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Determination of non-equilibrium electron energy and momentum relaxation rates in GaAs/AlGaAs multiple quantum well

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The results of the experimental techniques used in the determination of the power and momentum losses from a 2DEG were presented. These are the hot electron photoluminescence (HEPL), and mobility mapping techniques which involve the measurements of PL in synchronization with applied voltage pulse, high field I-V and Hall mobility. In the presence of electric field the carriers are heated, and the high energy-tail of the PL, which is described by Maxwell-Boltzmann distribution, can be used to obtain the temperature of the non-equilibrium carriers. The second technique called mobility mapping is used to verify the temperature of the non-equilibrium carriers.

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1. Introduction

The first investigation on hot electrons in solids started seventy years ago by Von Hippel (1937) who aimed to explain the electrical breakdown of insulator. His idea was that the electrical breakdown occurred by electrons which get more energy from the applied electric field and then they lose this excessive energy by inelastic collision with the lattice and consequently, starting avalanche process through impact ionization [1]. In 1937 Fröhlich pointed out that electrons were interacted with polar optical phonons above a critical electric field and no steady state was possible. This was the first demonstration to be proposed in connection with hot electrons. Later on, many research groups presented work in the field of hot electrons [2, 3]. Due to enhancement in growth and lithography techniques the issues of the effects of quantum confinement on the transport properties and device performance have been deeply investigated. Two-dimensional (2D) GaAs has been widely studied in both theoretically and experimentally. It was determined that the electron temperatures above the certain temperature were mainly as a result of electron-*LO* phonon interactions [4]. The study of hot electron energy and momentum relaxation for longitudinal transport in GaAs/$Ga_{1-x}Al_xAs$ quantum wells was extended. It was determined that the energy relaxation rates for electrons decreases with increasing electron concentration. However, the presence of large none-equilibrium population of *LO* phonons in momentum space, which are formed as a result of drift of hot electrons, reduces the energy relaxation rates while enhance the momentum relaxation rates and reduces the drift velocity at high fields inducing negative differential resistance which may arise from real-space or intervalley transfer [4, 5].

The goal of the study is to determine of non-equilibrium electron energy and momentum relaxation rates in the steady state 2D Semiconductor and discuss validity of the techniques which are implied for GaAs/GaAlAs MQW.

2. Experimental details and discussion

The investigated GaAs/$Ga_{1-x}Al_xAs$ (% x =24) Multi-quantum Well (MQW) sample was grown by Molecular Beam Epitaxy (MBE) on undoped semi-insulating GaAs substrate. GaAlAs was used as a barrier material in GaAs based heterostructure and x<0.4 was studied to have direct band gap material. The sample then was fabricated as Hall Barr geometry and ohmic contacts were formed by alloying Au-Ge-Ni. Hall bar structure helps to provide the simultaneous measurement of the carrier concentration and the mobility of hot electrons. In order to minimize Joule heating electric field pulses which are less than 5μs duration, with a duty cycle less than 3×10^{-3} were applied through the 2D layers. A weak intensity 647 nm continuous wave (cw) Kr laser was employed as an excitation source in the hot-electron photoluminescence experiment. The luminescence was detected from the sample in synchronization with the electric pulse. The most of the luminescence was collected from recombination of electrons and heavy holes which are distributed in *k*- space.

2.1. Hot electron photoluminescence

Energy relaxation of hot carriers in 2D systems was studied by using hot electron photoluminescence technique in the presence of electric field heating.

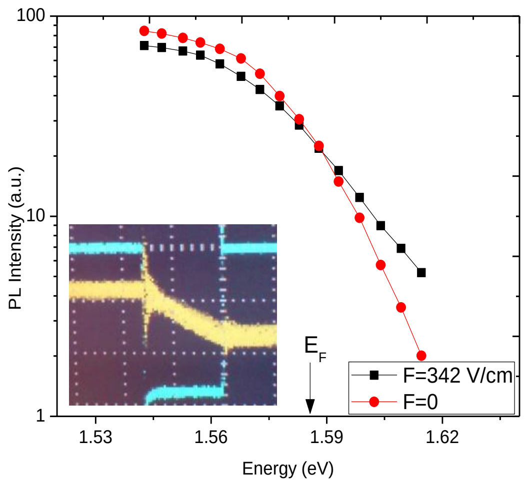

Fig. 1. The high energy tail of the PL spectrum of GaAs/Ga$_{1-x}$Al$_x$As (% x =24) at the lattice temperature T_L= 68K and two applied electric fields. The inset shows the PL signal which coincides with rectangular electric pulse.

