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Electron-phonon interactions and electron mobility of HEMT at low electron temperatures

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The variations of the electron mobility (μ) with electron temperature (T_e), electric field (E) and drift velocity (υ_d) for the 2DEG (2 Dimensional Electron Gas) channel of AlGaAs/GaAs HEMT (High Electron Mobility Transistor) have been investigated theoretically at low and moderate electric field regions. The results have been determined by using momentum and energy balance equations in the 2DEG at T_o=1.7 K lattice temperature under zero magnetic field. The results enable us to predict the electron temperature and mobility at various electrical field regions, which are very important for understanding of the transport mechanisms, performance of HEMT and other devices. The theoretical results which are obtained by including the acoustic phonon and the polar optic phonon scattering mechanisms are compared with the available experimental results. A good agreement is observed at the low field region. However, the experimental and the theoretical results seem to deviate at the high electric field region, which indicates that additional scattering mechanisms should be taken into account.

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1. Introduction

Over the last three decades, there has been a great deal of interest in the study of the transport properties of III-V heterostructures. The main attraction of heterostructure is the very high mobility of the 2DEG at low temperature [1]. The 2DEG in modulation doped AlGaAs/GaAs heterostructure exhibits a very high mobility because of spatial separation of electrons from their parent donors in AlGaAs. The advantages of using such a high mobility system are well known and applied to high-speed field effect transistor such as HEMT. Mobility enhancement in the modulation doped heterostructure was first achieved in 1978 [2]. Since then, there have been many studies on the transport and scattering theories of the 2DEG in heterostructure [3-13]. The theoretically calculated mobility, differ from each other, depending on the theoretical models adopted in their calculations. In order to test the various theoretical predictions about the behaviour of mobility due to different type of scattering mechanisms, which type of scattering is predominant in a given sample of material, temperature and electric field range should be known. The earlier works dealt with various scattering processes at certain temperature and electric field range and they seldom made direct comparison between theory and experiment. However, their analysis explained only the electron temperature dependence at very low temperatures.

In this study, we present theoretical results for the mobility of 2DEG electrons as a function of electron temperature, electric field and drift velocity. Momentum and energy balance equations are used to obtain the theoretical mobility results. The main contributions to momentum and energy loss of electrons are assumed to originate from acoustical and optical phonon scattering processes. Also, the expressions for the mobility and electron temperature of 2DEG are assumed to be of the same form as those of bulk GaAs. The experimental results of Ari et al[14] has been used, which were two different AlGaAs/GaAs HEMT samples, covering the 2DEG sheet carrier densities n_{s1}=2.65x10^{11} cm^{-2} and n_{s2}=5.00x10^{11} cm^{-2}.

The theoretical calculation carried out by using the model given by Conwell et al [11], Segeer [12] , Lee et al [13] and Ari et al. [15] which include the acoustic phonon scattering through deformation potential and piezoelectric coupling and the polar optical phonon scattering. We have obtained a good agreement between theoretical results and experimental results especially at low electric field region. However, a disagreement is observed between theoretical and experimental results at high electric field region, which indicate that the accuracy of the assumptions concerning the electron-phonon interaction processes made in the theory should be questioned.

2. Theoretical background

In the materials of interest, mobility is high, indicating that the interaction of electrons and phonons may be treated by perturbation theory. It is possible that the fraction of excess energy leading to the heating of electron

of 2DEG can be known by using the power supply to the electronic system. The energy gained by an electron can be deduced from input power. It can be assumed that the total excess energy is converted into electronic thermal energy in obtaining electrical power input. The power supply to the channel of HEMT can be used to obtain the electron temperature, drift velocity and mobility as a function of electric field. In steady state, the joule input power per electron is to be equated to the power loss rate of electron. Thus, power loss of electrons can be taken equal to the power loss rate of phonons.

A method of calculating the electric field and electron temperature dependence of mobility of warm electrons with simplifying of a Maxwell-Boltzmann distribution with an electron temperature T_e consist of averaging momentum relaxation time over this distribution and calculating the mobility as a function of electron temperature, also calculating the relationship between the electric field E and electron temperature T_e, from momentum and energy balance equations. The mobility and power loss terms can be given as,

$$\frac{1}{\mu}=\sum_j \frac{1}{\mu_j} \tag{1}$$

and

$$\sum_i \left\langle \frac{d\varepsilon}{dt} \right\rangle_i = e E^2 (\sum_j \mu_j) \tag{2}$$

The expressions for the various power loss rate terms $\langle d\varepsilon/dt \rangle_i$, and mobility terms μ_j as a function of electron temperature T_e, can be defined by considering different type of scattering processes.

