Hot electron scattering rates via LO-phonon emission in two-dimensional GaAs\(_{1-x}\)N\(_x\)

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The carrier energy loss rate is studied under low and high electric fields at low temperature with the help of electron-phonon interactions via deformation potential coupling mechanism for two dimensional GaAs\(_{1-x}\)N\(_x\). We observed that at low temperatures, the energy relaxation rate decreases with high electric fields but increases with nitrogen concentration. The electron energy loss rate decreases with nitrogen concentrations at low temperatures. The electron energy loss rate is found to be negative up to certain electric field due to phonon absorption and beyond that, there is phonon emission. The electron drift velocity increases with field but decreases with nitrogen concentration.

Keywords: Hot electron, Phonons interaction, Diluted nitride semiconductor, LO phonons

1 Introduction

The semiconductor alloy gallium (indium) nitride arsenide has attracted considerable attention in recent years. When a small fraction of arsenic atoms in GaAs is replaced by nitrogen the energy gap initially decreases rapidly, at about 0.1 eV/% of N for \(x \leq 0.03\) with the measured conduction band edge mass also showing unexpectedly large values\(^1\,^2\). This behaviour is markedly different to conventional semiconductors and is of interest both from a fundamental perspective and also because of its significant potential device applications. The strong bowing opens the possibility of using GaInNAs to get optical emission on a GaAs substrate at the technologically important wavelengths of 1.3 and 1.55 \(\mu\)m, considerably expanding the capabilities of GaAs for optoelectronics. Charge transport in any device is characterized by the charge carrier scattering with impurity, phonons and crystal defects or with other carriers. In recent years, electron scattering by acoustic phonons has been of great interest due to its role in the physics of semiconductor nanostructures and their potential applications as this controls the relaxation of carriers to their band bottoms, which is necessary for sufficient laser action, optical modulation and for other optical and transport phenomena\(^3\,^4\,^5\). Many heterostructures devices operate in high electric fields to achieve the desirable high speed or high frequency performance of these devices\(^6\). However, being accelerated in high electric fields, the electron mean energy and the average momentum acquired are far greater than those associated with thermal equilibrium. This leads to a strong non-equilibrium state of the electron gas. Strong non-equilibrium electrons not only move fast, but also exhibit a number of specific effects that find various practical applications because whenever, the devices are operated under high electric fields the electron mean energy and their average momentum acquired increase with the electric fields. 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 \(E=\frac{n k_B T_e}{2}\), 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 \(T_l\) only 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 strong enough 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. 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. The coupling of electrons with the
transverse-optic phonons is comparatively weak. 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, more than an order of magnitude greater than ə.

In our former work, the electron-acoustic phonon momentum scattering rate for two-dimensional GaAs$_{1-x}$N$_x$ for different thermal energies without any field has been calculated.$^7$ In the present work, the energy relaxation and energy loss rate are calculated for electron transport at low and high electric fields in GaAs$_{1-x}$N$_x$. The variations of electron drift velocity (acoustical and optical), impurity atoms, crystal defects etc.$^8$ The transition rate which is the frequency interrupted by collisions with phonons are also observed in the present work. The transition rate which is the golden rule by considering acoustical phonons deformation potential scattering for acoustic phonons and given as:

$$C_p = \frac{\pi m^* D^2_A}{\eta p \delta, \rho \Omega} \quad \ldots(6)$$

To evaluate scattering rates for acoustic phonon scattering via the deformation potential scattering in 2D nanostructure, Eq. (5) can be solved by substituting the value of $C_p$ from Eq. (6) for the acoustical deformation potential scattering (ADP scattering) and expressed as:

$$\frac{1}{\tau} = \frac{\pi D^2_A k_B T_l}{W h C_i} g_z(E) \quad \ldots(7)$$

where $g_z(E) = m^*/\pi \hbar^2$ is the density of states in 2D system, $W$ is a width of the quantum well. $D_A$ is the acoustic deformation potential (ADP) given by $D_A = k_B T_l (M/m^*)^{1/2}$:

$$m^* = \frac{\hbar^2}{\Psi^2 E / \Psi k^2} \quad \ldots(8)$$

$m^*$ is electron effective mass and $M$ is atomic mass (in g), which varies with lattice temperature$^7$ and $C_i$ is the longitudinal elastic constant.

When the electric field $E$ 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 Frohlich 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.$^9,10$:

$$\frac{dE}{dt} = e |F| \left| W_E \right| \quad \ldots(9)$$
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:

\[
W_E = \frac{(T_e - T_l)n}{\tau_e} \quad \ldots(10)
\]

where \( T_e = \frac{FV_d T_E}{k_B} \) is electron temperature and \( n \) is electron density.

The relation between momentum relaxation time and energy relaxation time under electric field is given by\(^{11}\):

\[
\tau_E = \frac{E(p)}{\hbar \omega_{LO}} \tau_p = \frac{1/2 m^* v_d^2 + 3/2 k_B T_L}{\hbar \omega_{LO}} \tau_p \quad \ldots(11)
\]

In the stationary case,

\[
\tau_E = E(p) = E_{eq} + e|FV| \tau_E \quad \ldots(12)
\]

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. Further, the drift velocity of electrons is also observed as a function of electric field \( v_d = \mu F \).

where \( \mu \) is the acoustical phonons scattering mobility defined as\(^{12}\):

\[
\mu = \frac{3.17 \times 10^{-5} d u^2}{\left(\frac{m^*}{m_e}\right)^{3/2} D_A T^{3/2}} \quad \ldots(13)
\]

where \( d \) is the density of material, \( u \) the average sound velocity, \( D_A \) the acoustical deformation potential and \( T \) is absolute temperature. The sound velocity can be found out by the relation:

\[
u = \frac{k_0 T^3}{\hbar} \left(\frac{V}{6 \pi^2}\right)^{1/3}
\]

where \( \theta_D \) is the Debye temperature and \( V \) is the average atomic volume.

### 3 Results and Discussion

The electric field dependent electron energy relaxation rates are calculated using Eq. (12) for different nitrogen concentrations in 2D GaAs\(_{1-x}\)N\(_x\) and shown in Fig. 1. Here, we present only the variation for the low field. Fig. 1 shows that the energy relaxation rate decreases with field but increases with nitrogen doping. The reason behind the reduction of electron energy relaxation rate with field is that as the field increases the electron energy increases with it and the field dependence of electron energy can be seen from Eq. (12). So 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 dependent on concentration so...
as the electric field increases the ratio of energy gain to energy absorbed increases but the optical phonon energy $\hbar\omega_{\text{LO}}$ 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. The electron energy loss rates calculated using Eq. (10) for the two dimensional GaAs$_{1-x}$N$_x$ (for $x=0.0$, 0.1, 0.3, 1.0) are shown in Fig. 2. This shows 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 temperature $T_l$.

For sufficient large field, the electron temperature exceeds $T_l$, which results in phonon emission, which increases significantly at high field. Further, the variation of drift velocity with electric field is calculated and presented in Fig. 3. It is seen from Fig. 3 that as the field increases, the electron drifts velocity also increases but decreases with nitrogen concentration.

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**References**