Fig. 1 shows the high energy tail of the PL spectrum of GaAs/Ga$_{1-x}$Al$_x$As (% x =24) which was measured at a lattice temperature of T_L = 68 K. As the electric field zero, high-energy tail of the spectrum goes down sharply at photon energies $\hbar w > E_F$ (E_F is the Fermi energy which is calculated as ~50 meV) [1]. Therefore, applied electric field changes the slope of the high-energy tail. At a given electric field the linear dependence of the photon energy can be described by a Maxwell-Boltzmann distribution characterized by a carrier temperature $T_e > T_L$ [6]

$$I_{PL} \approx \exp(\frac{-\hbar\omega}{kT_e}) \qquad (1)$$

where I_{PL}, $\hbar w$, T_e and k are the PL intensity, emitted photon energy, electron temperature and Boltzmann constant, respectively. The slopes of the high-energy-tail used to determine the electrons temperature which is in thermal equilibrium with each other through electron-electron scattering. In steady state, the power input per electron is equal to that lost to the lattice through scattering process. The energy loss per electron can therefore be obtained as a function of electron temperature as shown Fig. 2. The lines drawn through the experimental points have slopes close to $\hbar\omega_{LO}$~36 meV which is the energy of the *LO* phonon in GaAs as expected from electron-*LO* phonon scattering involved in the energy relaxation of electrons. In order to calculate the energy loss from the experimental results the power balance equation was used. In the steady state the input power (*p*) is equal to the power loss (*dE/dT*) to the lattice through scattering processes [7].

$$p = e\mu F^2 = \frac{dE}{dT} \qquad (2)$$

The power loss per electron can also be obtained as a function of electron temperature by using equation (2) together with Fig. 2 that is shown as the logarithm of the power input (loss) per electron (*p*) is plotted versus inverse electron temperature ($1/T_e$). Power loss involving the emission and absorption of *LO* phonons at T_L = 68 K is shown in the form

$$\frac{dE}{dT} = p = \frac{\hbar\omega}{\tau_0}[\exp(\frac{-\hbar\omega}{kT_e}) - \exp(\frac{-\hbar\omega}{kT_L})] \qquad (3)$$

$$\frac{1}{\tau_0} = \frac{e^2\omega}{2\pi\hbar}(\frac{m^*}{2\hbar\omega})^{1/2}(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_s}) \qquad (4)$$

where ε_∞, ε_s are the high-frequency and static permittivities. Taking the following values for GaAs: m^*/m_0 = 0.067, $\hbar\omega_{LO}$ =36 meV, the electron- *LO* phonon scattering time was found as τ_0 = 128 fs. However, as can be seen the slope of the Fig. 2 decreases with decreasing temperature, indicating the prevalence of lower-energy (acoustic) phonons in the energy loss with a non-exponential temperature [7, 8]. At high electron temperature the experimental loss rate is gradually reduced. This behaviour would be expected if the carrier density were reduced by increasing field, or if there were hot phonons present at high fields. In order to calculate the effect of hot-phonon production on the energy relaxation rates the non-equilibrium phonon model developed for two-dimensional GaAs by Ridley was used [4],

$$p_e = \frac{\hbar\omega_{LO}}{\tau_{eff}}\exp(\frac{-\hbar\omega_{LO}}{kT_e}) \qquad (5)$$

where, p_e, $\hbar\omega_{LO}$, τ_{eff}, T_e are the power input per electron, *LO* phonon energy, effective energy relaxation time, which is considered all the hot-phonon effects, τ_{eff} =2.7 ps, electron temperature, respectively [7]. In this equation, e-*LO* phonon scattering time constant τ_0 was replaced by the effective energy relaxation time τ_{eff} in order to take into consideration hot-phonon effect. It is clearly showed that obtained effective energy relaxation time is much greater than the e-*LO* phonon scattering time. This observation proves that energy relaxation of electrons can not only be involved in e-*LO* phonon scattering also related to the presence and distribution of the non-drifting hot-phonons in *k*- space.