In order to obtain the electric field and electron temperature dependence of mobility, the energy and momentum balance equations are used. The main contributions to energy loss of electrons are assumed to be from acoustic phonon scattering due to deformation potential and piezoelectric coupling and inelastic polar optic phonon scattering mechanisms. We also assume that the distribution function of the central valley electrons to be a drifted Maxwell-Boltzmann distribution. We further assume the expressions for mobility and electron temperature are the same form as those bulk GaAs. In addition, the electron densities are assumed to be constant in the whole electric field range.

We expect that the energy flow from the electronic system will be mainly through the acoustic phonon emission via deformation potential and piezoelectric coupling which dominant mechanisms of energy loss in AlGaAs/GaAs 2DEG channel for T_e<40 K temperature range. The scattering of conduction electron by acoustic phonons requires the theorem of the deformation potential. The variation of conduction band edge with lattice constant can be taken linear for a small change in the lattice spacing as it occurs in an acoustic phonon. The change in energy of electron is proportional to the periodic dilation in an acoustic phonon. The factor of proportionality is the deformation potential constant of the conduction band.

The power loss and mobility equations can be obtained by using the theoretical model of some researchers [11-13, 15]. In steady state, when all the acoustic modes are fully excited, the average energy loss per unit time of an electron to the crystal lattice due to acoustic phonon emission via deformation potential at temperature T_e, is given by,

$$\left\langle \frac{d\varepsilon}{dt} \right\rangle_{dp} = \frac{2mD^2}{\pi^{3/2}\eta\rho}\left(\frac{2mk_BT_e}{\eta^2}\right)^{3/2} \left(\frac{T_e-T_o}{T_o}\right)\frac{F_{1/2}(\eta)}{F_1(\eta)} \tag{3}$$

where η is the reduced fermi energy, $F_j(\eta)$ are fermi integrals, D is the deformation potential constant, k_B is the Boltzmann constant, ρ is the density of GaAs and m is the effective mass of electron.

The mobility due to acoustical deformation potential for both degeneracy and non-degeneracy cases is;

$$\mu_{dp} = \frac{8}{3\pi}\frac{e}{m}\frac{\pi^{3/2}\eta^2\rho u_l^2}{2m^2D^2k_BT_o}\left(\frac{m}{2k_BT_e}\right)^{1/2}\frac{F_1(\eta)}{F_{1/2}(\eta)} \tag{4}$$

where u_l velocity of sound and e is the electric charge of electron.

Also, if a crystal consists of dissimilar atoms such as GaAs, the bonds are partly ionic and the unit cell does not contain a center of symmetry, electron may be scatter by the acoustic phonons due to piezoelectric coupling. The electron mobility due to this effect can be written as;

$$\mu_{pz} = \frac{16\pi^{1/2}\eta^2\varepsilon\varepsilon_o}{3m^{3/2}eK^2(k_BT_o)^{1/2}}\mu_{dp} \tag{5}$$

where, K^2=0.052 is the electro-mechanical coupling coefficient of GaAs, ε =1.16×10^{-10} F/m is the material dielectric constant of GaAs and ε_o is the free space dielectric constant.

In polar semiconductors, the interaction of electrons with the optic phonons is known as polar optical phonon scattering which is dominant scattering process at T_e>40 K for GaAs. To obtain the average rate of energy loss for all electrons, it is necessary to specify the distribution function. A distribution that has been found convenient to use in this connection is the drifted Maxwell-Boltzmann distribution. The validity of this distribution, which depends on the dominance of the electron-electron scattering over other scattering mechanisms in thermalising the electron distribution, is expected to hold

even a high field due to the high concentration of the 2DEG electrons. Then, the average rate of change of electron energy due to polar optic phonon interactions is found:

$$\left\langle \frac{d\varepsilon}{dt} \right\rangle_{po} = \left(\frac{\eta\omega_o}{\pi m} \right)^{1/2} 2eE_o \frac{e^{X_o - X_e} - 1}{e^{X_o} - 1} \left(\frac{X_e}{2} \right)^{1/2} e^{X_e/2} K_o\left(\frac{X_e}{2} \right) \quad (6)$$

and the mobility of electron,

$$\mu_{po} = \frac{3\pi^{1/2} (k_B T_e)^{3/2}}{4m^{1/2} E_o \eta\omega_o} \left(\frac{e^{X_o} - 1}{e^{X_e/2}} \right) \left[\left(e^{X_o - X_e} + 1 \right) K_1(X_e/2) + \left(e^{X_o - X_e} - 1 \right) K_o(X_e/2) \right]^{-1} \quad (7)$$

where, $X_e = \eta\omega_o / k_B T_e$, $X_o = \eta\omega_o / k_B T_o$, the effective field strength E_o =5.95 kV/cm, optical phonon frequency ω_o=8.8×10^{12} Hz for GaAs. K_o and K_1 are the modified Bessel function of the second kind.

