1.1.3 Phonons in Semiconductors

The periodicity of the semiconductor lattice also allows the description of the quantized vibrational modes of the lattice in terms of phonon energy vs. wavevector diagrams or phonon dispersion relations [1.1, 4, 5, 7]. GaAs has more than one atom per unit cell so that both acoustic and optical phonon modes are present in GaAs. The acoustic phonons can be classified in terms of Longitudinal (LA) and Transverse (TA) Acoustic phonons with different velocities. There are also Longitudinal (LO) and Transverse (TO) Optical modes with a splitting at $q = 0$ because of the polar interaction in GaAs. Inelastic neutron scattering provides an experimental technique for measuring the dispersion relations. Neutron scattering results for the dispersion relations of the phonons in GaAs [1.38] are shown in Fig. 1.5.

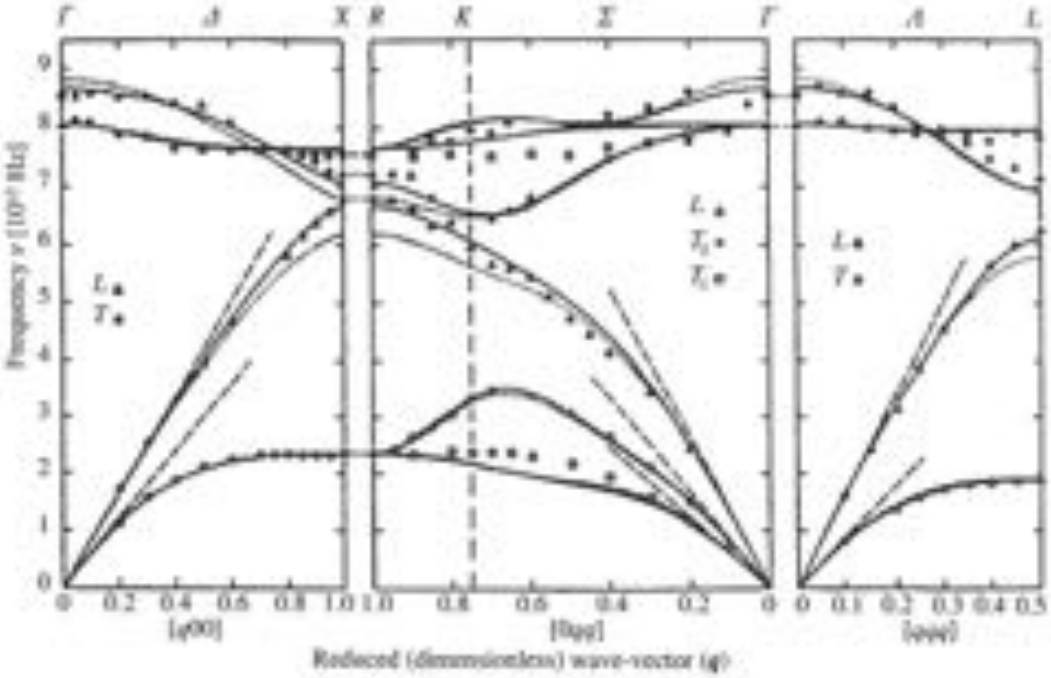

Fig. 1.5. Room-temperature dispersion curves of acoustic and optical phonons in bulk GaAs obtained from inelastic neutron scattering data [1.38]

A reduction in the dimensionality of the semiconductor also leads to a substantial change in the phonon modes. Different kinds of phonon modes, such as confined, propagating and interface modes, are present in quantum wells. The acoustic and optic phonon modes in quantum wells and quantum wires have been discussed quite extensively in the literature [1.39, 40] and will not be discussed here. We will, however, refer to the complicated phonon modes in reduced dimensionality structures during our discussion of experimental results, especially in Chap. 5 on phonon dynamics.

1.1.4 Scattering Processes in Semiconductors

The dynamics of electrons, holes, excitons and phonons is influenced by their interaction with each other, as well as with defects and interfaces of the system. There are once again extensive discussions of these interactions in the literature. In the following subsections, we present essentially a catalog of important interactions, with some representative references for further information.

