Low Temperature Magnetotransport in 2D GaN Quantum Wells

Arindam Biswas, Aniruddha Ghosal, Hasanujjaman, Sahnawaj Khan

Abstract— 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. Hall mobility at such low temperatures has agreed with the results obtained by other researcher.

Index Terms— Hall Mobility, Magnetoresistance, Scattering Theory .Bolzman transport equation, 2D quantum wells.

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I INTRODUCTION

Recent work on III-V nitride family, InN, GaN, and AlN, have led to significant progress in improving material quality. Alloys and heterostructures based on these materials are already exits in literature through some theoretical and experimental investigation [1–7].However, there has been a revival of interest in magnetic-field-induced transitions in the integer quantum Hall effect [8-11]. According to the scaling theory of localization, at zero magnetic field, all states of a noninteracting two-dimensional electron system (2DES) are localized. On the other hand, in the presence of a perpendicular magnetic field, the theoretical understanding of the integer quantum Hall effect (IQHE) requires the existence of extended states in a 2DES. In order to explain the evolution from extended states at finite magnetic field to localized states at zero magnetic field, Laughlin [12] and Khmelnitskii [13] showed the picture of extended states at Landau-levels centers and at localized states between Landau levels. It is argued that to be consistent with the scaling theory, as the magnetic field is decreased, the energy of the extended states will float up and exit through the Fermi level of the 2DES. Furthermore, a 2DES is in an insulating phase when all the states below the Fermi level become localized at zeromagnetic field.

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 [14]. 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 Hall mobility in GaN quantum wells in nonquantizing 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 at such low temperatures have agreed with the experimental results [15].

II. Theoretical model

In $Al_{0.13}Ga_{0.87}N$ / GaN structure, the conduction band offset is about 2.26eV [16]. 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.

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In our model we consider a rectangular Cartesian co-ordinate system with z-axis perpendicular to the interfacial planes so that the 2D transport occurs parallel to the *xy* plane. The electric field ε is assumed to be along x- axis and non-quantizing magnetic field B along z- axis. The carrier distribution function can be written as

$$f(\mathbf{k}) = f_0(E) - \left(\frac{e\hbar}{m^*}\varepsilon\right) \frac{\partial f_0}{\partial E}\left[k_x\xi_x(E) - \omega_B k_y \xi_y(E)\right] \qquad (1)$$

Where *k* is the 2D wave vector of electrons with energy, f_0 (E) is the equilibrium Fermi-Dirac function, e is the electronic charge, ħ is Planck's constant divided by 2π, m^* is the electron effective mass.k_x and k_y are the x and y component of k, $\omega_B = \frac{eB}{m^*}$ is the cyclotron resonance frequency, and ξ_x and ξ_y are the perturbation functions. The perturbation functions obtained from the Boltzmann Transport equations are,

$$\xi_x(E) = \tau(E) / 1 + \omega_B^2 \tau^2 \qquad (2)$$

$$\xi_x(E) = \tau^2(E) / 1 + \omega_B^2 \tau^2 \qquad (3)$$

where, τ (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.[16,17]. The Hall mobility and the longitudinal magneto-resistivity is calculated with the help of the expressions given in Refs. [18].

$$\mu_H = \frac{\mu_{xx}(0)\,|\,\mu_{xy}\,|}{B(\mu_{xx}^2 + \mu_{xy}^2)} \qquad (4)$$

and $$R_m = \mu_H B \mu_{xx} / \,|\mu_{xy}| - 1 \qquad (5)$$

Where,

$$\mu_{xx} = \frac{e}{\pi N_{2D}\hbar^2} \int_0^{\alpha} \left(-\frac{\partial f_0}{\partial E}\right) \times \frac{\tau(E)}{1+\omega_B^2\tau^2(E)} E\,dE \ ,$$

$$\mu_{xy} = \frac{e\omega_B}{\pi N_{2D}\hbar^2} \times \int_0^{\alpha} \left(-\frac{\partial f_0}{\partial E}\right) \frac{\tau^2(E)}{1+\omega_B^2\tau^2(E)} E\,dE$$

and the drift mobility $\mu_{xx}(0)$ is the value of μ_{xx} for *B*=0.