3. Results and discussion

The mobility of 2DEG electrons (μ) as function of electron temperature (T_e) determined by using equations (1, 4, 5, 7), is shown in Fig. 1. The data in Fig. 1 enabled us to determine the variation of mobility with electric field by using energy balance equations. The variation of mobility as a function of electric field E has been obtained by using equation (2). The results are plotted in Fig. 2. For each electric field we have also simultaneously determined the drift velocity and assuming that the electron density is independent of electric field. The average electron energy increases above its thermal value and the drift velocity υ_d deviates from the value of the electric field for the lattice temperature T_o. The energy loss per electron is also given by $\langle d\varepsilon/dt \rangle = eE\upsilon_d$ which are used to determine the drift velocity and electron temperature as a function of electric field. Then, we were able to obtain the drift velocity dependent mobility by using the values of power loss and plotted in Fig. 3. The theoretical results of electron mobility as a function of electron temperature T_e, electric field E and drift velocityυ_d were shown by continuous line curves in Figs. 1-3. The experimental results [15] have also been given in the Figs. 1-3 as the circles and the triangles.

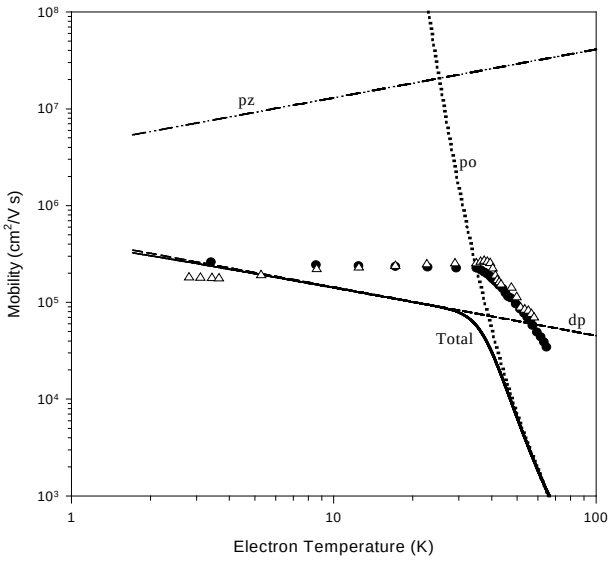

Fig. 1. The electron mobility (μ) versus electron temperature (T_e) at lattice temperature of T_o=1.7 K under zero magnetic field. The triangles (n_{s1}=2.65×10^{11} cm^{-2}) and the circles (n_{s2}=5.0×10^{11} cm^{-2}) represent the experimental results [14]. The dotted line shows theoretical results due to polar optic phonon mechanism (po). The dash line shows the theoretical results due to acoustic phonon emission via deformation potential coupling (dp) and the dash dot line represents the mobility via acoustic phonon emission due to the piezoelectric coupling (pz). The total mobility (Total) are shown by solid line.

We have compared the theoretical results with the experimental results of mobility versus electron temperature curves as shown in Fig. 1. The agreement between theoretical and experimental results is reasonable good at low electron temperature. However, the results start to deviate from each other at high electron temperature, although, the shape of curves have the same characteristic. At high electron temperature range, the contributions from acoustic phonon scattering via deformation potential and piezoelectric coupling are much smaller than polar optic phonon scattering. Figure 1 also shows that, the experimental results of electron mobility almost does not change with electron temperature at low temperature region, but the mobility decreases rapidly where the optic phonon scattering mechanism start to dominate at moderate and high electron temperature region. However, the theoretical results show different behaviour. The theoretically obtained mobility gradually decreases with T_e at low temperature region. At high temperature region, it decreases rapidly with electron temperature which is similar behaviour with experimental results.

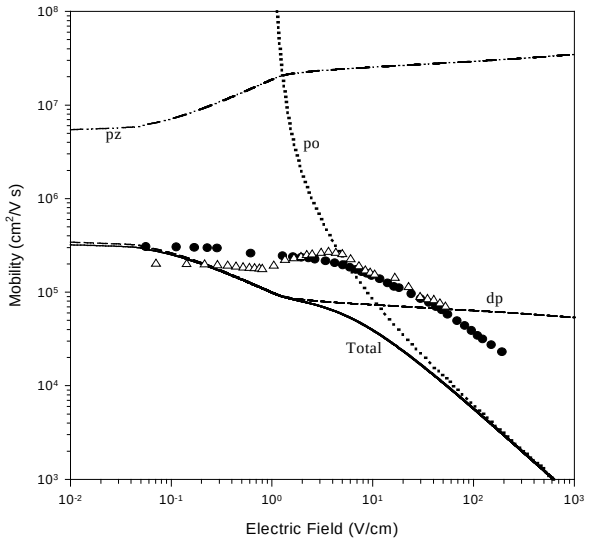

Fig. 2. The variation of mobility (μ) with electric field (E). The circles and the triangles show the experimental results [14]. The dotted line shows the theoretical calculation of polar optic phonon, the dash line shows the theoretical calculation of acoustic phonon emission due to deformation potential, and the dash dot line shows the theoretical results of acoustic phonon via piezoelectric coupling. The solid line shows the total mobility (Total).

