Longitudinal magnetoresistivity and Hall Mobility of Two-dimensional Electron Gas in GaN Quantum Wells

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Abstract

Longitudinal magnetoresistivity and Hall mobility of the two-dimensional electron gas in GaN quantum wells are calculated in the temperature range 1K-14K incorporating deformation potential acoustic, piezoelectric, background and remote ionized impurity scatterings. The Boltzmann transport equation is solved by a numerical iterative technique using Fermi-Dirac statistics. The variations of longitudinal magnetoresistivity with magnetic field and temperature agree with the available experimental results at temperature T=1.38 K. The Hall mobility is found to decrease sharply at low magnetic fields and the variation becomes less sensitive to higher field values.

Keywords

Quantum wells, Semiconductors, Electronic transport.

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I. Introduction

Recent investigations have revealed that GaN material has widespread applications in optoelectronic devices, such as blue light emitting diodes (LEDs), laser diodes and high frequency field effect transistors [1]. The existence of a 2D electron gas (2DEG) in AlGaN/GaN heterostructures was first observed [2] and was confirmed by optical and electrical studies [3]. Theoretical study of magneto-transport characteristics of 2DEG in GaN quantum wells will be relevant in understanding the carrier transport mechanism. The aim of the present paper is to study some aspects of magneto-transport properties, namely, longitudinal magnetoresistivity and Hall mobility in GaN quantum wells in non-quantizing magnetic fields.

We have considered Fermi-Dirac statistics and the relevant scattering mechanisms like deformation potential acoustic, piezoelectric, background and remote ionized impurity scatterings in the low temperature range 1K-14K. Based on numerical iterative technique we have solved the Boltzmann transport equation considering the above mentioned scattering mechanisms both individually and in combination with the help of Matthiessen's rule. The intersubband scattering has not been incorporated in our calculations because of its insignificant contribution in the low temperature range of interest here. Our calculations of Hall mobility and longitudinal magnetoresistivity at such low temperatures have agreed with the experimental results [4].

II. Theoretical model

In $Al_{0.13}Ga_{0.87}N$ / GaN structure, the cunduction band offset is about 2.26eV [5]. The maximum Fermi energy of the electrons considered here is found to be 0.013 eV. So ΔE_c is about 174 times E_f . Hence the GaN square well can be considered to be infinite. Moreover, we assume that the electrons occupy only the lowest sub-band, since the next upper sub-band is higher than $2E_f$ times in energy than the lowest sub-band.

We consider a rectangular cartesian co-ordinate system with the z-axis perpendicular to the interfacial planes, so that the 2D electron transport occurs parallel to the xy-plane. The electric field ε is assumed to be along the x-axis and the magnetic field B along the z-axis. The electron distribution function can be written as

$$f(k) = f_0(E) - [(e\hbar/m^*)\, \varepsilon\,](\partial f_0 / \partial E) \\ [\, k_x \Phi_x(E) - \omega_B k_y \Phi_y(E)\,] \qquad (1)$$

where k is the 2D wave-vector of electrons with energy E. fo(E) is the equilibrium Fermi-Dirac function, e is the electronic charge, ħ is Plank's constant divided by 2π , m* is the electron effective mass, k_x and k_y are the x- and y- components of k, $\omega_B = e_B/m^*$ is the cyclotron resonance frequency, Φ_x and Φ_y are the perturbation functions. The electron distribution has been expressed in terms of perturbation functions in our formalism, so iterative procedure is needed for the convergent solutions of the Boltzmann transport equation with different scattering mechanisms, to obtain relaxation times and hence the mobility.

The combined relaxation time for all the scatterings, namely deformation potential acoustic, piezoelectric and ionized impurity (background and remote) is evaluated by the numerical iterative solution of the Boltzmann transport equation. We have used Mathiessen's rule to calculate the resultant mobility, because here more than one scattering mechanism, namely, deformation potential acoustic phonon and ionized impurity scatterings dominate. The perturbation functions obtained from the Boltzmann transport equation are

$$\phi_x(E) = \tau(E) / [1 + \omega_B{}^2 \tau^2(E)] \qquad (2)$$

and

$$\phi_y(E) = \tau^2(E) / [1 + \omega_B{}^2 \tau^2(E)] \qquad (3)$$

where, $\tau(E)$ is the combined relaxation time for all the scatterings. The expressions for relaxation times of the acoustic scattering via deformation potential and piezoelectric couplings and that for the background and remote ionized impurity scatterings have been taken from Refs.[6,7]. The Hall mobility (μ_H) and the longitudinal magneto-resistivity (ρ_{xx}) are calculated with the help of the expressions given in Refs. [8,4].

III. Results and discussions

We have used the following data in our calculations: effective mass of electron $m^* = 0.218\, m_o$, where mo is the rest mass of the electron, 2D electron concentration is taken as $N_{2D} = 4.8 \times 10^{15}/m^2$. The background ionized impurity concentration is taken as $N_i = 8.6 \times 10^{22}/m^3$ to fit the experimental value of magnetoresistivity (ρ_{xx}) at temperature T=1.38K [4]. The well width (L_z) is taken as 67nm. The other parameter values for GaN are taken from Ref.[9]. Fig. 1 shows the variations of the longitudinal magnetoresistivity and Hall mobility as a function of magnetic field B. The Hall mobility variation is exhibited for temperature T=1.38K, while the longitudinal magnetoresistivity variation is shown for temperatures T=1.38K and T=0.7K respectively.

