Influence of electron-hole scattering on the plasma thermalization in doped GaAs

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The cooling of an electron-hole plasma in bulk *n*- and *p*-type doped GaAs is calculated without assuming complete thermalization between electrons and holes. Electron-hole scattering and nonequilibrium optical phonons are included in the simulation. In *n*-doped GaAs, we show that at low excitation density (i.e., when the photogenerated plasma density is small compared to the donor density), the electrons are at first colder than the holes but heat up quickly and subsequently stay close to the hole temperature. At low density in *p*-doped GaAs, however, the holes stay cold and the electron cooling is mainly controlled by electron-hole scattering.

I. INTRODUCTION

The advances in the development of ultrafast laser sources[1] have opened up possibilities to study directly the dynamics of carriers in semiconductors (for a review, see, e.g., Ref. 2). Several phases of the relaxation process can be distinguished: (i) the initial relaxation of photoexcited carriers from the creation energy up in the bands to the band edge takes place on a femtosecond time scale; (ii) at the band edge, the carriers form (at higher excitation densities) a thermalized electron-hole plasma (EHP), which has initially a temperature much higher than the lattice; (iii) the *cooling of this plasma* to the lattice temperature by emission of optical and acoustical phonons occurs on a time scale of a few hundreds of picoseconds and can be easily traced by time-resolved optical techniques.[3,4] Most of the experimental work in this time range has been done for III-V compounds, in particular GaAs and GaAs/$Al_xGa_{1-x}As$ heterostructures.

Experiments on both bulk semiconductors[5-12] and quantum wells[13-21] (QW's) have shown that the cooling of the hot EHP can be surprisingly slow, at least at higher carrier densities. In particular, it turned out that the energy-loss rates (ELR's) to the lattice by polar-optical scattering (Fröhlich interaction), which is the most important scattering process for plasma temperatures above about 60 K, can be strongly reduced when compared to a simple theoretical calculation of the energy-loss rate. This simple calculation assumes that (i) electron and holes can be described by thermalized distributions, (ii) electrons and holes have the same temperature, and (iii) the phonon system is in equilibrium with the lattice. It was discussed by several authors[5,6,22-25] whether free-carrier screening of the polar-optical interaction could explain the difference between theory and experimental results. Recent experimental investigations of the cooling of hot carriers in $Al_xGa_{1-x}As$,[26] however, have shown that screening is unimportant up to the rather high density of 7×10^{17} cm^{-3}. Theoretical calculations of Collet[27] agree with this experimental result and indicate that screening is only important in the density regime above 10^{18} cm^{-3}.

Calculations of the *coupled carrier-phonon system* have shown that the LO-phonon system is driven considerably out of equilibrium in the comparatively narrow *k*-space volume where the interaction with the carriers takes place. These "hot phonons" are reabsorbed by the carriers and delay the cooling of the plasma. The limiting process for the transfer of the energy from the carriers to the lattice is the decay of optical into acoustic phonons with a decay time of about 10 ps (Refs. 28 and 29) in GaAs at low temperatures. The importance of a phonon nonequilibrium has also been pointed out for quasi-two-dimensional systems (quantum wells) in several theoretical studies.[30-34] The influence of carrier scattering and electron-hole scattering in the fs range was also investigated in the bulk[35] and in QW.[36]

The initial calculations of Pötz and Kocevar[24] assumed equal electron and hole temperatures. Recently, Pötz[37] and Asche and Sarbei[38,39] presented calculations of the cooling with different electron and hole temperatures ($2T$ model) including nonequilibrium phonons. One of the main results was that the electron temperatures in a $2T$ model are always higher than in a $1T$ model. One lack of these calculations was the description of the hole system by Maxwell-Boltzmann (MB) statistics when calculating the electron-hole (e-h) scattering rates. This assumption simplifies the numerical calculations, but becomes inaccurate at high densities and low temperatures. All these calculations addressed cooling in undoped samples.

In this paper, we present calculations of the carrier-phonon dynamics in bulk GaSa. We use a $2T$ model which includes the electron-hole scattering rates without assuming that the holes are nondegenerate. We address the problem of cooling in doped semiconductors, which has not yet been studied theoretically. For *n*-doped GaAs, we show that at low plasma density (i.e., when the number of photogenerated carriers is small compared to the doping density) the electron temperature is first much lower than the hole temperature, but quickly rises and exceeds the hole temperature slightly for later times. At low density in p-doped GaAs, the holes stay cold and the electron cooling is controlled by *electron-hole scattering rather than phonon emission.* Luminescence experiments which extract (from the decay of the luminescence high-energy tail) an effective temperature close to that of electrons could be a valuable tool to study the electron-hole scattering rate in p-doped samples.

