Electron electron interaction and classical mesoscopic phenomena in semiconductors

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Abstract

I discuss the effect of electron-electron interaction on classical mesoscopic phenomena in semiconductor devices, as manifested by the well-known phonon conductivity oscillations in tunnel junctions. The central idea is the realization that the temperature dependence of the oscillation amplitude contains a direct and unambiguous information about the rate of electron-electron scattering in the material studied. Quantitative theory to be developed and device modeling based on this theory should enable a unique characterization of electron-electron interaction, extracting parameters relevant to the operation of important semiconductor devices.

I. Electron-electron interaction in modern devices

Electron-electron (e-e) interactions are important in the operation of all modern semiconductor devices. Their primary consequence is the equilibration of electron distributions. Starting from any initial distribution, e-e collisions lead [Ga-87] to an equilibrium within the electron gas, expressed by a "displaced" Fermi distribution function and characterized by three parameters: the effective temperature T_e, the drift velocity $\langle \mathbf{v} \rangle$, and the Fermi level E_F – determined respectively by the conservation of total energy, momentum, and particle number. In the reference frame that travels with the velocity $\langle \mathbf{v} \rangle$, this distribution looks like an equilibrium Fermi function.

Electron-electron interaction becomes the dominant scattering mechanism when the bulk concentration of carriers exceeds 10^{17} cm^{-3}. The analogous number for a two-dimensional electron gas is believed to be about 10^{11} cm^{-2}. At high carrier concentrations, the effect of e-e interaction is included via the electron temperature approximation. This amounts to assuming the energy distribution in the form of a displaced Fermi function.

Once the quasi-equilibrium form of the carrier distribution function is assumed, the e-e interaction is no longer of central interest in conventional devices. Indeed, the e-e scattering rate τ_{ee} is of little importance (so long as it is short enough) for such practical issues as the carrier mobility, etc., since inter-electron collisions do not contribute significantly to the momentum relaxation in the electron gas. In contrast, for semiconductor devices whose dimensionality is reduced by quantum confinement on the nanoscale level, the effect of e-e interactions remains important – sometimes dominant – even in the quasi-equilibrium ensemble.

A primary example of this situation is provided by quantum well (QW) lasers, where polarization dephasing effects due to carrier collisions give an important contribution to the width of the lineshape function. These effects are commonly included via an effective decay rate approximation, treating the dephasing rate as an input to the calculations. However, to design QW lasers for an expanding range of

applications, it is necessary to predict their gain spectra accurately. As shown recently by Chow [Ch-98], the decay rate approach leads to significant inaccuracies as compared to QW laser gain spectra calculated via the semiconductor Bloch equations [Ha-94] with Coulombic correlations included at the level of a quantum kinetic theory.

Similar effects – but of even greater significance – are expected in the *unipolar* (intersubband) QW laser gain media. A class of useful nanoscale devices, such as quantum cascade lasers (QCL), have recently emerged, where the dephasing effects associated with e-e interactions are no longer small perturbation to a well-understood classical behavior, but rather the central mechanism controlling the kinetics of the dominant *functional* activity. It is well understood that the dephasing of intersubband transitions by scattering severely limits the QCL gain [Go-96]. So far, only phonon and impurity scattering have been considered rigorously [Ge-96, Ki-97]. However, at the experimentally relevant carrier densities the dephasing due to e-e collisions is important and must be taken into account.

Other important issues related to e-e interaction in nanoscale devices are associated with *departures* of the electron distribution from the quasi-equilibrium form. The most widely studied case arises in high-field transport in transistor channels [Pi-93], leading to such technologically important effects as velocity overshoot. The influence of e-e interaction on high-field transport, while important, is difficult to identify experimentally. Beyond simple estimates, most of the insight about these processes has been gained through Monte Carlo simulations [Ja-98].

