CHAPTER 1

INTRODUCTION AND ORGANIZATION

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1.1 INTRODUCTION:

The remarkable advancement in the techniques of crystal growth such as fine-line lithography, metalorganic chemical vapour deposition (MOCVD) and molecular beam epitaxy (MBE), has stimulated active researches on quasi-low dimensional electronic transport in quantum wells and wires of widths comparable to the electron de Broglie wavelength [1.1 - 1.25]. These structures are often referred to as quasi low dimensional structures (LDS) or nanostructures. They possess radically different properties from those of bulk semiconductors because they quantum mechanically restrict the degrees of freedom of the conduction electrons to two or one. This change in the effective dimensionality offers fascinating changes in electronic, magnetic, optical, and vibrational properties [1.26]. Nanostructures are now recognized as a promising basis for the study of the physics of LDSs and their future technological applications. Researches on the physics of LDSs continue to be both challenging and exciting, as novel structures with different materials having different properties are developed [1.27].

A thin layer of a lower bandgap semiconductor (like GaAs), sandwiched between the layers of a higher bandgap material (like
(AlGaAs) forms a quantum well (QN) [1.28]. The electron gas here is free to move parallel to the interface, so that the motion is two-dimensional (2D). A further quantum confinement in the transverse direction leads to a one-dimensional (1D) electron gas, free to move only in longitudinal direction. Such a structure is referred to as the quantum wire (QWR) [1.29, 1.30]. In the quantum structures, the density-of-states and the scattering rates of the carriers are different from those in the bulk material [1.31 - 1.32].

In QWs and QWRs, modulation doping separates the electrons from their parent donor atoms, reducing thereby the influence of ionized impurity scattering [1.33 - 1.35]. Therefore, the electron mobility is high, particularly at low temperatures where phonon scattering is reduced [1.36]. Impurity scattering can be reduced further by increasing the separation of the electrons and the ionized donor impurities. The electrons in the potential well of the abrupt heterojunction are separated from the donor atoms, but are still close enough to be subjected to a coulomb attraction. A thin spacer layer of undoped AlGaAs can be placed between the doped AlGaAs and the undoped GaAs [1.37]. Increasing the separation between the carriers and the ionized donors increases further the electron mobility, since there is even less coulomb interaction [1.38 - 1.39]. Quantum structures...
thus show promise for application in fast miniature devices [1.40 - 1.42]. Some of the unusual properties of LDSs like quantum Hall effect (QHE) have received much attention in recent years[1.43-1.46].

Investigations on electronic transport in quantum structures are extremely important for an understanding of the carrier kinetics under confined conditions. Such studies also help in optimising the performance of the structures in devices and in exploring the possibilities of new applications. LDSs are useful for millimeter and submillimeter-wave applications, because they can respond very quickly and sensitively to voltage control [1.47 - 1.49]. In addition, they have potential advantages which make them attractive for nonlinear functions. Most of the investigations on quantum structures use GaAs because of its direct bandgap, high electron mobility, and advanced technology. In addition to GaAs, quantum structures of In$_{0.53}$Ga$_{0.47}$As are also currently receiving attention [1.50-1.52]. The low electronic effective mass in (In,Ga)As gives a high electron mobility despite the detrimental effect of alloy disorder scattering. A large peak drift velocity, a large conduction band offset providing an improved carrier confinement in the channel, and a high sheet carrier concentration are the additional advantages of (In,Ga)As quantum structures that can be directly
integrated with communication systems [1.53 - 1.55].

Hot electron conditions are developed if the applied electric field is sufficiently high so as to cause a pronounced deviation from Ohm's law. At these fields the drift energy of the electrons may be compared to the thermal energy and the symmetric term is no longer the equilibrium distribution at the lattice temperature. Whether the two-term Legendre Polynomial expansion is still a good approximation or not depends on the nature of scatterings encountered by the electrons. The average electron energy is also much higher than that in thermal equilibrium with the lattice. The whole character of the electron transport may change radically at such high electron energies. Under such high electric fields, the mobility exhibits a complicated dependence on the electric field.

Under hot electron condition, the hot carriers, photoexcited by ultrashort pulses in polar semiconductors, initially lose energy rapidly by emitting longitudinal optic (LO) phonons in a few hundreds of fsecs via the dominant Fröhlich coupling [1.56, 1.57]. As the LO phonon lifetime is long enough [1.57], a nonequilibrium population of LO phonons, called hot phonons, builds up, leading to their reabsorption by the carriers [1.58]. In effect, the carrier energy-loss rates slow down considerably [1.56, 1.59].
In this thesis, the candidate reports the calculations of high-frequency response of 2D hot electrons in GaAs and (In,Ga)As quantum wells. Since the dimensions of quantum structures are small, the application of a moderate voltage produces hot electrons in such structures. The effects of nonequilibrium LO phonons or hot phonons are also investigated. Galvanomagnetic transport coefficients of the 2D hot electrons in GaAs QWs under high heating electric field and cross low nonquantizing magnetic field are also studied. Calculations of one-dimensional hot electron ac mobility in GaAs quantum wire and microwave and millimeterwave transport of one dimensional hot electrons in (In,Ga)As quantum wire are also investigated. Results are obtained for different combinations of system parameters.

1.2: ORGANISATION OF THE THESIS:

The basic aspects of transport theory and formulae utilized in the present work for the calculation of transport parameters of the low-dimensional structures are presented in chapter 2. The energy band structures for 1D and 2D systems, the carrier distribution function, the Boltzmann transport equation (BTE) and the different scattering processes are outlined.

