Chapter 4

Hot electron – phonon interaction

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4.6. Summary

4.1 Introduction

In the previous chapter, the study of carrier transport is under thermal equilibrium and the carrier does not have excess energy with which it has a resultant direction of momentum. The momentum and energy of the carrier changed drastically after its each collision with phonons. The entire picture of interaction includes only the loss of energy and momentum and there was no any gain of energy from any source. As a result, the average number of the carriers passing through any cross- sectional area for any desired time duration is zero due to random motion of the electron. Hence, no electric current flows through the device.

The study of carrier interaction under the effect of electric field is of considerable interests. Being accelerated in high electric fields, the electron mean energy and the average momentum acquired are far greater than those associated with thermal equilibrium. Many heterostructures devices are utilized in high electric fields to achieve the desirable high speed or high frequency performance of these devices. This leads to a strong non-equilibrium state of the electron gas. Such strong non-equilibrium electrons not only move fast but also exhibit a number of specific effects that find various practical applications. So whenever the devices are operated under high electric fields the electron mean energy and their acquired average momentum increases with the electric field. Hence, it is convenient to consider the electron effective temperature, T_e, instead of the mean electron energy. The relationship between the temperature and the mean energy in the thermal equilibrium is $E=nk_BT_e/2$, where n is the dimensionality of the structure. Under thermal equilibrium, the electron temperature T_e coincides with the lattice temperature T_l. If T_e exceeds T_l slightly and the electron transport still obeys Ohm's law,

the electrons are said to be warm electrons. Under non-equilibrium conditions these two temperatures may differ. When applied electric field is enough strong so that electron temperature T_e is too much greater than the lattice temperature T_l then the electrons are said to be "hot electrons", which are far from equilibrium. Such situation is frequently referred to as the hot electron problem.

Till last two decades there has been an increased activity in the field of hot electrons in semiconductors. The reason for this is mainly the advent of crystallographic techniques, such as molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD) and lithographic techniques, such as x-ray and electron beam lithography. It has been therefore possible to deposit crystalline layers of a few atoms thick, and to fabricate devices with physical dimensions where hot electrons are the norm. Thus the question of effect of quantum confinement on the transport properties on one hand and improvement of device performance on the other have stimulated much research in this area. Two dimensional (2D) GaAs has been most widely studied material both theoretically and experimentally. At electron temperature T_e >40 K the electronic transport properties of bulk GaAs are largely determined by electron- LO phonon interactions [1].The experimental work on hot electron dynamics for longitudinal transport in 2D structures is far from presenting a unified picture [2]. This is partly because the reduction in physical dimensions had to be compensated by a deliberate increase of carrier concentration so that the meaningful experiments could be performed on such small devices. It is generally accepted that the energy relaxation time (ERR) for electrons deceases with increasing electron concentration and among many possibilities explored for the cause of low ERR, the presence of a large non equilibrium population of

LO phonon is shown to give a reasonable agreement with the experimental results [3, 4]. Most theoretical treatments of hot-phonon effects consider a forward displaced distribution of nonequilibrium phonons in momentum space that arises from the drift of hot electrons. Consequently phonon reabsorption reduces the energy relaxation rates; it has however, only a small effect on the electron drift velocity at high fields [5].There is, however, some scattered evidence in the literature that the hot phonon production may enhance the momentum relaxation. Ridley [6] and Gupta and Ridley [7-10] suggested that a randomization of the hot phonon distribution may take place via elastic scattering of phonons interacting with, for instance, interface imperfection and well width fluctuations. Hence the drift of hot phonon can be neglected. Consequently the production of hot phonons not only reduces the energy relaxation rate, as predicted by conventional theories, but also enhances the momentum relaxation rate.

In the present chapter, we discuss the electron transport phenomena under the influence of electric field [11-18] as to understand the operation and performance of many heterostructure devices under high electric field. In this chapter we study the variation of electron scattering rate (e.g. momentum and energy relaxation rate), carrier drift velocity and mobility, electron energy loss rate by means of phonon emission and phonon absorption with respect to electric field and doping concentration.