Another important case of a non-equilibrium departure arises in ballistic injection structures [Lu-98]. Here, the main technological interest is in the ballistic mean free path of minority carriers in the base of heterojunction bipolar transistors (HBT). Ballistic HBT has been the first transistor to reach subpicosecond speeds [Ch-89]. In such a device, carriers are launched at high energies into a small angular cone perpendicular to the base-emitter junction. The fact that the velocity distribution is sharply peaked in the direction perpendicular to the base layer, is beneficial for downscaling the device area [Ja-89]. This opens an intriguing possibility of implementing a HBT with ballistic minority carriers forming a collimated and monoenergetic beam. Such a regime has been predicted [Gr-93] to exhibit peculiar "coherent" effects, manifested in resonances in the common-emitter current gain at frequencies far exceeding the usual transit-time cutoff frequency f_T. The extended frequency is limited by the dispersion in the minority-carrier times of flight across the base, rather than the time of flight itself and reaches, in principle, into the terahertz range.

II. Classical mesoscopic ensembles

In the above examples, the non-equilibrium distributions are "microscopic" in the sense that they persist over only a very short time after a perturbation (the energy relaxation time $\tau_\varepsilon \lesssim 1\,\text{ps}$ for overshoot effects or even shorter momentum relaxation time τ_m for ballistic transport).

Useful non-equilibrium electron ensembles in semiconductors may form not only as a result of electron acceleration by high electric fields or barrier injection, but also due to electron-phonon interactions [Ga-87]. In principle, such interactions can also maxwellize the distribution, if independent scattering events exchange random energies with electrons. However, while scattering by acoustic phonons has this property, optical phonon scattering does not. If the latter were the only inelastic interaction, the equilibrium shape of the electron distribution function would be

dependent on the initial conditions and so would be thermodynamic properties of the electron ensemble. The peculiarity of optic phonons stems from their largely monochromatic nature, which quantizes the energy exchange in units of $\hbar\omega_{op}$.

At sufficiently high temperatures or high electron energies, the electron energy relaxation rate due to optical phonons ($1/\tau^{(op)}$) is higher than that due to acoustic phonons ($1/\tau^{(ac)}$) by several orders of magnitude. Typically, in semiconductors $\tau^{(op)} \lesssim 10^{-12}$ s and $\tau^{(ac)} \gtrsim 10^{-9}$ s [Co-67]. This disparity of the inelastic relaxation times leads to the formation of an electronic ensemble that is in equilibrium with optical phonons, but not yet with acoustic phonons.

Manifestation of the properties of such ensembles can be conveniently referred to as the ''classical mesoscopic effects'' – drawing a parallel to and a distinction from the quantum mesoscopic effects that occur when the coherence length of an electronic wave function exceeds characteristic system dimensions. Thermodynamic properties of electrons in the mesoscopic state are very different from those in true equilibrium, e.g., the average energy $\langle E \rangle \neq 3/2\,kT$ and the specific heat deviates from the classical value $3/2\,k$ [Gr-90a]. Also the electron mobility in the mesoscopic state shows a strong overshoot. The time scale of this effect is very different from the conventional velocity overshoot; the mesoscopic state is established in less than 1 ps and persists for a long time (up to nanoseconds!) – destroyed by acoustic phonon (and e-e!) scattering. Systematic study of the classical mesoscopic kinetics has been carried out by Grinberg [Gr-91a] by a combination of analytic and Monte Carlo techniques.

The classical mesoscopic regime manifests itself not only in the time domain, but also in spatially nonuniform systems. The conservation of mesoscopic properties is expressed by an appropriate continuity equation, that involves a vector field called the reduced differential current [Gr-91b]. This has proven fruitful in explaining [Gr-90b] the phonon oscillations in current-voltage characteristics of heterostructure tunneling diodes [Ea-85a] as well as the energy oscillations of the distribution function produced in thermionic transport over triangular barriers, as discovered by Venturi [Ve-91] in Monte Carlo experiments. In both of these instances the experimental situation (or theoretical model) were set up so that the e-e interaction was negligible due to low values of the carrier concentration.