Fig. 2 shows that the mobility varies slowly with electric field *E* at low field region but rather rapidly with *E* at moderate and high field region. This behaviour can be explained as follows: the agreement at low field region reasonable good between theoretical and experimental results. Considering the good agreement between theory and experiments it was concluded that acoustic phonon mode scattering is the dominant energy loss mechanism for the 2DEG electron. This agreement also shows the validity of the assumption that the 2DEG acquires energy from the applied power before it has relaxed by the acoustic phonon emission.

The agreement between theoretical and experimental results is not good at high electron temperature and high field region as at low field region which can be seen in both Figs. 1 and 2. The experimental results are higher than the theoretical results at high electron temperatures. The reason for this is that some different energy loss mechanisms may be involved in the scattering processes at this electric field region and these scattering mechanisms are no longer negligible. This shows that the other additional energy loss scattering mechanisms should be included in the theory. One possible mechanism is the intervalley scattering which is important at high field region. Another scattering mechanism is hot phonon effect which is also starts being effective process and it may be one of the reasons for the discrepancy between the theoretical results and the experimental results at high electric field region. These effects will lower the electron temperature and hence electric field for significant intervalley electron transfer for the same subband or between the neighbouring subbands. The other scattering mechanism could be the ionized impurity scattering which also affects the behaviour of electrons at this field region.

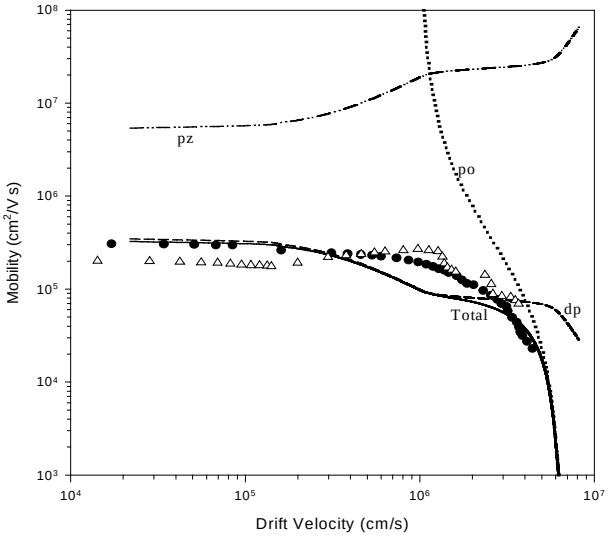

Fig. 3. Mobility (μ) versus drift velocity (υ_d). The triangles and the circles are for the experimental results [14]. The theoretical mobility results of optic phonon versus υ_d were shown by the dotted line. The dash line shows the theoretical mobility results of acoustic phonon via deformation potential versus υ_d. The mobility results of acoustic phonon due to piezoelectric coupling versus υ_d were shown by the dash dotted line. The solid line shows the total mobility versus drift velocity υ_d.

Fig. 3 shows that, a good agreement obtained between theoretical and experimental results. At T_e<40 K, the mobility is very slowly changing with drift velocity at acoustic phonon region. At T_e>40 K region in where optical phonon scattering process is the dominant scattering mechanism, the mobility is rapidly decreases with drift velocity υ_d. We also compared the obtained results with other worker's results [13, 16]. The results are consistent with each other for similar sample configurations.

4. Conclusions

We have investigated the variation of mobility of 2DEG in AlGaAs/GaAs HEMT channel with electron temperature, electric field and drift velocity by using momentum and energy balance equations. The electron temperature T_e is determined by a balance between power supplied to the electrons by the electric field and power lost by the electron to the lattice. We have determined the electron temperature as a function of electric field and correlated the changes in the electron temperature with changes in mobility determined simultaneously. The mobility begins to change slowly at moderate electric fields but than begins to decrease rapidly above T_e >40 K where polar optic phonon scattering process dominates. In

this region, the electrons are heated by an applied field leading to a rapid rise in electron temperature T_e and a reduction of electron mobility. At low electron temperature range, the theoretical results agree well with the experimental results. However, the results seem to deviate at higher electron temperature and hence high electric field. This deviation had been observed by using different theoretical model called electron temperature model [17]. The variation of mobility with electron temperature is qualitatively similar to the variation of zero field mobility with lattice temperature. However, there are substantial qualitative differences for T_e>40 K which needs to be further investigated. The other scattering mechanisms added to the model, would be useful in obtaining a better understanding of the transport mechanisms.

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