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Hot Electron Energy Loss Mechanism and Longitudinal Conductivity of Narrow-gap Semiconductors in Parallel Electric and Magnetic Fields

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Abstract: The influence of various scattering mechanisms on the energy-loss rate and longitudinal hot electron conductivity of narrow-gap semiconductors, in n-HgCdTe in the extreme quantum limit has been investigated theoretically both for equilibrium and nonequilibrium phonon distributions. Investigations have been made for different temperature regions, and in the presence of parallel electric and magnetic fields. In the present analysis, various complexities such as, band nonparabolicity, non equipartition of acoustic phonons, Landau level broadening due to impurities and the modified screening due to the application of quantizing magnetic field, have been taken into consideration.

The magnetic field dependence of hot electron energy loss mechanism and electric field dependence of longitudinal hot electron conductivity at both low and high temperatures have also been studied. The acoustic phonon scattering via deformation potential and piezo electric coupling has been found to dominate at low temperatures, while the longitudinal optical phonon scattering has been found to be responsible for the hot electron energy loss at high temperatures. For nonequilibrium distributions, the energy loss rate has been found to depend directly on the magnetic field strength whereas that for equilibrium distribution is proportional to the square of the field strength.

Keywords: Hot electron, energy loss rate, longitudinal conductivity

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1. Introduction

Hot electron transport has been one of the interesting aspect of electron transport in view of the applications in devices and in understanding the physics of phonon scattering mechanisms together with band structure effects. The hot electron behaviour in the presence of a quantizing magnetic field is significantly different from that in absence of magnetic field due to following reasons a) the nature of electron gas becomes quantized due to the formation of Landau level in the presence of high magnetic field (magnetic quantization), b) the different scattering mechanisms described by scattering matrix elements get modified due to one dimensional density of states in the presence of high magnetic field. In addition to this the distribution of carriers are significantly altered, the total energy of system remaining the same. The application of the high magnetic field also changes the screening.

High electric field causes the electron system to deviate from the equilibrium carrier distribution. It can be characterised by the electron temperature T_e, different from the lattice temperature T_L. Significant difference between T_e and T_L causes phonon emission at higher rate. There reabsorption by the system ultimately modifies the energy transferred rate from the heated electron system to the lattice causing a slower cooling rate. This has been found to be an important effect in explaining the energy loss rate in semiconductors in presence of high electric field.

A simplified model assuming displaced Maxwellian distribution for carriers occupying the lowest Landau level has been developed. The various other complexities such as band nonparabolicity, free carrier screening, Landau level broadening have also been included. The effect of disturbance in phonon distribution due to hot phonon effect[1] has also been taken into account for proper understanding of the magnetic field dependence of energy loss rate

In the present paper the expressions for energy loss rate for low and high temperatures have been presented assuming acoustic phonon scattering via deformation potential and piezo electric coupling, and longitudinal polar optical phonon (POP) scattering respectively both for equilibrium and nonequilibrium phonon distributions. The effect of different scattering mechanisms on the energy loss rate and longitudinal hot electron conductivity has been examined for different temperature regions and in the presence of parallel electric and magnetic fields.

2. Theory

When a narrow gap semiconductor is subjected to a quantizing magnetic field B applied along z-direction, the energy dispersion relation for electrons in a non-parabolic band is given by[2]

$$E = \frac{\hbar^2 k_z^2}{2m^*} + \frac{E_g}{2m^*}(a_n - 1) \tag{1}$$

where k_z is the z-component of electron wave vector, E_g is the band gap and a_n is the band nonparabolicity factor given by

$$a_n = [1 + \frac{4\hbar\omega_c}{E_g}(n + 1/2)]^{1/2} \tag{2}$$

where $\hbar$ is the reduced planck's constant, $\omega_c = \frac{eB}{m^*}$ is the cyclotron frequency, m^* is the band edge effective mass and the integer n represents the Landau level index.

When a strong electric field is applied parallel to the quantizing magnetic field, the electrons with magnetic field dependent effective mass gain energy from the electric field and at the same time loose energy by interacting with available phonons. At low temperatures, the electrons transfer energy to the lattice via acoustic phonons and piezoelectric scattering, whereas at high temperatures the energy transfer is only due to POP scattering.

The energy loss rate due to electron phonon scattering may be expressed as [3,4]

$$P = \frac{2\pi}{V\hbar}\sum\hbar\omega_0|C_q|^2 2\sum\sum E_{\nu\nu'}(q)f(\epsilon_\nu, T_e)[1 - f(\epsilon_\nu, T_e)] - A_{\nu\nu'}(q)f(\epsilon_{\nu'}, T_e)[1 - f(\epsilon_\nu, T_e)] \tag{3}$$

where ω_0 = phonon frequency, T_e = electron temperature, ϵ_ν and $\epsilon_{\nu'}$ are electron energies in the Landau states ν and ν' respectively, $|C_q|^2$ is electron phonon coupling constant, which depends on the scattering mechanism. $E_{\nu\nu'}$ and $A_{\nu\nu'}$ are the absorption and emission terms respectively.