The role of e-e interaction in carrier thermalization has been studied in greatest detail in connection with optical spectroscopy experiments in which photoexcited electron-hole plasma is investigated via pump-probe and luminescence spectroscopic techniques, including time resolved studies on the femtosecond scale (cf. an early review by Esipov and Levinson [Es-87] and a very recent review by Shah [Sh-98]. A partial reference list to the relevant publications follows: experimental [Kn-86, Kn-88, Be-88, Ka-89, El-91, Bi-91, Sn-92a, Sn-92b, Ka-93] and theoretical [Es-84, DS-88, Os-87, Ku-91, ES-92, ES-93, Sn-93, Sn-94, ES-94, Hu-96, Ha-96, Sm-96, Se-97, Le-97].

Previous theoretical investigations of mesoscopic distributions had focused on their manifestations. Consequently, the e-e interaction was viewed as a "spoiler" in these studies: it was understood and deplored that the cute structures in the distribution function and the resultant mesoscopic effects would be washed out by e-e scattering in some unremarkable way. Monte Carlo studies of the comparative kinetics of the formation and destruction of a mesoscopic state [Gr-91a] showed that practically no effects could be observed in a bulk semiconductor already for carrier concentrations as low as 10^{16} cm^{-3}. This has been viewed as a sobering conclusion, since most contemplated

applications of the mesoscopic distribution would require higher carrier concentration. Because of such considerations, researchers interested in practical applications of classical mesoscopic effects have turned to systems of reduced dimensionality, where the detrimental effects of the e-e interaction would be somewhat suppressed compared to the bulk situation [Le-92, Ci-98, Ry-98, ST-98].

Remarkably, it has been left unnoticed that the very washing out of the mesoscopic phenomena may be used as an effective handle to study the e-e interaction itself. *It is precisely this fact that animates the present discussion*. It is argued below that the destruction by e-e interaction of classical mesoscopic phenomena can be made easily observable and, moreover, practically unobscured by other effects. Additionally, I argue that such a quantifiable destruction had in fact been observed very clearly (but not recognized as such!) already in 1991 in an experimental study of phonon conductivity oscillations in tunnel junctions [Al-91]. In that study Alikacem reported an exponential suppression of the amplitude of phonon oscillations with increasing temperature, but incorrectly interpreted this observation and did not relate it to electron-electron interactions.

With the proper interpretation, described below, it should be feasible to develop a quantitative theory of the phonon conductivity oscillations, which will in turn permit a rigorous experimental study of the electron electron interaction in semiconductors, both in the bulk and in reduced-dimensionality systems.

III. Brief Review of the Phonon Oscillation Experiment: a Puzzle

Current-voltage characteristics of single-barrier heterostructures show an oscillatory structure in applied voltage with a well defined period.

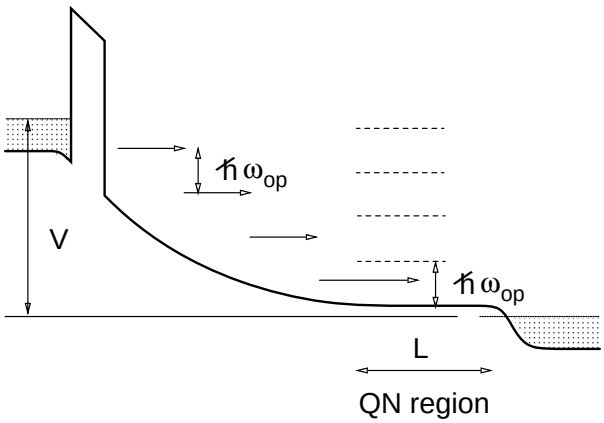

Fig. 1: Phonon-induced conductivity oscillation experiment. Schematic energy-band diagram with a sample under bias. Arrows indicate the energy of an individual electron as it emits optical phonons. Impedance of the quasi-neutral (QN) region to the motion of injected hot carriers depends on the "phase" ϕ with which the entire energy distribution of injected current folds into the range $(0, \hbar\omega_{op})$. The voltage drop, associated with the hot-carrier current through the QN region is a quasi-periodic function of the applied voltage V.