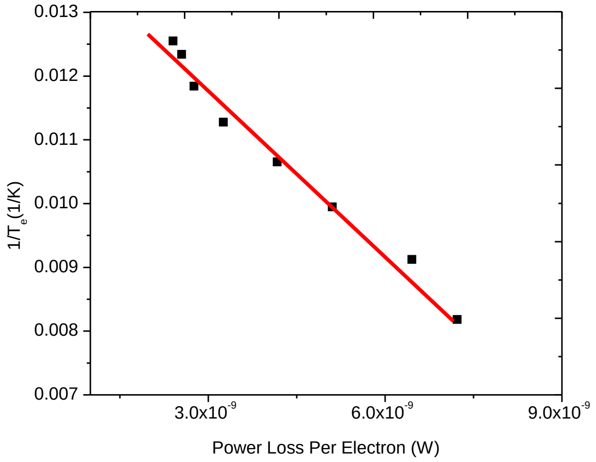

Fig. 2. Inverse electron temperature versus power loss per electron. The slope of line corresponds ~ 36 meV.

2.2. Mobility mapping technique

The technique is used to determine the temperature of the non-equilibrium electrons. This measurement consists of the electric field dependence of the mobility at a low lattice temperature (T = 68 K), and the lattice temperature dependence of the mobility at a fixed low electric field. Thus by plotting the electric field dependence of the mobility at a fixed lattice temperature (Fig. 3.a) and lattice temperature dependence of mobility at a fixed low field (Fig. 3.b) and by comparing the two plots, it is possible to obtain the electron temperature as a function of the electric field as shown Fig. 4 [7, 8]. At low electric fields (ohmic regime), the electron temperature is 68K, which corresponds to the lattice temperature as expected. It then increases with increasing field reaching a value of 140 K at a field of approximately 3.8 kV/cm for 2D system. The method is valid if the following assumptions take into consideration *i.* the carrier density does not change with field and e-e scattering rate thermalize the hot electrons amongst themselves, hence the non-equilibrium electron distribution can be represented by an electron temperature which is greater than the lattice temperature. *ii.* the field dependence of momentum relaxation is considered identical to its dependence on lattice temperature. If these conditions are satisfied electron temperatures and hence energy relaxation rates obtained from the mobility comparison method.

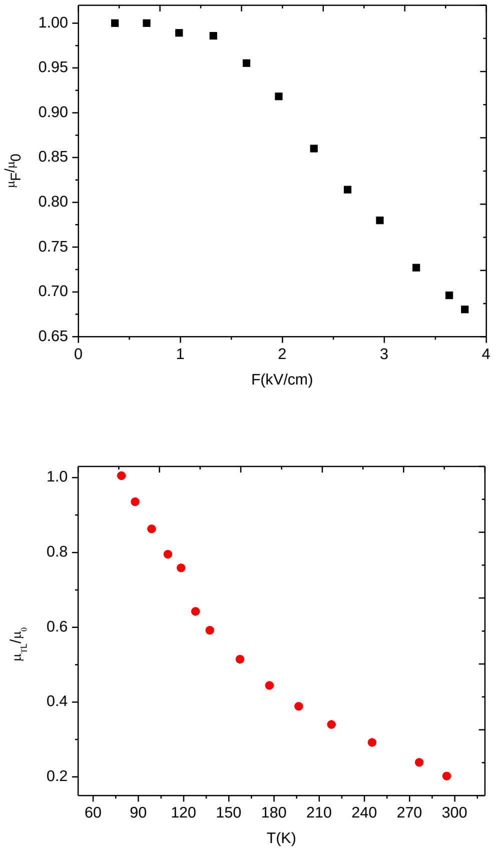

Fig. 3(a). Field-dependent electron mobility at lattice temperature, T_L = 68 K normalized with respect to the ohmic mobility, Fig. 3(b) the temperature - dependent mobility normalized with respect to the ohmic mobility.