Now substituting the expressions of $E_{\nu\nu'}(q)$ and $A_{\nu\nu'}(q)$ in the above expression and after some simplification, the above equation reduces to

$$P = \frac{em_{av}^* B}{n_0(2\pi)^3\hbar^4}\sum\sum\int_{Q_{nn'}^2}^{\infty}\frac{dq_z^2}{q_z^2}\int_0^{\infty} dq^2\hbar\omega_0|C_q|^2[N(\hbar\omega_0, T_e) - N(\hbar\omega_0, T_L)][f(\epsilon, T_e) - f(\epsilon + \hbar\omega_0, T_e)]|M_{n'n}\frac{\hbar q^2}{2eB}|^2 \tag{4}$$

where T_e and T_L are the electron and lattice temperatures respectively, n, n' represent the Landau index for initial and final states respectively.

2.1 Thermal phonons

We first assume the case of thermal phonons for which the distribution is Bose-Einstein Statistics, which is independent of applied electric and magnetic fields given by

$$N_R = [Exp(\frac{\hbar\omega_0}{k_B T_L}) - 1]^{-1} \tag{5}$$

The energy loss rate per electron for acoustic scattering via deformation potential and piezoelectric coupling, and that for POP scattering are obtained respectively as

$$P_{ac} = \alpha_{ac}[(N_R + 1)Exp(-v_e) - N_R Exp(v_e)] \tag{6}$$

$$P_{pz} = \alpha_{pz}[(N_R + 1)Exp(-v_e) - N_R Exp(v_e)] \tag{7}$$

$$P_{pop} = \alpha_{pop}[(N_R + 1)Exp(-v_e) - N_R Exp(v_e)] \tag{8}$$

where α's are the constants depending on the scattering considered[5].

2.2 Non-Equilibrium Phonons

During the process of heating, the large phonon emission rate changes the phonon distribution quite significantly deviating it from the Bose-Einstein phonon distribution. This would have a feedback effect on the electron temperature and hence it would alter the electron energy loss rate. This would also make energy loss rate slower compared to the equilibrium case and also cause different magnetic field dependence. However, in this case N_R will be modified according to the following rate equation

$$\frac{\delta N_R^{neq}}{\delta t} = \frac{N_R^{neq} - N_R}{\tau_p} \tag{9}$$

where τ_p is the phonon life time.

Then energy loss rate for various electron phonon scattering processes may be written in the following general form,

$$P = \alpha[(N_R^{neq} + 1)Exp(-v_e) + N_R^{neq} Exp(v_e)] \tag{10}$$

where α's are the same constant as equations(6-8) depending on the type of the electron phonon scattering mechanism and N_R^{neq} is the nonequilibrium phonon occupation number given by

$$N_R^{neq} = \frac{N_R + A\alpha\tau_p Exp(-v_e)}{1 - A\alpha\tau_p[Exp(-v_e) - Exp(v_e)]} \tag{11}$$

τ_p being the phonon life time[5].

In order to evaluate the hot electron drift velocity, one needs momentum as well as energy relaxation times unlike low field case, where momentum relaxation time is required. The energy relaxation rates due to acoustic, piezoelectric and longitudinal optical phonon scattering have already been obtained with thermal and non thermal phonon distributions. The momentum relaxation rates may be obtained following the similar approach[5].

We know the drift velocity of electrons can be obtained from the relation

$$V_d = \mu\varepsilon \tag{12}$$

where μ is the mobility and ε is the electric field.

At the steady state, the energy loss rate can be written as a function of electric field as

$$< \frac{dE}{dt} >= eV_d\varepsilon \tag{13}$$

Again mobility μ is given by

$$\mu = \frac{e < \tau >}{m^*} \tag{14}$$

where τ is the average momentum relaxation time of the electrons which includes the contributions of the acoustic phonon scattering via deformation potential and piezoelectric coupling for low temperature, and polar optical phonon scattering for high temperature. From the above expression we get the conductivity of the electron as $\sigma = n_e e\mu$, where n_e is the electron concentration.