The characteristic period ΔV of these oscillations corresponds to the LO phonon energy $\hbar\omega_{op}$, $e\,\Delta V = \hbar\omega_{op}$. This effect was originally discovered by Katayama [Ka-67] in InSb and then rediscovered in GaAs by Hickmott [Hi-84] at low temperatures ($T \lesssim 4$K) and high magnetic fields ($B \gtrsim 4$T). Soon after that Eaves [Ea-85a] observed the oscillatory structure in similar devices at $B = 0$ and higher temperatures. Energy band diagram of a typical experimental n^+GaAs/(AlGa)As/n^-GaAs/n^+GaAs sample is illustrated in Fig. 1.

The precise mechanism of phonon-induced oscillations has been the subject of some controversy. A number of untenable models had been proposed initially, some relying on obscure effects due to the magnetic field (such models, of course, faded way once the effect was found in the absence of a field), others postulating an unphysical picture of carrier freeze-out in the field region of the diode. At this time, it is generally

agreed that the oscillations are due to a periodic modulation of the impedance of the undepleted (quasi-neutral, QN) section of the lightly-doped GaAs layer immediately adjacent to the collector contact. However, precisely how this modulation occurs has remained controversial. It is generally accepted that carriers enter the QN region having emitted all the optical phonons they could emit. Because of this and since the time of flight is sufficiently short that no other inelastic processes occur, it is understood that in the QN region electrons have a kinetic energy distributed within the interval $(0, \hbar\omega_{op})$ from the conduction band edge.

If the distribution of the tunneling carriers were narrow in energy (on the scale of $\hbar\omega_{op}$), one could then visualize this narrow distribution replicated in the QN region in such a way that the position of the narrow peak would vary periodically within the range $(0, \hbar\omega_{op})$ from the conduction band edge in the QN region. Based on such a picture, Eaves [Ea-85b] proposed a model in which hot electrons entering the QN region modulate its conductivity by impact ionizing the donor centers. Thus, the model [Ea-85b] assumes a co-existence in the QN region of two groups of carriers: hot electrons entering from the depletion layer and secondary electrons produced by impact ionization of shallow donors in the QN layer. The secondary electrons form a quasi-equilibrium ensemble in the conduction band of the QN region; the associated impedance of the QN region is assumed to be in series with the barrier and the field regions of the diode. The effectiveness of impact ionization process depends on the position of the energy distribution peak. If the peak is below donor ionization threshold, then impact ionization is suppressed. Position of the peak is periodically modulated as the voltage is applied to the device, wherein, according to the model, lies the origin of the current oscillations.

An essential feature of the model by Eaves [Ea-85b] (and a similar model by Leburton [Le-88]) is that the phonon-induced conductivity oscillations are attributed to the medium of the QN region, as modulated by an interaction with the injected "hot" carriers.

There are good reasons for doubting the validity of these models. Firstly, the actual current-voltage trace in such a model would depend on the voltage sweep rate, since the recapture of band electrons by the rare ionized impurity centers at low temperatures is a slow process. Secondly, the energy distribution of electrons injected by tunneling from a degenerately doped emitter is not at all narrow on the scale of $\hbar\omega_{op}$. Finally, and most importantly, there is no reason to believe that the quasi-equilibrium carrier ensemble in the QN layer is connected "in series" with the diode current flow – so long as the injected hot carriers have not equilibrated.

The model proposed by Grinberg and Luryi [Gr-90b] also explains the conductivity oscillations by the periodically varying impedance of the QN region, but the impedance involved is not the quasi-equilibrium impedance of the region itself. Instead, the relevant dynamic impedance is associated with the motion of injected hot carriers through the QN region.[1] To a good approximation this impedance is *independent* of the quasi-equilibrium carrier concentration in the QN region.