4.2 Hot Phonon Problem

In principle, for high electric fields, hot electron relaxation through the emission of phonons should drive the phonon subsystem out of equilibrium. Indeed, electrons emit phonons that do not obey the Plank distribution

$$N_{q,S} = \frac{1}{\exp\left(\frac{h\omega(q,s)}{2\pi k_B T}\right) - 1} \tag{4.1}$$

These non-equilibrium phonons eventually decay into thermal phonons as a result of anharmonic interactions. As an example, optical phonons are decay into a pair of short wave- length acoustic phonons with lifetime in generally picoseconds. If the generation rate of non-equilibrium phonons is slower than their decay rate, the approximation of phonon equilibrium is justified. However if the electron concentrations are high and their excess energy is high as well, the generation of non-equilibrium phonons becomes effective and cannot be compensated for by phonon decay. As a result, the non-equilibrium phonon populations grow rapidly and exceed the thermal- equilibrium populations by orders of magnitude. This situation is referred as the non-equilibrium or "hot phonon problem". Non-equilibrium phonons affect all major electron transport and optical characteristics by dramatically modifying the scattering rates. Non-equilibrium phonons are responsible for the slow relaxation of photo excited hot electrons and phonon drag effects in transport. The phonon population growth in high electric fields can be estimated by the crystal- energy – balance equation

$$\frac{dN}{dt} = \frac{jF}{h\omega/2\pi} - \frac{N - N_0}{\tau_{ph}} \tag{4.2}$$

where N is the total phonon population in a unit volume of the crystal, N_0 is the equilibrium- phonon population, j is the current density and F is the electric field, $_{ph}$ is the phonon decay or thermalization time. The stationary solution of above equation in steady electric fields is

$$N = N_0 + \frac{jF\tau_{ph}}{\hbar\omega} = N_0 + \frac{env_d F\tau_{ph}}{\hbar\omega_{ph}} \tag{4.3}$$

Where n is electron concentration and v_d is drift velocity.

For III-V semiconductors the major electron scattering mechanism is scattering by longitudinal-optical (LO) phonons. Therefore the predominant growth is in the optical - phonon population. Also, in general, the energy relaxation of electrons, through the emission of acoustic phonons, is very slow on account of the low energy of the phonons involved. The ensemble Monte Carlo method can solve the non-equilibrium phonon problem rather accurately. Electrons gain energy in an applied electric field, which is, dissipated to the lattice via the emission of LO phonons. The rate of emission of LO phonons is usually an order of magnitude faster than the rate of decay of these phonons. For example, the lifetime of the LO phonons in GaAs has been measured to be ~5-7 ps [10], more than an order of magnitude greater than $_0$.

4.3 Hot Electron Phonon Interaction in Heterostructures

There is an important intermediate case of classical transport in active layers of submicrometer thicknesses. According to the general analysis of possible transport regimes, if the characteristic diffusion lengths become comparable with the layer thickness L, the appearance of classical size effects corresponds to transverse size effect is expected. For hot electrons, the energy relaxation time $_E$ corresponds to diffusion energy relaxation length $L_E = (D\ _E)^{1/2}$ where D is diffusion coefficient. A hot electron diffuses in space for distance ~L_E before losing its excess energy. If the layer thickness is ~L_E or less, the energy relaxation on layer boundaries should affect the electron

distribution over the energy. If there is an additional mechanism of energy relaxation on the boundaries, the heating of electrons can be suppressed.

As an example, we can consider a Si sample with a modest donor doping, n_D 10^{13} cm^{-3}. At nitrogen temperature or below, L_E exceeds 1 m. Thus, for actual submicrometer active layers, the size effect can be an important factor in hot electron phenomena. However, the electron heating is suppressed considerably for narrow layers, which improves the current - voltage characteristics and it becomes ohmiclike with larger currents. So, to consider the hot electron problem for the case of heterostructures, one should consider the set of new features peculiar to heterostructures like,

1. changes in the scattering rates due to the quantization of electrons and phonons
2. additional mechanism of scattering
3. intersubband transitions
4. electron escape from the confining potential wells