(a) Carrier-Phonon Interactions. Interaction of carriers with phonons plays a major role in the exchange of energy and momentum between carriers and the lattice, and hence determines the relaxation of photoexcited semiconductors as well as the transport properties of semiconductors. Textbooks as well as books on high-field transport in semiconductors have extensive discussions on these processes [1.3, 5–7, 41–44]. The scattering rates are derived using the Fermi golden rule and are also discussed in detail in these references.

GaAs-like semiconductors are intermediate between the covalent semiconductors like Si and Ge, and ionic semiconductors like CdS. Polar optical phonons, therefore, play an important role in carrier-phonon scattering processes in GaAs-like semiconductors. Low energy electrons, because of their s-like wavefunctions, interact with optical phonons only through polar coupling. The matrix elements of this *Fröhlich interaction* varies inversely with the wavevector q of the phonon being emitted or absorbed. Holes also interact with LO phonons via Fröhlich interaction. Since the Fröhlich interaction rate is expected to vary as $m^{1/2}$, the heavier holes might be expected to interact more strongly with the LO phonons than the lighter electrons. However, the complicated band structure of holes leads to an effective reduction of the rate by a factor of 2 [1.45–49].

The electron polar optical mode scattering rate (Fröhlich interaction) is given by [1.3, 5]:

$$W(E) = W_0(\hbar\omega_{LO}/E)^{1/2}[n(\hbar\omega_{LO})\sinh^{-1}(E/\hbar\omega_{LO}) + [n(\hbar\omega_{LO})+1]\sinh^{-1}[(E/\hbar\omega_{LO})-1]] \,, \tag{1.1}$$

where $n(\hbar\omega_{LO})$ is the phonon occupation number and

$$W_0 = \frac{e^2(2m\hbar\omega_{LO})^{1/2}}{4\pi\hbar^2}\left(\frac{1}{\varepsilon_\infty}-\frac{1}{\varepsilon_s}\right) \,. \tag{1.2}$$

Here $\hbar\omega_{LO}$ is the LO phonon energy, m is the electron mass, and ε_∞ and ε_s are the optical and static permittivities. The calculated electron-LO phonon normalized scattering rates for the Fröhlich interaction for electrons in a simple parabolic band with effective mass m are depicted in Fig. 1.6 for the lattice at 300 K. Values for electrons in the Γ valley of GaAs can be obtained by using $W_0 = (125\ \text{fs})^{-1}$.

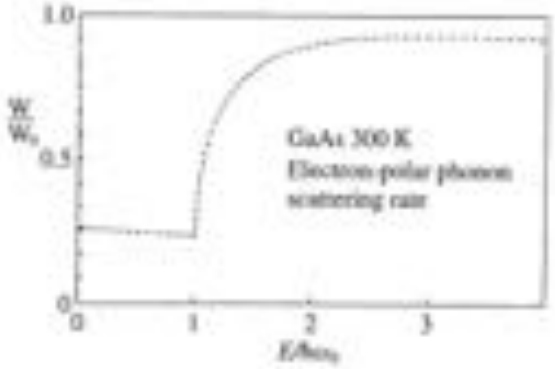

Fig. 1.6. Rate for polar optical mode scattering of Γ valley electrons in GaAs as a function of the energy of the electron

High-energy electrons, electrons in subsidiary valleys and holes can also interact with optical phonons through *non-polar optical deformation potential scattering* whose matrix elements are independent of the phonon wavevector. Coupling to both the LO and the TO phonons can occur through this mechanism. This interaction is also responsible for *intervalley scattering* of electrons.

Interaction with both LA and TA phonons can also be important. *Deformation potential* and *piezoelectric scattering mechanisms* play an important role, with the former dominating in most cases. If the carrier has sufficient energy to emit an optical phonon, then the optical phonon scattering rate is generally considerably higher than for the acoustic phonons. Phonon emission processes are independent of the phonon occupation number and hence temperature. Phonon absorption, on the other hand, is proportional to the phonon occupation number and hence is strongly temperature dependent.

