Hot-phonon effects on the transport properties of an indium phosphide $n^+\!-n-n^+$ diode

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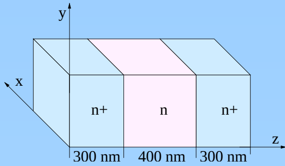
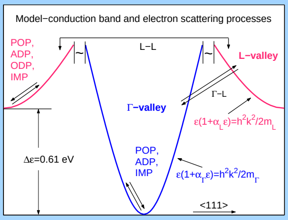
The InP-Diode

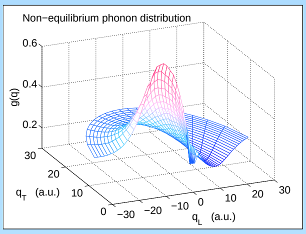
Non-equilibrium polar optical (pop) phonons strongly influence the transport properties of the electron gas in III-V compound semiconductors, such as InP and GaAs. We present simulations of an InP $n^+\!-n-n^+$ diode taking into account these hot-phonon effects. For the diode, donor concentrations of $5\times10^{17}\,\mathrm{cm}^{-3}$ in the n^+-region and of $2\times10^{15}\,\mathrm{cm}^{-3}$ inside the channel are assumed. The conduction band of InP is approximated by non-parabolic energy-momentum relations for the central Γ-valley and the four equivalent L-valleys along $\langle 111\rangle$.




Model−conduction band and electron scattering processes

Hot-Phonon Effects

When the coupled system of electrons and pop phonons is exposed to an electric field, far-from-equilibrium phonon distributions are found. The non-equilibrium pop phonons modify the electron scattering rates and, therefore, re-affect the electrons.


Non−equilibrium phonon distribution

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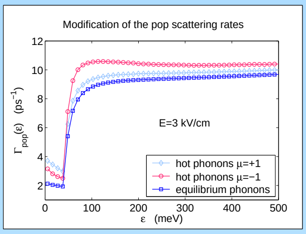

Modification of the pop scattering rates

Kinetic Model

The simulation of the InP diode is treated as a one-dimensional problem in the physical space, and cylindrical symmetry is assumed in the momentum space. We consider the set of Boltzmann equations

$$\partial_t\phi^\nu+\partial_z(a_1^\nu\phi^\nu)+\partial_\varepsilon(a_2^\nu\phi^\nu)+\partial_\mu(a_3^\nu\phi^\nu)=C^\nu(\{\phi^\nu\},g),\quad \nu=1,2,$$
$$\partial_t g=C^p(\{\phi^\nu\},g)$$

for the distribution functions $\phi^\nu(\varepsilon,\mu,z,t)$ of electrons in the Γ- and L-valleys ($\nu=1,2$) and the pop phonon distribution function $g(k,\mu,z,t)$. Here, ε denotes the electron energy, k the modulus of the momentum vector $\boldsymbol{k}$ and μ is the cosine of the angle between $\boldsymbol{k}$ and the z-axis. The coefficients a_1^ν and a_2^ν are proportional to the z-component of the electric field $E_z=-\partial_z V(z,t)$, which is coupled with the electron density $n(\boldsymbol{r},t)$ and the donor density $n_0(\boldsymbol{r})$ via the Poisson equation

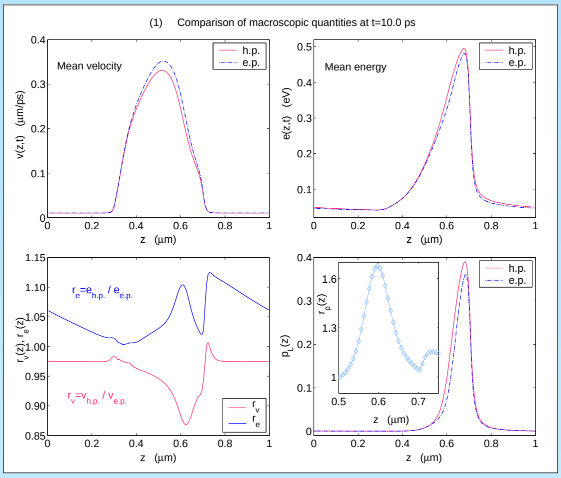
$$\Delta_r V(\boldsymbol{r},t)=\frac{e_0}{\epsilon_0}[n(\boldsymbol{r},t)-n_0(\boldsymbol{r})].$$

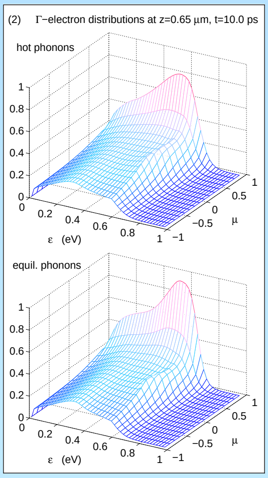
Electron scattering processes are taken into account by the collision operators C^ν. Temporal changes of the phonon distribution due to electron-phonon and phonon-phonon interactions are determined by C^p.

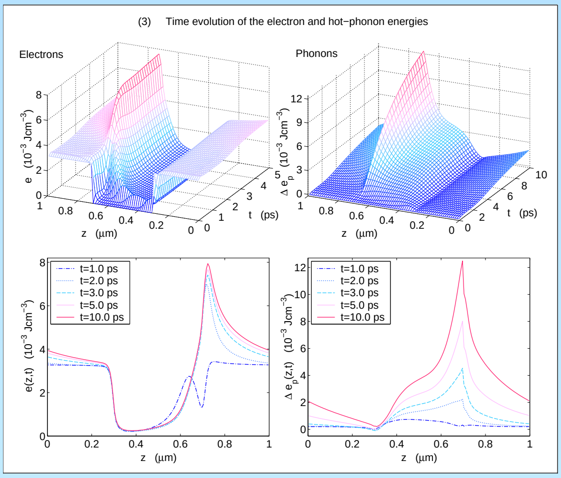
Numerical Treatment

We apply a direct solver for the system of the Boltzmann equations for electrons and pop phonons coupled with the Poisson equation. Uniform discretizations of the (ε,μ,z)- and the (k,μ,z)-space are performed and a set of evolution equations for the cell averages of the distribution functions is considered. In our conservative scheme the shock-capturing ENO and WENO methods are used to obtain high-order approximations of the partial derivatives with respect to ε, μ and z. The collision operators are treated according to the multigroup model. For the time integration we apply a second-order Runge-Kutta type TVD scheme.

Results


(1) Comparison of macroscopic quantities at t=10.0 ps


(2) Γ−electron distributions at z=0.65 μm, t=10.0 ps


(3) Time evolution of the electron and hot−phonon energies

The calculations are performed for a diode at $T=300$ K and an applied bias of 1 V. Figure (1) presents a comparison between the macroscopic quantities resulting from simulations considering non-equilibrium and equilibrium pop phonons. Hot phonons lower the average electron velocity and increase the mean electron energy inside the channel of the diode. We find maximal deviations of 10 percent. The most significant changes are obtained for the population p_L of the L-valleys. Non-equilibrium phonons increase the L-valley population up to 60 percent. Our kinetic approach allows us to directly investigate the distribution functions. The Γ-valley distribution functions of electrons interacting with hot phonons and equilibrium phonons are displayed in figure (2). Both distribution functions show a far-from-equilibrium behavior. The maximum value of the distribution function is decreased, when electrons interact with non-equilibrium phonons. A study of the energy transfer between electrons and pop phonons is presented in figure (3). The obtained results prove that hot-phonon effects must be taken into account for accurate simulations of InP devices.

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