When the electric field **F** is applied to the device, the electrons gain energy from the applied electric field, which increases with the field. Electrons gain energy in an applied electric field which is dissipated to the lattice via the emission of LO phonons. Electron transport at high electric fields in semiconductors is dominated by electron – LO phonon scattering by the Fröhlich interaction Hamiltonian H_p. The rate of the emission of LO phonons is usually an order of magnitude faster than the rate of decay of these phonons. The changes in the electron energy in an electric field is given by [19]

$$\frac{dE}{dt} = e\left|Fv_d\right| - W_E \qquad (4.4)$$

where, the first term on right hand side corresponds to the power gained by electron from the electric field and the second term represents the rate of the electron energy dissipation to the lattice via the emission of LO phonons

$$W_E = \frac{(T_e - T_l)n}{\tau_E} \tag{4.5}$$

where $T_e = {}^{v_d F \tau_e}/_{k_B}$ is electron temperature and n is electron density. The acoustical deformation potential scattering (ADP scattering)

$$\frac{1}{} \quad \frac{D_A{}^2 k_B T_L}{W\hbar C_l} g_c \; E \tag{4.6}$$

where, $g_c(E) = {}^{m^*}/_{\pi\hbar^2}$ is the density of states in 2D system. W is a width of the quantum well. $\mathbf{D_A}$ is the acoustic deformation potential (ADP) given by $D_A = K_B T_L \left({}^{M}/_{m^*}\right)^{1/2}$, where $m^* = \frac{\hbar^2}{\partial^2 E / \partial k^2}$ is electron effective mass and M is atomic mass (in g), which varies with lattice temperature and $\mathbf{C_t}$ is the longitudinal elastic constant. The relation between momentum relaxation time and energy relaxation time without electric field is given by

$$\tau_E = \frac{E(p)}{h\omega_{LO}} \tau_p = \frac{k_B T_L}{h\omega_{LO}} \tau_p \tag{4.7}$$

The relation between momentum relaxation time and energy relaxation time under electric field is given by

$$\tau_E = \frac{E(p)}{h\omega_{LO}} \tau_p = \frac{{}^{1}/_{2} m^* v_d^2}{h\omega_{LO}} \tau_p \tag{4.8}$$

where, the thermal energy is neglected as the calculation is carried out for low temperature and high electric field. In the stationary case,

$$E(p) = E_{eq} + e|FV|\tau_E \tag{4.9}$$

Under thermal equilibrium, the electron temperature T_e coincides with the lattice temperature T_l. Under low applied field, T_e is less than T_l so that the phonons are absorbed, but under non-equilibrium conditions, (i.e. with high electric fields), T_e exceeds greatly from T_l and hence the LO phonons are emitted during electron phonon interactions and is called hot electron problem.

4.4 Results and Discussion

The present section describes the study of hot electron - phonon interaction is carried out for both dilute nitride and dilute magnetic semiconductors. The electric field dependence of energy relaxation rate, electron energy loss rate and electron drift velocity are calculated using the relaxation rates.

4.4.1 Dilute Nitride Semiconductors

The electric field dependent electron energy relaxation rates are calculated for different nitrogen concentrations in 2D $GaAs_{1-x}N_x$ by using Eqn. (4.8) and presented in figure 4.1. We have calculated for both high and low field but we present here only for low field as the trend is quite similar. It is seen from Figure (4.1) that the energy relaxation rate decreases with field but increases with nitrogen concentration. This may be due to the fact that the reduction of electron energy relaxation rate with field is due to the increase of the electron energy increases with it.

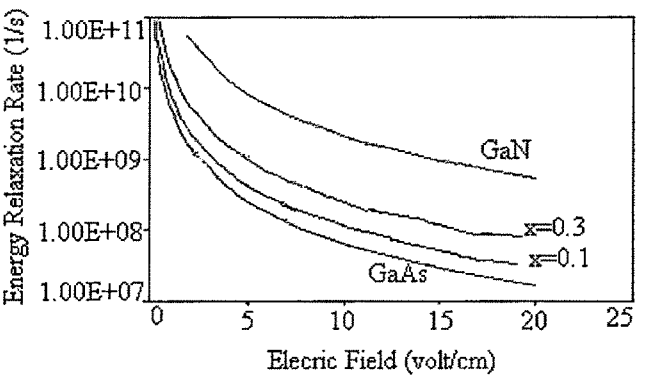

Fig.4.1 Electron energy relaxation rate variation with electric field for different nitrogen concentration.