(b) Carrier-Carrier Scattering. Carrier-carrier scattering determines the exchange of energy between carriers, and is primarily responsible for the thermalization of photoexcited non-thermal carriers (Sect. 1.1.5). This process is mediated by Coulomb interaction and includes electron-electron, hole-hole and electron-hole scattering. The difference in the masses between electrons and holes reduces the energy exchange between these two species. The long-range Coulomb interaction diverges in the absence of screening. Screening is generally included by calculating the frequency and wavevector dependent dielectric function of the semiconductor with a proper treatment of the plasmon-phonon coupling [1.50]. This may present a difficult challenge in many cases. Some aspects of this problem are discussed in Chap. 4.

(c) Spin Relaxation Processes. In addition to the energy and momentum relaxation processes discussed above, spin relaxation processes can also play an important role in the dynamics of photoexcited systems. This aspect can be investigated by studying the variation of the optical spectra for different polarizations. Exciton spin relaxation processes will be discussed in Chap. 6.

(d) Scattering Processes Specific to Quantum Wells. The scattering processes in quasi-two-dimensional semiconductors are similar to those discussed above

for bulk semiconductors, but the scattering rates are modified by several factors such as different band structure, phonon modes and density-of-states in these semiconductors. One major difference in the carrier-phonon scattering rates results from the fact that only $k_{\parallel}$, the momentum parallel to the interface planes, is conserved. There is a large literature on electron-phonon scattering rates in quantum wells [1.51, 52].

Some scattering processes specific to quantum wells are also important. Inter-subband scattering, capture of carriers from the barriers into quantum wells, and real space transfer of carriers from quantum wells into the barriers play an important role in specific situations. Tunneling of carriers between quantum wells and thermionic emission over the barriers contribute to the transport of carriers in MQW structures, and may well determine the speed of quantum well devices based on MQW. We will discuss these transport-related processes in Chap. 7 on tunneling and Chap. 8 on perpendicular transport.

1.1.5 Carrier Relaxation: Four Regimes

After a semiconductor in thermodynamic equilibrium is excited by an ultrashort pulse, it undergoes several stages of relaxation before it returns once again to the thermodynamic equilibrium. Investigation of these relaxation processes is a major theme of this book, but before we get into details, it is useful to provide a bird's eye view of these relaxation processes. The carrier relaxation can be classified into four *temporally overlapping* regimes:

(a) Coherent Regime. Excitation of a semiconductor with an ultrashort laser pulse creates excitation in the semiconductor with well-defined phase relationship within the excitation and with the electromagnetic field that created the excitations. The laser pulse can create either real or virtual excitation. This coherent regime exhibits many interesting phenomena which are elegant manifestations of basic quantum mechanics in semiconductoes. Coherences in atomic and molecular systems and defects in solids have been investigated extensively, but coherence of intrinsic states in semiconductors has been explored only in recent years. This is because the scattering processes that destroy the coherence are extremely fast in semiconductors and pico- and femtosecond techniques are required to study the coherent regime in semiconductors. Chapter 2 will discuss many of the interesting recent investigations of coherence in semiconductors, as well as investigation of various scattering processes that destroy the coherence.

(b) Non-Thermal Regime. In the case of real excitation, the distribution of the excitation (free electron-hole pairs or excitons) after the destruction of coherence through dephasing is very likely to be non-thermal, i.e. the distribution function can not be characterized by a temperature. Investigation of this regime provides information about various processes (such as carrier-carrier or exciton-exciton scattering) that bring the non-thermal distribution to a hot,

thermalized distribution. Non-thermal carriers and excitons can be probed by optical spectroscopy, and are discussed in Chaps. 3 and 6, respectively.

(c) Hot-Carrier Regime. Carrier-carrier (or exciton-exciton) scattering is primarily responsible for redistributing the energy within the carrier (exciton) system, and leads to a thermalized distribution function of carriers (excitons), i.e. a distribution that can be characterized by a temperature. The temperature can be, and usually is, higher than the lattice temperature, and may be different for different sub-systems (electrons, holes, excitons). The thermalization times depend strongly on many factors such as carrier density. Typically, the electrons and holes thermalize among themselves in hundreds of femtoseconds, while the electrons and holes achieve a common temperature in a couple of picoseconds. The thermalized electron-hole pairs reach lattice temperatures in hundreds of picoseconds through interaction with various phonons in the semiconductor. This interaction may lead to a large, wavevector-dependent population of non-equilibrium phonons. Therefore, this regime is described by various systems such as electrons, holes and non-equilibrium phonons which are not in equilibrium with each other.