II. RESULTS

A. Theoretical background

The electron and hole systems are assumed to be thermalized, i.e., both electron and hole distribution are Fermi-Dirac distributions with (generally different) temperatures T_e and T_h. This assumption can be used for calculations which are compared with experiments with pulse lengths and time resolution in the ps regime. Such a model is obviously not suitable for comparison with fs experiments, where nonthermal carrier distributions are expected.[35] However, recent experiments in $Al_xGa_{1-x}As$ demonstrate that each band is quasi-thermalized within a few hundred fs.[40] Light and heavy holes are approximated by a single hole band with heavy-hole mass. This approximation should be rather good, since the emission of LO phonons by light holes is much less important than the emission by heavy holes due to the smaller mass of the light holes. The shape of the laser pulse is approximated by a Gaussian profile with 6 ps pulse duration.

One main part of the simulation is the calculation of the coupled carrier-phonon system. The algorithms used are similar to the model used in Ref. 24. Three phonon scattering mechanisms are important in temperature range above 20 K (see Fig. 5 in Ref. 20): polar-optical scattering with LO phonons (Fröhlich interaction), deformation-potential scattering of the holes with TO phonons, and deformation-potential scattering with acoustic phonons. One problem is that the calculation of the energy-loss rate due to the latter two interactions relies on assumptions on the deformation potentials. The acoustic deformation potential for holes can be rather accurately determined by analyzing the cooling in the low-temperature range.[20,41] The optical deformation potential, however, is not very well known. It is difficult to discriminate this scattering mechanism in the described experiments due to the very similar temperature dependence of the polar-optical scattering. The available values for the optical deformation potential indicate that the ELR due to optical deformation potential scattering is about one order of magnitude lower than the ELR due to polar-optical scattering.

A frequently discussed problem is the influence of screening on the energy transfer rates. Earlier calculations used the static limit of the random-phase approximation (RPA).[37–39] It was recently shown by Collet[27] that this approximation tends to overestimate the effect of screening. According to the dynamic RPA,[27] the total ELR by the Fröhlich interaction is virtually not changed by the screening up to densities of up to 7×10^{17} cm^{-3}. We therefore neglect screening for the interactions with optical phonons.[42] The static screening approach can be used for the interaction with acoustical phonons, as discussed by Pugnet, Collet, and Cornet.[23]

The phonon decay is described by a relaxation-time ansatz. We use a phonon decay time constant of 10 ps (Ref. 29) for both LO and TO phonons. For acoustical phonons, we set the phonon occupation to the occupation corresponding to the lattice temperature, i.e., no hot phonon effects are taken into account for acoustical phonons.[24] The electron-hole scattering is calculated assuming Coulomb scattering in parabolic bands. The energy transfer rate between electrons and holes reads:[43]

$$\frac{1}{\rho}\frac{d\langle E\rangle}{dt}\bigg|_{e\text{-}h}=\frac{1}{2\pi^2\rho}\int_0^\infty\sqrt{\xi}f_e(\xi)\frac{dE(\xi)}{dt}\bigg|_{e\text{-}h}d\xi\;, \tag{1}$$

where $dE(\xi)/dt$ is the energy transfer of a single electron of energy $\xi=(\hbar^2/2m_e)k^2$ to the hole system given by

$$\frac{dE(\xi)}{dt}\bigg|=S\int_0^\infty\frac{d\rho}{|\eta+\eta_D|^2}\int_{-1}^{1}d\phi\,\Delta E\frac{1-f_e(\xi-\Delta E)}{\exp[(-\Delta E/k_BT_h)]-1}\ln\left[\frac{1+\exp[(-\lambda_0+\mu_h)/k_BT_h]}{1+\exp[(-\lambda_0-\Delta E+\mu_h)/k_BT_h]}\right]. \tag{2}$$

Here, $\eta_D=(\hbar^2/2m_e)q_D^2$, $S=m_h^2e^4k_BT_h/m_e\pi\hbar^3\epsilon_0^2$, and μ_h is the hole Fermi level; λ_0 is equal to

$$\lambda_0=\frac{1}{\sigma}\left|\sigma\phi\sqrt{\xi}-\frac{\sigma+1}{2}\sqrt{\eta}\right|^2\;, \tag{3}$$

with $\sigma=m_h/m_e$. The screening vector q_D is used in the Debye-Hückel form of

$$q_D^2=-\frac{4\pi e^2}{\epsilon_0}\sum_{k,\lambda}\left[\frac{\delta f_\lambda(k)}{\delta E_\lambda(k)}\right]\;. \tag{4}$$