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1. The situation is reminiscent of the minority carrier passage through the base of a bipolar transistor: it is associated with a voltage drop which depends on the minority carrier mobility but does not depend in the mobility or conductivity of the majority-carrier ensemble. The quasi-Fermi level of injected minority carriers varies across the base and is responsible for the entire impedance of the base in the emitter-to-collector circuit, while the majority carriers remain at equilibrium.

In the Grinberg-Luryi model the modulation arises due to the energy dependence of the elastic scattering rate of hot carriers moving in the QN region with an energy distribution – which is a periodic function of the applied voltage. What matters is not a narrowly peaked distribution of carrier energies that periodically slides past the impurity level, but rather the entire broad energy distribution of current density, which varies relative to the conduction band edge in a periodic fashion.[2] This translates into a periodic modulation of the mobility μ in the QN region, because of the energy dependence of the elastic scattering rates that govern the mobility. The oscillation in μ causes a quasi-periodic variation in the voltage drop in the QN layer;[3] despite its smallness, this variation affects other regions of the diode, resulting in a modulation of the tunnel current.[4]

In the [Gr-90b] model *position of the donor level is immaterial.* The model was hence challenged by the experiment of Alikacem [Al-91], who had identified an experimental feature related to the impurity energy level. In that experiment, the amplitude of phonon oscillations was found to depend exponentially on the inverse temperature – with the characteristic activation energy related to the impurity energy. Experiment [Al-91] was carried out with holes rather than electrons and the activation energy $E_a \approx 13\,\text{meV}$ on the Arrhenius plot of the oscillation amplitude turned out to be close to half the Be acceptor binding energy in GaAs.

This has left our understanding of the effect in a puzzling state. On the one hand, there is a clear evidence that the impurity binding energy is relevant; on the other, the impact ionization model is theoretically unsatisfactory. Recently, the impact ionization model was dealt a final blow by experiments of the Princeton group [Gr-98] who observed phonon oscillations when tunneling into the edge of a two-dimensional electron system – i.e., in a sample with no dopant impurities!

IV. Resolution of the puzzle: electron-electron scattering

The largest amplitude of conductance oscillations in a given sample is obtained when the QN layer thickness L is highest, provided it is below the mesoscopic coherence length λ. Conversely, if the length λ shrinks for whatever reason, the oscillation amplitude will decrease when λ becomes shorter than L. In the Alikacem experiment [Al-91] the increasing temperature increases the equilibrium "cold" carrier concentration in the QN layer and the enhanced e-e scattering shortens the mesoscopic coherence length, thus suppressing the oscillation amplitude.

As is well known, in the cryogenic regime of an uncompensated semiconductor ($N_A \ll N_D$) there is a range where the band concentration n of electrons is an exponential function of the inverse temperature with an activation energy that is half the impurity binding level, $E_a = 1/2\,E_D$, viz.

$$n = \left[1/2\,N_D\,N_C\right]^{1/2} e^{\frac{1}{2}\beta E_D} \quad . \quad (1)$$

2. Strictly speaking, it is not the current density but the so-called *reduced differential current* (RDC) which exhibits the periodically reproduced energy distribution. The RDC is defined [Gr-90b, Gr-91b] as the sum of the differential currents $\mathrm{d}J(E)/\mathrm{d}E$, over a discrete set of energies E differing by an integral number of optical phonon energies. The RDC is rigorously conserved in any scattering model that takes LO-phonon scattering to be the only inelastic interaction.
3. "Quasi" because the length L of the QN region slowly decreases with increasing V – resulting in a slow decrease of the amplitude of the impedance oscillations.
4. Incidentally, this picture naturally explains why the effect is "strengthened" by a magnetic field along the current direction: it simply lowers the mobility of hot carriers in the QN region.