The energy acquired by electron from field is absorbed for emission of phonons of energy $\hbar\omega_{LO}$ which is concentration dependent. The electric field increases the ratio of energy gain to energy absorbed but the optical phonon energy $\hbar\omega_{LO}$ increases for nitrogen

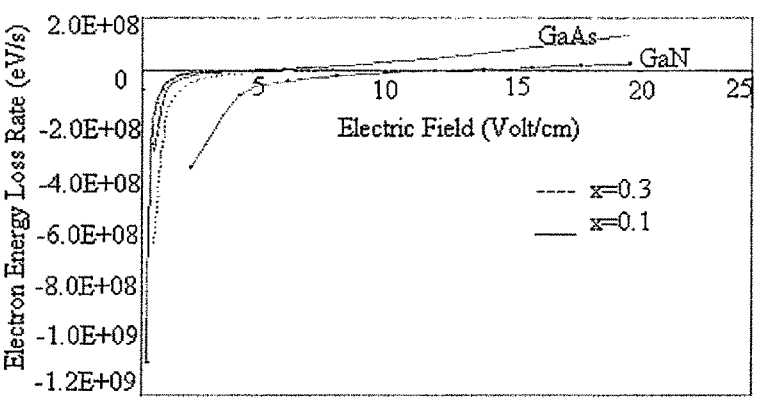

Fig.4.2 The electron energy loss rate at low electric field

concentration in $GaAs_{1-x}N_x$. The electron energy loss rates calculated using Eq. (4.5) for the two dimensional $GaAs_{1-x}N_x$ (for x=0.0, 0.1, 0.3, 1.0) have been presented in figure 4.2. The figure 4.2 reveals that the electron energy loss rate increases with the electric field.

The negative values of loss rate indicate the phonon absorption by electrons, which means that for this region of field, the electron temperature is lower than the lattice

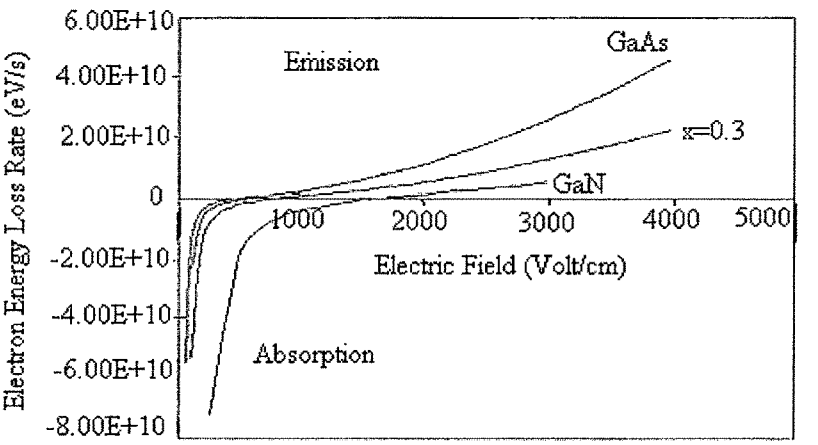

Fig.4.3 The electron energy loss rate at high electric field

temperature T_l. For sufficient large field the electron temperature exceeds T_l, which results in phonon emission, which increases significantly at high field which presented in figure 4.3.

Further the variation of drift velocity with electric field is calculated and presented in figure 4.4. It revealed from figure 4.4 that as the field increases, the electron drift velocity also increases but decreases with nitrogen concentration.

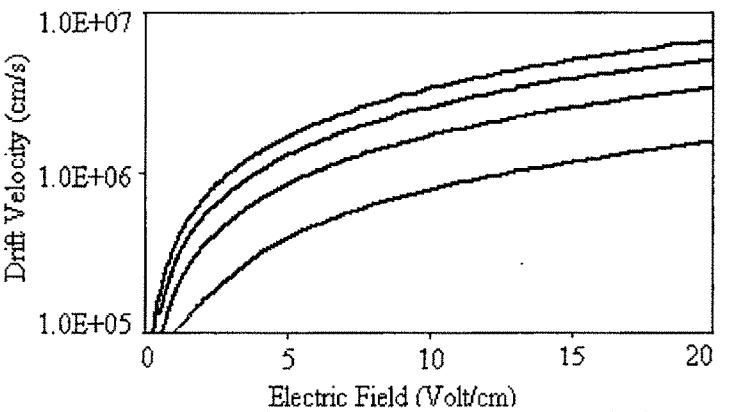

Fig 4.4 The electrons drift velocity variation with electric field for different nitrogen concentration.

