accordance with Fig. 2, the mobility reduction for higher doping levels with temperature is less. Fig. 3 shows the electron drift velocity as a function of the applied electric field for different temperatures. The strongest temperature dependence is seen near the peak velocity. At higher electric field, only a minor impact is observed.

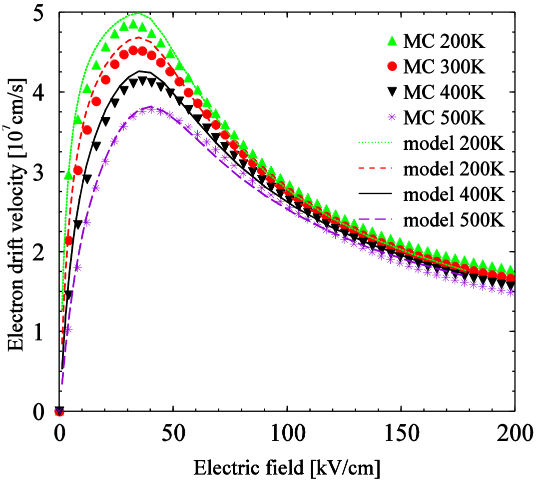

Fig. 3: Electron drift velocity dependence on electric field in InN for a carrier concentration of 10^{17} cm^{-3} and different lattice temperatures.

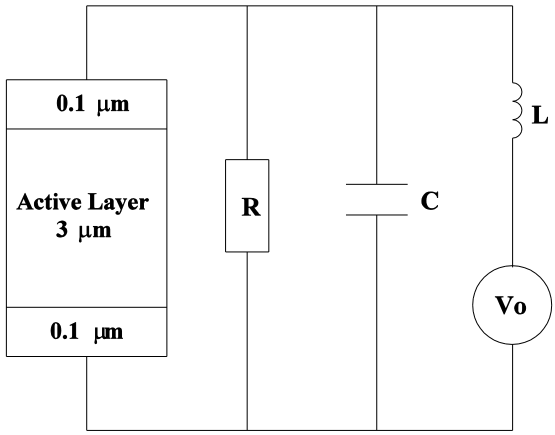

Fig. 4: Schematic of the Gunn diode and the resonant cavity.

Mobility Model

In order to properly model temperature effects in semiconductor devices, there is the need to derive an appropriate mobility model, that takes into account the relevant stochastic and scattering mechanisms considered in the Monte Carlo simulation. Such mobility models are derived for low-field as well as for high-field conditions. The model for the low-field condition is expressed as follows [10]:

$$\mu^{\mathrm{LI}} = \mu^{\min} + \frac{\mu^{\mathrm{L}} - \mu^{\min}}{1 + \left(\dfrac{C_{\mathrm{I}}}{C^{\mathrm{ref}}}\right)^{\gamma_0}}$$

$$\mu^{\mathrm{L}} = \mu_{300}^{\mathrm{L}} \left(\frac{T_{\mathrm{L}}}{300\mathrm{K}}\right)^{\gamma_1}, \quad \mu^{\min} = \mu_{300}^{\min} \left(\frac{T_{\mathrm{L}}}{300\mathrm{K}}\right)^{\gamma_2}, \quad C^{\mathrm{ref}} = C_{300}^{\mathrm{ref}} \left(\frac{T_{\mathrm{L}}}{300\mathrm{K}}\right)^{\gamma_3},$$

where μ^{L} is the electron mobility in undoped material, $\mu^{\min}$ is the mobility at high doping, C^{ref} and γ_0 model the mobility decay with rising impurity concentration C_{I}. γ_1, γ_2 and γ_3 are used to model the mobility and concentration dependence on the lattice temperature T_{L}. The calibrated model parameter values are summarized in Table I. As can be seen in Fig. 1 and Fig. 2, these values provide an excellent agreement to the Monte Carlo simulation data.

To model the high-field mobility in InN, a hydrodynamic transport model is employed [11], which accounts for intervalley transfer of electrons at higher electric fields and the subsequent abrupt decay in their velocity (Fig. 3).

Table I: Parameter values for the low-field InN mobility model.

Ref.	μ_{300}^{L} [cm²/Vs]	μ_{300}^{min} [cm²/Vs]	C_{300}^{ref} [cm⁻³]	γ_0	γ_1	γ_2	γ_3
[13]	10200	500	3.4×10^{17}	0.65	-2.7	-2.7	4.5
This work	11980	700	2.2×10^{17}	0.65	-2.6	-0.6	4.2

Such high-field mobility model uses the already discussed low-field mobility expressions, constant energy relaxation times as taken from the Monte Carlo simulation, and the electron saturation velocity v_{sat} as input parameters. While a detailed discussion of the model is given elsewhere [11], this work focuses on a profound description of the temperature-dependent parameters. The saturation velocity v_{sat} is modelled as a function of lattice temperature by [12]:

$$v_{sat}(T_L) = \frac{v_{sat,300}}{(1-A) + A\cdot\left(\frac{T_L}{300\text{K}}\right)}$$

where $v_{sat,300}$ is the saturation velocity at T_L=300 K and A is a parameter that models the v_{sat} decay at higher temperatures. The values obtained after calibration against the Monte Carlo simulation data ($v_{sat,300}=1.21\times10^7$cm/s and A=0.3) ensure a proper approximation of the electron velocity dependence on lattice temperature at high electric fields (Fig. 3). The pronounced decrease of the peak electron velocity, observed for high applied fields, predicts the existence of a negative differential resistance for InN. This is a requirement for the occurrence of the Gunn effect.