It must be stressed that Eq. (2) holds if the hole distribution is degenerate. This particular situation occurs in weakly excited p-doped samples as will be shown in the next section. The ansatz of static screening is a good approximation if electron and hole masses are rather different (see the Appendix of Ref. 43). The material parameters for GaAs we have used are listed in Ref. 20. Detailed results for the energy transfer by carrier-carrier scattering as a function of density and temperature are given in Ref. 44.

B. Cooling in doped semiconductors

The study of cooling in undoped semiconductors is complicated by the fact that one always has to deal with the carrier-carrier scattering *and* with the interaction of electrons and holes with the phonons. This problem might be simplified by studying doped semiconductors, where it should be possible to study the cooling of one type of carrier alone. Such investigations have been performed for modulation-doped quantum wells.[14–17,20,21] Recently, infrared free carrier absorption was introduced[8] as a powerful tool to study the electron and phonon dynamics without creating holes at all, which even more simplifies the experimental situation.

In the following, we present calculations of the plasma cooling in doped bulk systems. These calculations can also be helpful to understand the qualitative features of the cooling in modulation doped quantum wells. Figure 1 shows the electron (solid line) and hole temperature (dashed line) in n-doped GaAs (doping density $n_0=8\times10^{17}$ cm^{-3}) for various excitation densities $n_{\rm exc}$ (as indicated in the figure). The lattice temperature is set to 4 K. At higher densities, the temperatures of electrons and holes are rather similar after a few ps. The cooling, however, is slower than for the undoped sample because of the stronger influence of hot phonons on the cooling of electrons. For the lower densities, the electrons need about 10 ps to be heated up to the hole temperature; subsequently, the holes have a somewhat lower temperature than the electrons due to their more efficient cooling. These calculations show that the electron temperatures (which are usually obtained experimentally from the luminescence line shapes) reasonably describe the temperatures of the plasma components, at least for times longer than 10 ps. A quantitative analysis of experimental data, however, should take the difference between electrons and holes of up to 10 K into account: The exponential temperature dependence of the polar-optical scattering might otherwise lead to comparatively large errors. Another difficulty is that the electrons do not reach temperatures where the polar-optical scattering is important, i.e., experiments cannot give information about this most important scattering mechanism.

Figure 2 shows the result of calculations of the cooling in a p-doped sample ($p_0=6\times10^{17}$ cm^{-3}) for various excitation densities. At high excitation densities (top), when the density of photoexcited carriers exceeds the doping density, the cooling is similar as in an undoped system. The electron and the hole system thermalize within about 10 ps, and the determination of the (electron) temperature from the luminescence spectra gives a reasonable description of the cooling of the system. At lower excitation densities, however, the situation changes rapidly: The holes are only weakly heated, and at very low densities ($n_{\rm exc}\lesssim10^{16}$ cm^{-3}), their temperature stays close to the lattice temperature. Note that the hole distribution is

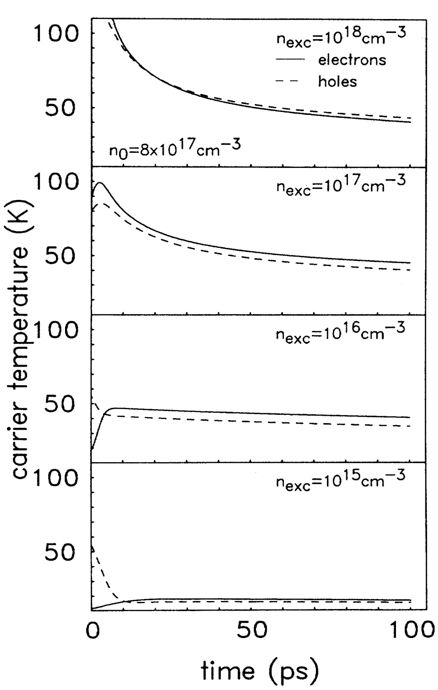

FIG. 1. Cooling curves calculated for an n-doped sample with a doping density of 8×10^{17} cm^{-3} and various excitation densities. The lattice temperature is set to 4 K. The electron and hole temperatures are the solid and dashed lines, respectively.

