Ultrasonic Wave in Semiconductor Quantum Well structures

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Abstract

The effect of intra sub-band scattering by LA phonons on the dc field transport properties of electrons in quasi – 2D semiconductors is investigated using Phonon Boltzmann Transport Equation (PBTE), within the frame work of a simple theoretical model n which acoustic attention (amplification) effects are studied. The model assumes the electrons distribution is a displaced Fermi function with scattering confined to LA phonons which are in intimate contact with 2D-electron gas. The numerically calculated dependence of attenuation coefficient on phonon wave vector and quantum well width are shown and discussed.

Introduction

We consider the Quantum Well (QW) semiconductor heterostructures for the study of acoustic wave amplification (attenuation). When a acoustic wave propagates in a semiconductor, the electron phonon interaction takes place and that manifests in the form of attenuation or amplification of the wave. As a result, electrons cannot follow the wave. As a result, electrons follow the wave completely; this energy is lost from the wave. To understand the mechanism through which the acoustic wave loose or gain energy from the charge carrier, a careful theoretical treatment of the model calculation on both electron and lattice vibration is necessary. In this investigation, a generalized scheme is used for the acoustic wave amplification (attenuation) by two – dimensional electron gas (2DEG) in single QW structures considering the degenerate distributions for charge carriers. In a QW structures subjected to dc electric field is to produce a drift velocity of the electrons, when this drift velocity exceed the sound velocity; in this situation the acoustic phonon amplification (attenuation) occurs and same has been extensively studied in the bulk semiconductor [1,2]. Further, ultrasound attenuation is studied in QW structures [3, 4], it is shown that attenuation increases with the decreasing well width and it may enhance over that of bulk. The origin of this phenomenon remains a subject of discussion in spite of extensive investigation. It is therefore important to present this work on the acoustic wave amplification under the influence of dc field in a QW heterostructures.

In this communication, we extend the quantum theory of acoustic wave attenuation and amplification restricted to intra sub-band scattering by LA phonons in which the transfer of energy and momentum to acoustic phonon is direct through hot electrons excited by dc field. The acoustic wave attenuation coefficients are numerically computed and their dependence on the phonon wave vector and quantum well width, are discussed.

Model

The attenuation coefficient for longitudinal acoustic phonon interacting with electrons confined to move in 2DEG system can be calculated quantum mechanically by relating it to the transition probability for the free carriers to make a transition from initial state with the phonon absorption and emission processes in a scattering [5]. In other words, the attenuation coefficient is obtained from the change of phonon population from the processes in which a phonon is absorbed from those process in which a phonon is emitted can be written as.

$$\gamma = \left\{\frac{1}{N_a \upsilon_s}\right\}\left[\frac{dN_a}{dt}\right]_{e-ph} \qquad (1)$$

Here N_a is the Bose distribution of acoustic phonons and $N_a\upsilon_s$ represents the phonon flux. The expression for attenuation coefficient for QW subjected to a dc electric field capable of producing hot carriers in 2D system is calculated using the PBTE due to electron-phonon interaction by assuming electrons to be in the lowest sub-band. Employing first order perturbation theory with appropriate matrix element (M_d) for LA phonons via deformation potential; is given by

$$\left[\frac{\partial N_a}{\partial t}\right]_{e-ep} = \left(\frac{2\pi}{\hbar}\right)\sum_{m'k}\left|M_d\right|^2 \delta_{k_x,k_x-q_x}\delta_{k_y^{'},k_y-q,} \times$$

$$\left\{\begin{matrix} f_{n\vec{k}}\left(1-f_{n'\vec{k}-\vec{q}}\right)\left(N_a+1\right)\delta_{qz'}\left(-\pi/L\right)\left(n'-n\right) \\ \delta\left(E_{n\vec{k}}-E_{n'\vec{k}-\vec{q}}-\hbar\omega\right)-f_{n'\vec{k}-\vec{q}}\left(1-fn\vec{k}\right)Na \\ \delta_{qz'}\left(\pi/L\right)\left(n'-n\right)\delta\left(E_{n'\vec{k}-\vec{q}}-En\vec{k}-\hbar\omega\right)\end{matrix}\right\} \qquad (2)$$

Where $f_{n\vec{k}}$ is the displaced Fermi – Dirac distribution function, with electron temperature $T_e;\hbar\vec{k}$ is the average electron drift momentum in the k- space; $\beta = 1/k_BT_e$; and the Fermi energy is related to two dimensional electron density n_e is given by

$$E_F = \left(\pi\hbar^2 n_e / m^*\right) \qquad (3)$$

After some algebraic manipulation and using the properties of the Kronecker Dirac delta functions, and on performing the integration over the polar angle and k to dimensional variable by defining the following

$$\zeta_n = \left[\int\frac{dy}{\left(e^{y^2+z_2}+1\right)} - \int\frac{dy}{e^{y^2+z_1}+1}\right]; z_F = E_F/k_BT_e;$$