Device/Circuit Simulation Results

In order to assess the influence of the temperature in a transferred-electron device, we construct an InN Gunn diode with an active layer (10^{17} cm^{-3}) of 3 µm length and two highly-doped (10^{19} cm^{-3}) contact regions of 0.1 µm each. The device of area 2000 µm^2 is connected to a LCR-cavity (L=10 pH, C=0.1 pF, R=50 Ω , V_0=13 V), so that it can operate as an oscillator (see Fig. 4). The temperature-dependent mobility model for InN, calibrated against the Monte Carlo simulation data, is implemented in MINIMOS-NT, which was already successfully employed for the high-temperature study of GaN-based high electron mobility transistors [14]. The simulation tool allows a mixed-mode device/circuit simulation of the Gunn diode. Fig. 5 shows voltage waveforms as resulting from isothermal simulation at different ambient temperatures. Fig. 6 shows the voltage waveforms when self-heating of the device is taken into consideration. The amplitude of the voltage oscillations decreases strongly with temperature for both conditions considered, which must be attributed to the temperature-driven decrease of the electron mobility. The output power of the diode is shown in Fig. 7, for isothermal conditions, and in Fig. 8 for self-heating respectively. A significant power decrease with increasing temperature is observed. At 500 K the swing of the output power waveforms is strongly damped.

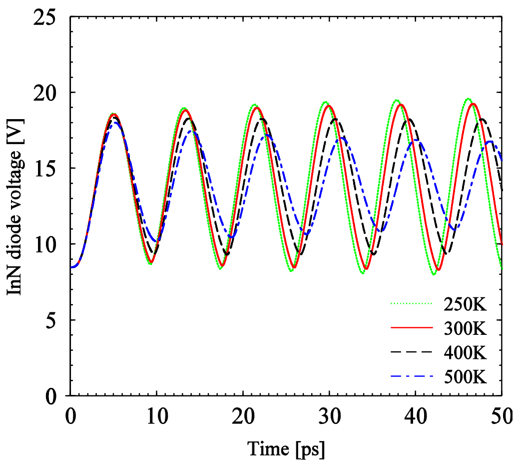

Fig. 5: InN diode voltage waveforms for different temperatures and isothermal condition.

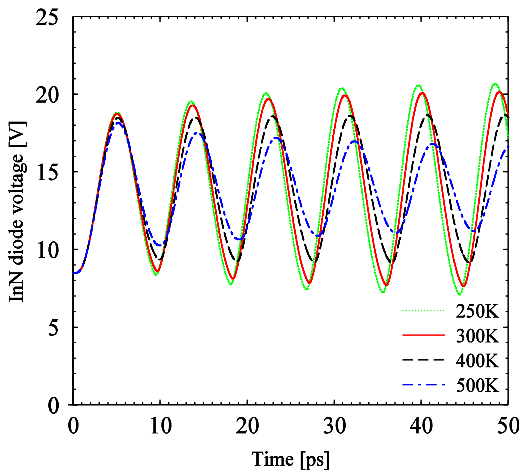

Fig. 6: InN diode voltage waveforms for different temperatures when self-heating is considered.

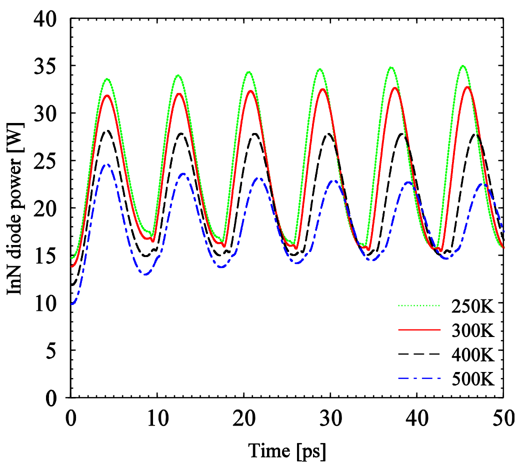

Fig. 7: InN diode output power for different temperatures and isothermal condition.

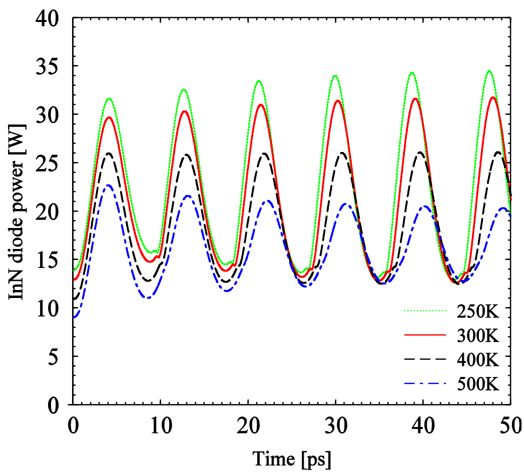

Fig. 8: InN diode output power for different temperatures when self-heating is considered.

Conclusion

A temperature-dependent mobility model for InN is established based on Monte Carlo simulation results. It is implemented in a device simulation tool, which is used to evaluate the temperature-dependent performance of a InN Gunn diode oscillator. Our results show that the output power of the diode exhibits a strong temperature dependence, which is an important parameter to be accounted for when designing such devices for practical applications.

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