4.4.2 Hot Electron–Magneto-Transport on Diluted Magnetic Semiconductors

The variation of hot electron-phonon energy and momentum relaxation rates with the variation of electric and magnetic fields is calculated and presented for two dimensional structure of $Ga_{(1-x)}Mn_xN$ in figure 4.5 and 4.6 respectively. It is observed from the Fig.4.5 that the relaxation rates for hot electrons decrease exponentially with high electric fields under applied magnetic field but increase with magnetic field is also observed. These figures also reveal that as the manganese concentration is decreased, the energy relaxation rate also reduce noticeably. This may lead to important conclusion that the lower concentration of manganese is beneficial for its application in carrier transport. The present study has also been successful in bringing out the effect of magnetic field on the hot carrier relaxation time and may lead to understand the transport behavior of electrons in$Ga_{(1-x)}Mn_xN$.

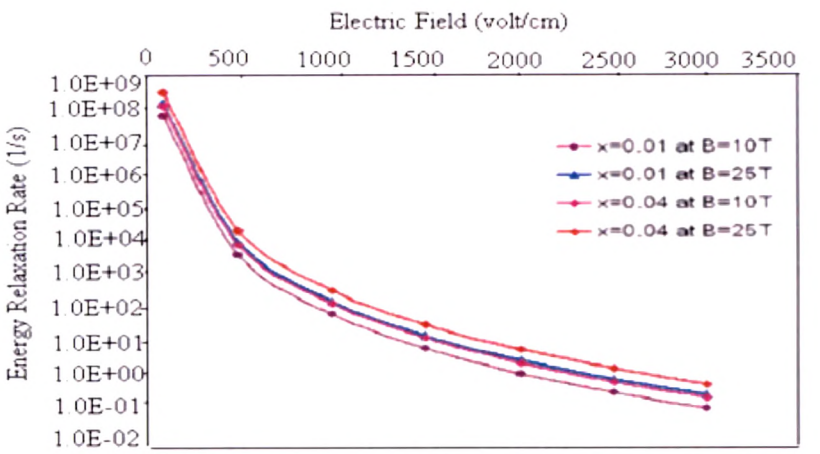

Fig 4.5 Energy relaxation rate variation with electric field with different Mn concentration and magnetic field

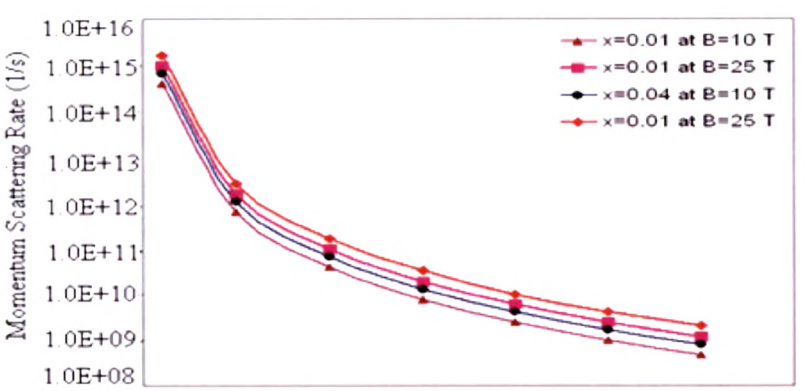

Fig. 4.6 Momentum relaxation rate variation with electric field with different manganese concentration and magnetic field

4.5 Summary

In the present chapter, the electron transport phenomenon under the influence of electric field is discussed which has application in the operation and performance of many heterostructure devices under high electric field. The variation of electron

scattering rates (e.g. momentum and energy relaxation rates), carrier drift velocity, electron energy loss rate by means of phonon emission and phonon absorption with respect to electric field and doping concentration are considered. The relaxation rates for hot electrons decrease exponentially with high electric fields under applied magnetic field. It is revealed from the present study that as the field increases, the electron drift velocity also increases but decreases with nitrogen concentration. It can be concluded that the energy acquired by electron from field is absorbed for emission of phonons of energy $\hbar\omega_{LO}$ but this energy is concentration dependent so as the electric field increases the ratio of energy gain to energy absorbed increase but the optical phonon energy $\hbar\omega_{LO}$ increases for nitrogen concentration in $GaAs_{1-x}N_x$. So the energy relaxation rate is number of optical phonons emitted times the momentum relaxation rate.

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