$X_n = \beta E_o n^2 z_1 = x_1 + x_n - Z_F$; $Z_2 = Z_1 + Z_q$;

$$N_{Do} = \left[\exp\left(\frac{z}{q}\right)-1\right]^{-1}; X = \frac{\upsilon_d}{\upsilon_s}z_q = -x_o q_s / q\left(1-X\right);$$

$$x_1 = \frac{x_o}{4}\left[1+\frac{q_s}{q}\left(1-X\right)\right]^2; q_s = \frac{2m^*\upsilon_s}{\hbar}; x_o = \frac{\hbar^2 q^2}{2m^* k_B T_e}$$

One can obtain the attenuation coefficient by taking the term proportional to N_a and (N_{DO} / N_a) from equation (2) and substituting in equation (1), here N_{Do} is the rate of generation of acoustic phonon due to hot electrons in the temperature T_e, υ_d is drift velocity of electrons, we get

$$\gamma^{deg} = [4\gamma' - \gamma'']\xi_n \qquad (4)$$

Where $$\gamma' = \left\{ \frac{E_d^2 m^* \left(2m^* k_B T_e\right)^{3/2}}{\hbar^3 \upsilon_s^2 L \rho} \right\} (\xi_n), \qquad (5)$$

$$\gamma'' = \left[\frac{N_{Da}}{N_a} \right] (\gamma' \xi_n)$$

Here it is interesting to note that γ' is independent of lattice temperature and depends only on the electron temperature (T_e). It is also seen that γ' is inversely proportional to the thickness of well width L and independent of energy these results are in fully agreement with the work [3,9]. However, γ'' is dependent of both lattice and electron temperatures. The condition for acoustic wave amplification or attenuation $(1-X)$ are met through the ξ_n and satisfy the same.

Results and Discussion

In order to calculate γ' we have made use the following material parameters [6] for QW provided by the structure $GaAs/Al_xGa_{1-x}As$: $m_1 = 0.067 m_o$, $\rho = 5.36 gm\ cm^3$, $E_d = 7 eV$ and $\upsilon_3 = 5.24\ x 10^5 cm / s$. The nature of variation of γ' versus q for different values of X is shown in fig. It is clear that γ' has pronounced value in the range $q = (1.5-2.5) x 10^6\ cm^{-1}$ indicating the unequal probability that an electron posses the drift momentum required to emit or absorb a phonon and decreases to negligible value beyond this range of q. This may be understood in the following manner, for $X < 1$ as noted above the drift is small and the momentum conservation permits a certain range of phonons tobe in contact with electron/ on the other hand $X > 1$ the momentum conservation limits the phonon q range; however, the maximum γ' is at $q = 1.\ 8 x\ 10^6\ cm^{-1}$.

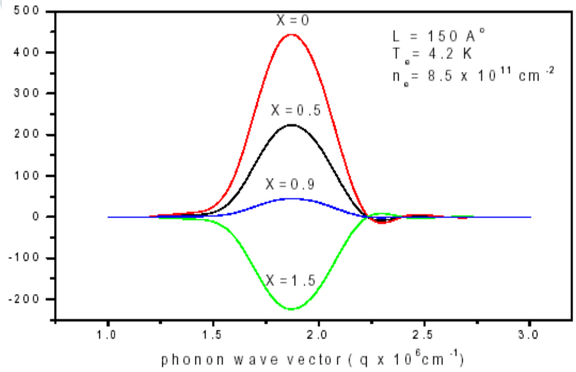

Fig 1. Attenuation coefficient (γ') versus Phonon wave vector.

Further, we have shown in fig.2 the behavior of γ' for different values of X as a function of quantum well width which get enhanced compared with bulk [7, 8]. We find γ' suddenly decays for smaller values of L. Therefore it seems that such a semiconductor heterostructures could be useful for the development of semiconductor devices efficient traveling wave amplifiers for ultrasound.

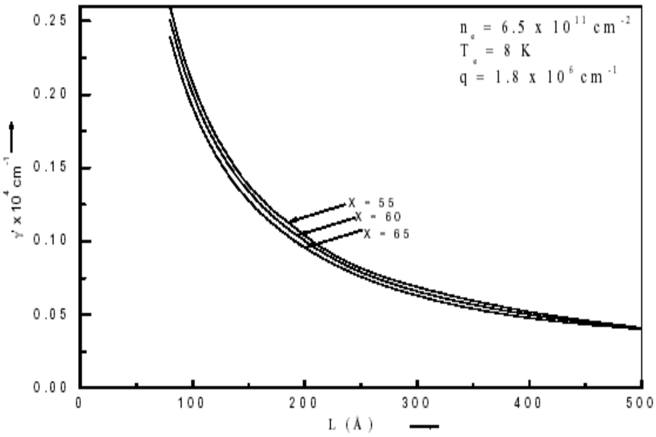

Fig. 2 Attenuation coefficient (γ′) as a function of quantum well width

In conclusion, acoustic amplification (attenuation) in a quasi – two-dimensional electron gas in QW semiconductor heterostructrues in presence of dc field and in the extreme quantum limit has been theoretically studied. The attenuation coefficient values are numerically computed and their dependence on phonon wave vector and quantum well width are presented.

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