3. Results and discussions

The energy loss rate of longitudinal hot electrons in n-$Hg_{0.8}Cd_{0.2}Te$ as a function of applied magnetic field and electrical conductivity as a function of the applied electric field at lattice temperature T_L = 4.2K and 30K and electron temperature T_e = 5K and 32K, have been calculated with the material parameters[6]. The phonon life time for the present calculation is about 100 ns[7]

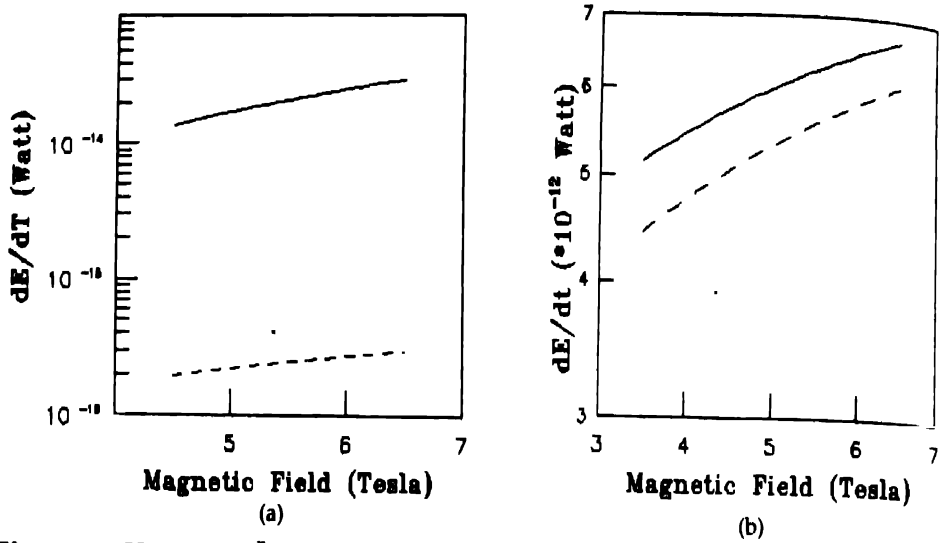

Figure 1. Variation of energy loss rate of hot electron in n-HgCdTe in the extreme quantum limit as a function of magnetic field at $T_L = 4.2$K, $T_e = 5$K (figure (a)) and $T_L = 30$K, $T_e = 32$K (figure (b)). The solid and dashed curves represent equilibrium and nonequilibrium cases respectively.

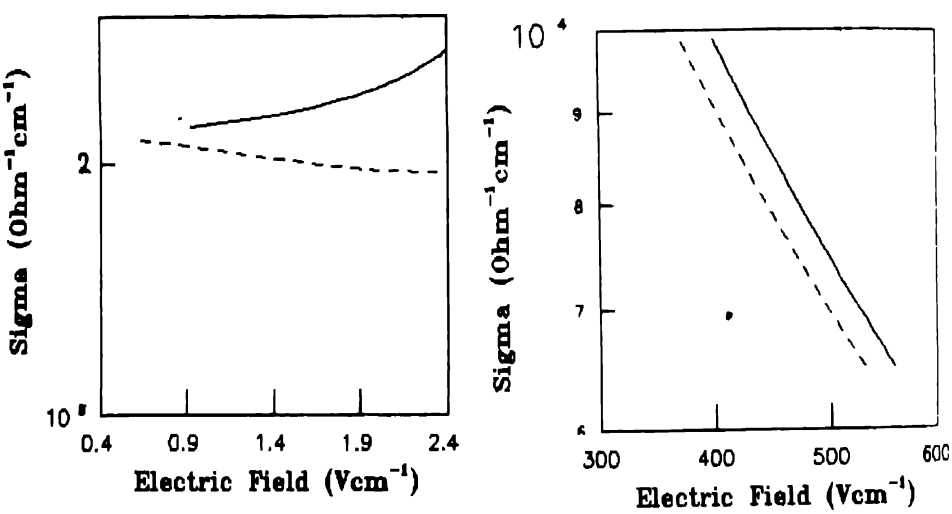

Figure 2. Variation of hot electron conductivity in n-HgCdTe with electric field at $T_L = 4.2$K, $T_e = 5$K (figure (a)) and $T_L = 30$K, $T_e = 32$K (figure (b)).

in case of low temperature regimes where acoustic and piezoelectric scattering have been taken into consideration. It is about 100 ps[8] in case of high temperature regimes where polar optic phonon scattering has been considered.

The variations of energy loss rate as a function of magnetic field both for low and high temperatures are depicted in the figure 1(a and b) respectively. Comparing the nature of these two figures, it is found that the value of the energy loss rate increases with increase in magnetic field. Again both for low and high temperatures, energy loss rate for nonequilibrium phonons is lower compared to that for equilibrium case. So we can conclude that energy loss mechanism for phonon scattering is enhanced with the magnetic field. The rate of increase is found to be higher for polar optical phonon scattering. The inclusion of nonequilibrium phonon slows down the cooling processes due to reabsorption of phonons emitted by hot electrons.This process may be considered as a feedback process leading to decrease in energy loss rate. The theoretical dependence is found to be proportional to B^2 and B for equilibrium and nonequilibrium distributions respectively.

From figure 2(a and b) it is found that at high temperatures, the conductivity is dominated by longitudinal optical phonon scattering which would lead to a conductivity decreasing with electric field. On the otherhand, at low temperature, the contribution of acoustic phonon scattering gives rise to a conductivity increasing with electric field. This type of variation is in agreement with the experimental results observed from without magnetic field[9].

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