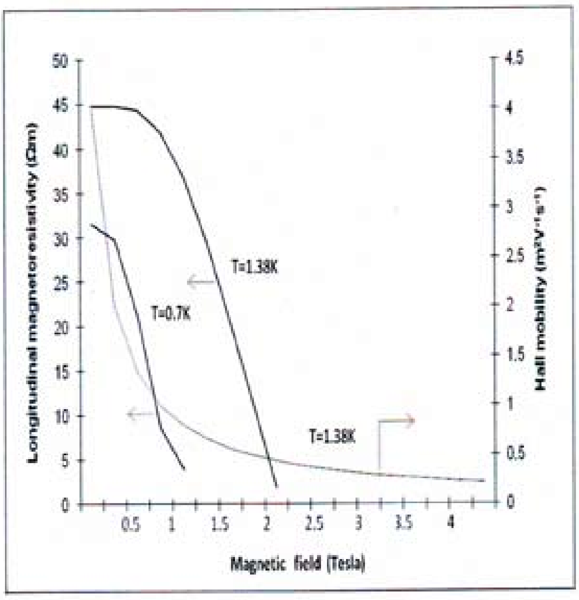

Fig.1: Variation of longitudinal magnetoresistivity (ρ_{xx}) and Hall mobility (μ_H) with magnetic field B for N_{2D} = 4.8 x 10^{15}/ m^2, N_i = 8.6 x 10^{22}/ m^3 and L_z = 67nm.

ρ_{xx} is high at low magnetic fields and the two-dimensional electron system behaves as an insulator. With increasing B, ρ_{xx} decreases sharply due to crossover from non-quantizing to quantizing fields, where Landau levels come into play.

At low magnetic fields ρ_{xx} decreases as magnetic field increases, which is in agreement with the experimental results given in Ref.[4]. The decrease of ρ_{xx} to almost zero value is theoretically attributed to the fact that the gaps between Landau levels increase as the magnetic field increases. So there occurs no scattering, as a result the resistivity reduces almost to zero. The Hall mobility (μ_H) has an inverse dependence on the magnetic field B, as given in Ref.[8]. So μ_H decreases with B.

Fig. 2 exhibits the variation of the longitudinal magnetoresistivity and Hall mobility with temperature. ρ_{xx} decreases with temperature for non-quantizing magnetic field B=1T. In the Fig. 2, the Hall mobility increases with temperature due to Coulombic nature of ionized impurity scattering; while the magnetoresistivity having an inverse temperature dependence, decreases with temperature. The decrease of ρ_{xx} with T is in agreement with the experimental results of magnetotransport measurements on two-dimensional electron system in GaN [Ref. 9].This also furnishes the comparison of our theoretical results with the experimental ones. The overall Hall mobility due to combined effects of all scatterings is exhibited by curve 2 of the Fig. 2.. The individual contribution of acoustic scattering to the mobility is found to be almost same as that of the overall mobility value, while curve 1 in Fig. 2 shows the Hall mobility for individual contribution of ionized impurity scattering.

Referring to the curve 3 in Fig. 2, the contribution of deformation potential acoustic scattering in case of ρ_{xx} coincides with that due to the total scattering mechanisms, while the ionized impurity scattering has been found to contribute negligibly.

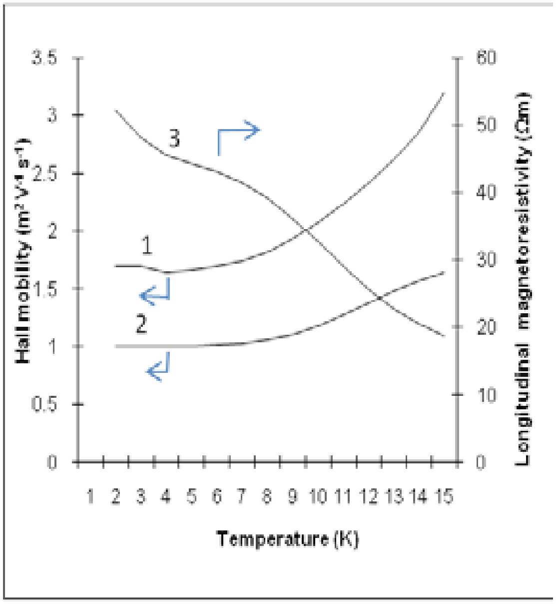

Fig. 2: Longitudinal magnetoresistivity (ρ_{xx}) and Hall mobility (μ_H) variation with temperature T at magnetic field B = 1T. Curve 1 shows the Hall mobility for individual ionized impurity scattering and curve 2 shows the overall Hall mobility due to combined effects of all scatterings. Curve 3 displays the longitudinal magnetoresistivity variation due to combined effect of all scattering mechanisms. The other parameter values are the same as in Fig 1.

IV. Conclusion

We have shown the variations of longitudinal magnetoresistivity with magnetic field and temperature. Fig. 1 shows that longitudinal magnetoresistivity ρ_{xx} decreases with magnetic field, which is supported by the theoretical reasoning that the gaps between Landau levels widen at higher fields and minimum scattering occurs. The magnetoresistivity also decreases with temperature.

We have shown the variations of the overall Hall mobility due to acoustic, piezoelectric and ionized (both background and remote) impurity scatterings and individual ionized impurity scattering in GaN quantum wells with magnetic field and temperature. We find that the Hall mobility decreases sharply at low magnetic fields and then becomes less sensitive to the field variations. The Hall mobility increases with temperature due to the Coulombic nature of ionized impurity scattering.

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