In chapter 3, we report investigations of small-signal ac response of 2D hot electrons in a GaAs QW in the presence of a
small-signal ac electric field superimposed on a moderate dc electrical field parallel to the heterojunction interfaces using a heated drifted Fermi-Dirac (FD) distribution function for the carriers. A review of the existing literature on the 2D transport of electrons relevant to this work is given. The carrier energy loss via polar optic phonons and momentum losses through polar optic phonons, deformation potential acoustic phonons, and background ionized impurity are considered. The formulae for the small-signal ac mobility and the phase lag of the alternating current behind the applied field are derived in this chapter. The variation of ac mobility and the phase lag with frequency are studied. The dependencies of the ac mobility and the 3dB cutoff frequency where the ac mobility falls to 0.707 of its low frequency value on system parameters such as the 2D carrier concentration and channel width are reported. The role of the lattice temperature and the bias field on the cutoff frequency are also investigated. The ac mobility $\mu_{ac}$ and the phase angle $\phi$ increase with the rise of the channel width and the 2D carrier concentration. However, the 3dB cutoff frequency $f_{3dB}$ is found to decrease with increasing channel width. The values of $\mu_{ac}$ and $f_{3dB}$ are higher but those of $\phi$ are lower at 300K than that at 77K.

The high-frequency response of degenerate hot electrons itinerant two-dimensionally in GaAs square quantum wells is
also studied in the framework of heated Fermi-Dirac distribution function incorporating the effects of nonequilibrium LO phonons or hot phonons. The 3dB cutoff frequency is found to be significantly enhanced when hot phonons are included in the calculation. The 3dB cutoff frequency is shown here to decrease and then rise slowly with increasing carrier concentration. \( f_{3dB} \) is also found to decrease with increasing channel width.

Chapter 4 deals with the calculations of microwave and millimeterwave response characteristics of the two-dimensional hot electron gas in (In, Ga)As quantum wells. The literature on the 2D transport of hot electrons relevant to our work in this thesis is surveyed. Scatterings by polar optic phonons, deformation potential acoustic phonons, ionized impurities, and alloy disorder are considered. The effect of degeneracy is also included. Results are obtained for different well widths, sheet carrier concentrations, lattice temperatures and corresponding bias fields. The (In,Ga)As system is found to have much higher cutoff frequency than the GaAs system. Consideration of nonequilibrium optic phonons or hot phonons is found to enhance considerably the 3dB cutoff frequency \( (f_{3dB}) \). \( f_{3dB} \) decreases initially and then increases with increasing carrier concentration, and decreases with increasing channel width when hot phonons are included in the calculations.
Chapter 5 is concerned with the study of galvanomagnetic coefficients of the 2D hot electrons in GaAs quantum wells at low temperature and the role of the system parameters, and the magnetic ($B$), and electric fields ($F$) on those coefficients. Our model and method of calculations are presented and the results are discussed. The contribution of LO phonon scattering is insignificant over the temperature range of our investigation and hence not included in the calculations. Screened carrier scatterings through acoustic phonons via deformation potential and with background ionized impurities are incorporated. Boltzmann transport equation is solved to obtain the galvanomagnetic coefficients viz: magnetoresistance ($R_m$), Hall mobility ($\mu_H^m$), and the Hall - to - drift mobility ratio ($r_H^m$). Our calculations clearly show the effects of different system parameters, magnetic field and heating electric field on the galvanomagnetic coefficients. Our studies indicate that $R_m$ is more sensitive than $\mu_H^m$ and $r_H^m$ to the changes in the magnetic field, the electric field, and the system parameters, namely, the channel width, 2D carrier concentration, and lattice temperature.

The author reports in chapter 6 the calculations of one-dimensional hot electron ac mobility in quantum wires of square cross-section at high temperatures in the framework of a heated drifted Fermi-Dirac distribution function and considering
the occupancy of the lowest subband only when a small-signal sinusoidal electric field of microwave or millimeterwave frequency is superimposed on a dc bias field. The arm of the square cross-section of the QWR is referred to as the channel width in this thesis. The results are obtained by solving the energy and momentum balance equations for the carriers including LO phonons, deformation potential acoustic phonons, and impurity scatterings for lattice temperatures of 77K and 300K. An increase of the channel width or the carrier concentration enhances both the magnitude and the phase lag of the ac mobility. The 3dB cutoff frequency increases with decreasing channel width and increasing bias field. It is higher for 300K than for 77K.

Chapter 7 is devoted to the investigation of the microwave and millimeterwave transport of one-dimensional hot electrons in (In,Ga)As quantum wires at high temperatures in the extreme quantum limit (EQL). A review of the existing literature on the 1D transport of electrons relevant to this work is surveyed. The carrier energy loss via polar optic phonons and momentum losses via interactions with polar optic phonons, deformation potential acoustic phonons, background ionized impurities, and alloy disorder are considered. Results are obtained for different wire widths, lattice temperatures, carrier concentrations, electron temperatures and corresponding bias fields. In this
initial work, a drifted Fermi–Dirac model is taken resort to. The ac mobility \( \mu_{ac} \) is shown to increase with increasing channel width and carrier concentration \( n_{1D} \). But the phase lag \( \phi \) increases slowly with channel width and increases initially and then falls with the rise of \( n_{1D} \). However, at a particular bias field, the 3dB cutoff frequency \( f_{3dB} \) is shown here to decrease with increasing channel width, and to initially decrease and then rise slowly with increasing carrier concentration. \( f_{3dB} \) increases with the bias field and the lattice temperature.

The author has summarised, in chapter 8, the outcome and the conclusions of the present study.

REFERENCES :