This range occurs at not too low temperatures when $N_A \ll n \ll N_D$; at all temperatures reported by Alikacem [Al-91] the equilibrium band carrier concentration in the QN region conforms to the law (1).

When the current is flowing, there are two kinds of electrons in the QN layer: (*i*) "hot" carriers in flux, whose energy distribution has been determined by the processes of tunnel injection and phonon emission and whose mobility depends on the phase with which this distribution has landed under the lowest rung of the optical phonon ladder (Fig. 1) and (*ii*) "cold" carriers whose density is governed by the equilibrium statistics (2). Scattering of hot carriers (*i*) by cold carriers (*ii*) destroys the mesoscopic order in the hot-carrier ensemble. As the temperature increases, the cold carrier concentration varies from low values – at which the rate of ee interaction is negligible – to higher values – where that rate is fast enough to destroy the mesoscopic structure over a length λ which is shorter than the thickness L of the QN region. In first approximation, the mesoscopic coherence length λ varies inversely to the concentration of scatterers (*ii*).[5] Herein, essentially, lies the mechanism of the temperature dependence observed by Alikacem (1991).

On the basis of this picture, we can expect that at very low carrier concentrations (e.g., at low temperatures in the [Al-91] experiment) the mesoscopic coherence length λ is longer than the entire length L of the QN region and, therefore, there should be no dependence on the concentration and temperature. This dependence "turns on" as λ becomes shorter than L. This seems to agree with the observations by Alikacem [Al-91].

If the concentration of cold carriers is increased by other than thermal means, e.g., by illumination, we should again expect the suppression of phonon oscillation amplitude. This prediction was verified by Grayson [Gr-98] who employed 3D to 2D tunneling with edge tunnel barriers and varied the "cold" carrier concentration in the 2D sample by field effect. The 2D geometry offers a unique possibility of studying the effect with a *controlled initial distribution* of carriers.

V. Phonon oscillations as a tool to study inter-electron interactions

Phonon conductivity oscillations contain a wealth of information about e-e interactions. In order to extract this information from a broad range of experiments under a variety of conditions, one needs a theory that will support and model these experiments.

Development of such a theory requires essentially two lines of study. For the sake of brevity, one of these will be referred to as phenomenological, the other as fundamental. *Phenomenological* treatment could be based on a small number of parameters describing the rate of relaxation of the classical mesoscopic structure in electron energy distribution – without inquiring into the precise mechanism of this relaxation. A simplest such theory will assume an exponential decay of the mesoscopic order, characterized by a single coherence length λ (or a single time constant τ). For $\lambda \gg L$ this parameter has little effect on the amplitude or shape of the conductivity oscillations and the simple theory [Gr-90b] should be applicable. On the other hand, for $\lambda < L$ the oscillation amplitude will be governed by oscillatory impedance developed within the initial segment λ of the QN region, with the remaining

5. At this time, it is difficult to make this statement more quantitatively, as discussed in the next Section. The concentration dependence of the relaxation rate has not been settled for low-density systems and highly non-equilibrium distributions. Investigation of phonon oscillations offers, potentially, a unique tool for the analysis of this very important scientific issue.

part $L - \lambda$ contributing only a series resistance.

These phenomenological considerations allow to extend the earlier theory [Gr-90b] in a straightforward fashion. Quantitative comparisons with experiment, however, require accurate transport modeling, especially in applications to 2D transport (as in Princeton experiments [Gr-98]). Development of the appropriate transport model can be guided by an analytic model of space-charge-limited current in thin films [Gr-89].

With the transport model in hand, one should be able to derive the empirical dependence $\lambda(n)$ for the electron-electron interaction. Determination of this dependence is important in its own right, as it can be used for the analysis of many situations arising in semiconductor devices. At the same time, this empirical dependence can serve as a testing ground in the development of a "fundamental" theory.