Investigation of this hot carrier regime focuses on the rate of cooling of carriers to the lattice temperature and leads to information concerning various carrier-phonon, exciton-phonon, and phonon-phonon scattering processes. These will be discussed in Chaps. 4, 5 and 6.

(d) Isothermal Regime. At the end of the hot-carrier regime, all the carriers, phonons and excitons are in equilibrium with each other, i.e. can be described by the same temperature, that of the lattice. However, there is still an excess of electrons and holes compared to the thermodynamic equilibrium. These excess electron-hole pairs (or excitons) recombine either radiatively or non-radiatively and return the semiconductor to the thermodynamic equilibrium. We will not be concerned with this last regime in this book, although radiative recombination of excitons will be discussed in Chap. 6 because it contributes to the initial dynamics of excitons in 2D systems.

These temporally-overlapping regimes are schematically illustrated in Fig. 1.7 with some typical processes that occur in each relaxation regime [1.53]. The time scale for each event depends very strongly on parameters such as band structure, excess energy, the nature of the excitation (free carrier vs exciton), the density of excitation, the lattice temperature and so on. Many of these processes will be discussed in subsequent chapters.

It should be emphasized that many of the physical processes leading to relaxation in the different regimes are occurring simultaneously. For example, the processes that destroy coherence may also contribute to thermalization of carrier distribution functions, and emission of phonons may occur while the electron and holes are thermalizing to a hot distribution. The non-thermal carrier distribution function created by a femtosecond pulse is influenced by the dephasing of coherent polarization during the pulse. Nonetheless, this description in terms of four relaxation regimes does provide a convenient

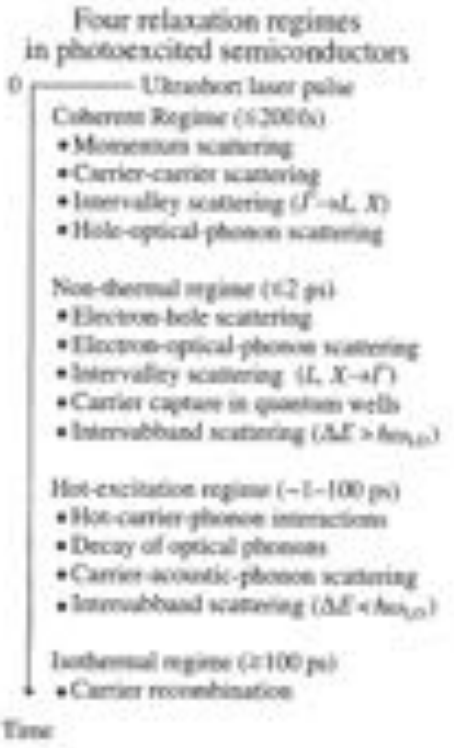

Fig. 1.7. Four temporally-overlapping relaxation regime in photoexcited semiconductors, with some typical scattering and relaxation processes for each regime [1.108]

framework for describing and discussing the dynamics of relaxation in semiconductors.

1.1.6 Carrier Transport

As we discussed at the beginning of this chapter, one of the strengths of optical spectroscopy is its ability of investigating the dynamics of carrier transport in semiconductors. For lateral transport (parallel to the surface), this is accomplished by monitoring linear or nonlinear optical properties at different points on the surface. Spatial resolution down to a small fraction of a micrometer can be achieved by spatial imaging techniques and recent advances in near-field scanning optical microscopy [1.54, 55]. For perpendicular transport (normal to the surface), the most commonly used technique is to incorporate *optical markers* in the semiconductors [1.56]. Optical markers are thin layers of semiconductors which have specific spectral properties that can be monitored to study the arrival or departure of carriers in that spatial region. There is a unique relationship between the spatial position and the spectral properties of the optical marker region. Chapters 7 and 8 will discuss how the techniques of optical markers and ultrafast optical spectroscopy can be combined to investigate the dynamics of carrier transport and tunneling in semiconductor nanostructures.