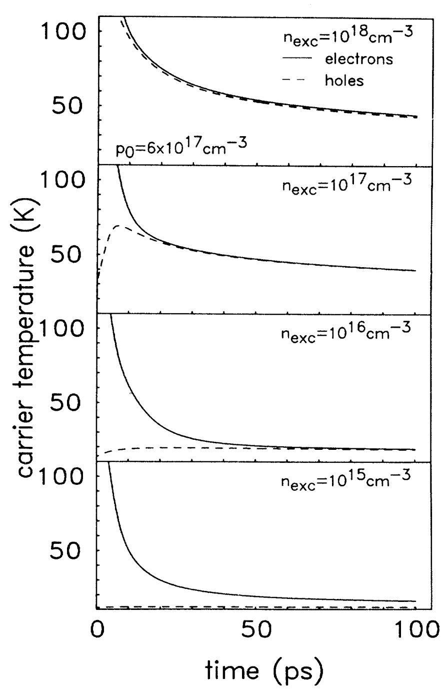

FIG. 2. Cooling curves calculated for a p-doped sample with a doping density of 6×10^{17} cm^{-3} and various excitation densities. The electron and hole temperatures are the solid and dashed lines, respectively.

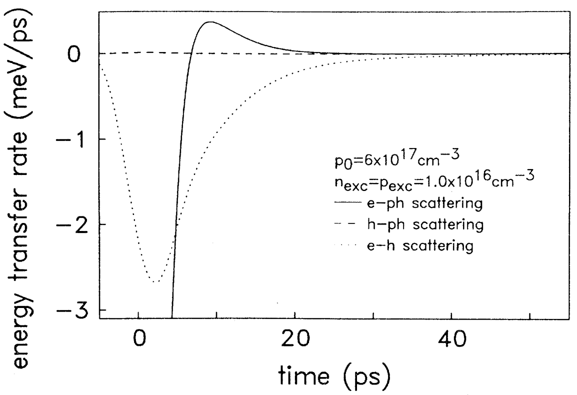

FIG. 3. Energy-loss rates of the carriers in a p-doped sample as a function of the delay time. Shown are the energy loss of the electrons (solid line) and holes (dashed line) due to scattering with phonons and the energy exchange between electron and holes due to Coulomb scattering (dotted line).

degenerate under these conditions ($p_0 \approx 6\times10^{17}$ cm^{-3}, $T \approx 10$ K). The cooling of the hot electrons after 10 ps (and $T_e \leq 50$ K) is *due to e-h scattering* and not due to phonon emission. This is evident in Fig. 3 where transfer rates of the electrons due to the different scattering processes have been plotted. In the first few ps, the electrons cool quickly due to phonon emission (solid line). However, then the electrons cool mainly due to scattering with the cold hole plasma (dotted line). A rather weak heating of the electrons occurs ($dE/dt \approx 0.3$ meV/ps) around 10 ps due to the reabsorption of optical phonons. These results show that the analysis of cooling in p-doped samples is rather intricate. The simple assumption[17,20,21] that the observed cooling curve reflects the cooling of a high-density hole plasma by phonon emission is obviously misleading. Cooling experiments in p-doped samples at low excitation densities do not yield information about the energy-loss rate of a high-density hole plasma due to phonon scattering, but rather yield the scattering rate of the low-density electrons with the holes. The conclusions about the screening of the hole-phonon interaction made in Ref. 21 ought to be reconsidered.

Although experiments in p-doped structures do not give information about the cooling rate due to phonon emission, they might give valuable information about the Coulomb interaction between electrons and holes. The electron cooling (as traced in luminescence experiments) directly reveals the scattering rate between a dilute hot electron plasma and a dense cold hole plasma. Time-resolved luminescence experiments in doped bulk semiconductors could directly yield scattering rates between electron and holes, without assumptions about the phonon scattering rates. A strong temperature difference between electron and holes has been observed in transport experiments by Höpfel, Shah, and Gossard.[45]

III. CONCLUSION

We have presented theoretical calculations of the thermalization of EHP with the lattice, taking different electron and hole temperatures and phonon nonequilibrium into account. Calculations for doped semiconductors show that large temperature differences between the electron and hole system can occur. For p-type samples, the commonly used data analysis assuming equal electron and hole temperatures can lead to incorrect conclusions. The cooling is mainly determined by the energy transfer between electron and holes due to Coulomb scattering rather than by the emission of optical phonons.

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