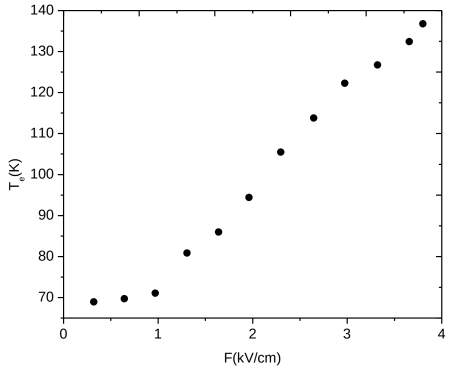

Fig. 4. Electron temperature versus applied electric field at lattice temperature of T_L = 68 K obtained by comparing the normalized mobility curves in Fig. 3.

2.3. High speed current- voltage measurement

High speed I-V measurement was performed using a 100 μm length simple bar. High voltage pulses of 40 ns with duty cycle better than 10^{-5} were applied along the simple bar. The drift velocity (V_d) versus electric field

(Fig. 5) is obtained, directly from the pulsed I-V characteristic assuming that the free carrier density is not a function of applied field [10]. V_d increases linearly with F for low values of the field (ohmic region) and then deviates from linearity reaching a saturation value as expected from increased momentum scattering of hot electrons with *LO* phonons. At 68 K, the drift velocity reaches the maximum values of 2×10^7 cm/s (at F ~ 3.6 kV/cm). However, at room temperature, the drift velocity tends to be saturated at the values of 4.12×10^7 cm/s (at F ~ 3.6 kV/cm). The saturation values are lower than those from Monte Carlo simulations. The reason for the reduced drift velocity might be associated with the production of non-equilibrium (hot) phonons which increase the momentum relaxation rate [7]. If these phonons are non-drifting in the *k*-space as proposed by Ridley [10, 11], their reabsorption by electrons influences the momentum relaxation decreasing the drift velocity and the energy relaxation rate of hot electrons.

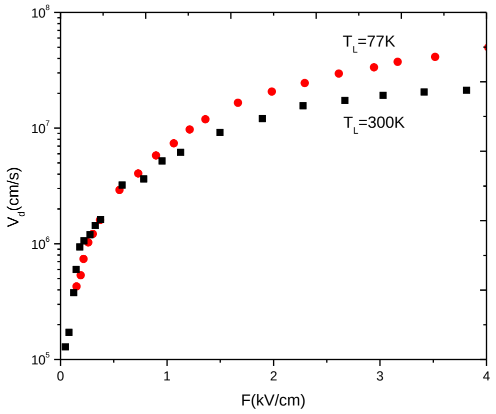

Fig. 5. Logarithm of electron drift velocity versus applied electric field at 68 K and 300 K.

3. Conclusions

The energy and momentum relaxation in GaAs/$Ga_{1-x}Al_xAs$ multi quantum-well structures using different experimental techniques was studied. Using the hot electron photoluminescence and mobility comparison methods, the electron temperature as a function of applied electric field have been evaluated. When the carriers are heated by an external electric field, electrons become hot, gaining energy from the field. In the steady state they release their energy through *LO* phonon emission. The electron-*LO* phonon scattering time was found as $\tau_0 = 128$ fs. However, the effective e-*LO* phonon scattering time (energy relaxation time constant) of $\tau_{eff} = 2.7$ ps. The discrepancy can be explained in terms of presence of non-equilibrium hot phonon effect which is tought to be responsible for the reduction in energy relaxation rate. The reason of the reduced drift velocity obtained from high speed pulsed I-V measurement is the presence of non-drifting hot phonons that induces an increase in the momentum relaxation rate. Overall, the experimetal results presented in the frame work of the this study has a good agreement with the theory which has been developed by Ridley and Gupta *et al.* [11].

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