Fundamental approach requires a first principles calculation of the kinetics of the mesoscopic order relaxation. Two contributing factors have been considered previously: interaction with acoustic phonons and the fact that optical phonons are not exactly monochromatic [Gr-91b]. The spatial scale of the degradation in mesoscopic order due to acoustic phonon scattering is of the order of 1 mm in GaAs; the effect of optical phonon dispersion was found to important only for unusually narrow electron distributions peaked at a high energy. Thus, we can safely conclude that phonon degradation effects are negligible on the submicron length scale. This is the key reason why phonon oscillation experiments provide a unique handle on the kinetics of interelectronic interaction.

In first approximation, the effect of e-e scattering is easy to include, if we assume that the distribution function of electrons of group (*i*) evolves under the interaction with electrons of group (*ii*) – the latter being assumed in equilibrium with the lattice. The rate of mesoscopic order degradation in this model would be similar to the energy relaxation rate of the hot electron ensemble interacting with the cold electron ensemble. In this case, the problem appears relatively simple and a closed form solution should be available. Surprisingly, however, the issue has not been settled in the literature even in this limit.

The unresoved problem seems to reside with the correct account of Coulomb screening at low concentrations. As is well known [La-37], without accounting for screening the Coulomb scattering integrals diverge. In most treatments of e-e interaction in semiconductors, either the static screening model [Es-87, Sm-96] was used or a dynamic model in the framework of RPA [ES-92, Sn-94, Hu-96]. The use of RPA expressions in which the equilibrium concentration is replaced by a non-equilibrium concentration is certainly questionable when applied to screening in non-equilibrium systems. On the other hand, the non-equilibrium screening theory, recently under intense development [Ku-91, ES-94, Se-97], remains rather opaque for qualitative analysis, e.g. for extracting concentration dependences of relaxation characteristics. Nonetheless, Harrison [Ha-96] recently discussed the feasibility of a physically transparent analytic theory that would explicitly show the dependence of the energy relaxation on the system parameters and at the same time include dynamical screening in a reasonable fashion.

It has been shown [ES-92, Sn-94] that the calculated relaxation rates of highly non-equilibrium distribution strongly depend on the screening model employed. Unfortunately, these issues have not been studied in detail for low-density systems and many questions remain. Thus, the experimentally observed saturation of the energy relaxation rate in GaAs at very low ($\lesssim 10^{13}$ cm^{-3}) concentrations [Sn-92a, Sn-92b, Sn-93] remains unexplained.

There are discrepancies between reported concentration dependences of the energy relaxation rate in the intermediate range $10^{13} - 10^{17}$ cm^{-3}, where one finds reports of both $\tau^{-1} \propto n$ [Es-87, Ha-96] and $\tau^{-1} \propto n^{1/2}$ [Sn-94, Ka-93]. Sublinear concentration dependence with an exponent close to 0.5 in the range $10^{15} - 10^{16}$ cm^{-3} was also reported in [Se-97]. Moreover, different stages of evolution of a non-equilibrium electronic system may be characterized by different relaxation rates [Sn-93, Le-97].[6]

Experimental investigations of e-e interactions by photoexcitation spectroscopy in semiconductors are essentially complicated by the co-existence of a hole subsystem. Phonon conductivity oscillations represent, therefore a unique tool for the analysis of a very important scientific issue. To take advantage of this tool requires a theoretical effort which represents an interesting and potentially rewarding problem in physics-based modeling of electronic transport.

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6. Another unsolved problem emerges when that the density of group (*ii*) carriers is not very different from that of group (*i*) in the temperature range of interest. The hot carrier group in the QN region has an estimated concentration in the range $10^{12} - 10^{13}$ cm^{-3}, while the cold carrier group ranges from about 10^{9} cm^{-3} at low temperatures all the way to $N_D \approx 10^{15}$ cm^{-3} at high temperatures. In the important region, therefore, we must consider the joint evolution of both groups and the kinetic equation becomes nonlinear in the electronic distribution and rather complicated. This is a straightforward technical complication to be sure, which can be handled in a known way.

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