III RESULTS AND DISCUSSIONS

We have used the following data in our calculations: effective mass of electron m*= 0.218 m_o, where m_o is the rest mass of the electron, 2D electron concentration is taken as N_{2D} = 4.8 x 10^{15}/ m^2. The background ionized impurity concentration is taken as N_i = 8.6 x 1022/m^3 to fit the experiment [15]. The well width (Lz) is taken as 67nm. The other parameter values for GaN are taken from Ref.[19]. Fig. 1 shows the variations of Hall mobility as a function of magnetic field B. The Hall mobility variation is exhibited for temperature T=1.38K.

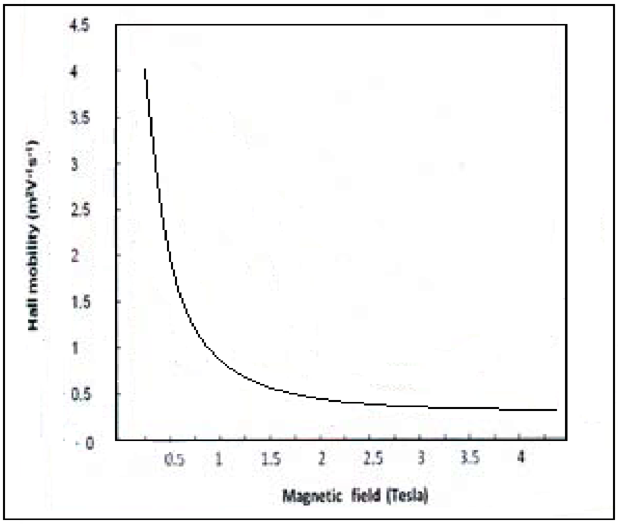


Fig.1: Variation Hall mobility (μ_H) with magnetic field B for N_{2D} = 4.8 x 10^{15}/ m^2, Ni = 8.6 x 1022/ m3 and Lz = 67nm

The Hall mobility has an inverse dependence on the magnetic field B, as given in Ref.[20]. So It decreases with B. Fig. 2 exhibits the variation of the Hall mobility with temperature.Fig. 2, the Hall mobility increases with temperature due to Coulombic nature of ionized impurity scattering.

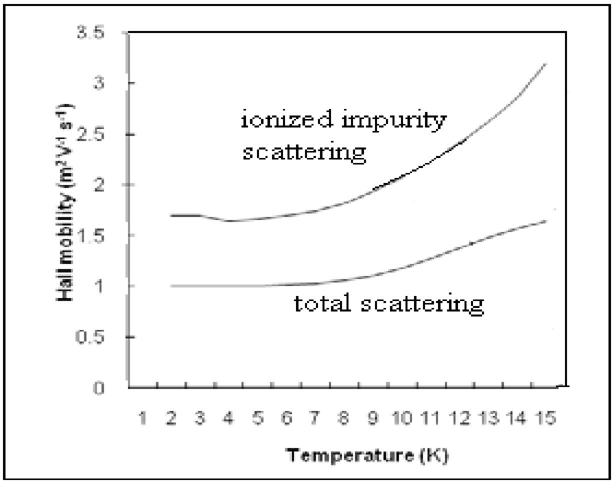
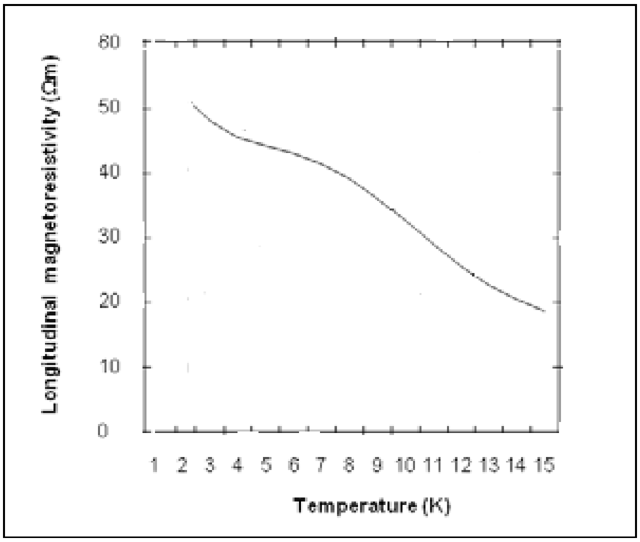


Fig 2a. and Hall mobility(μ H) variation with temperature T. The other parameter values are the same as in Fig 1.



2b. Longitudinal magnetoresistivity (ρ xx) temperature T at magnetic field B = 1T.The other parameter values arehe same as in Fig 1.

The decrease of ρ_{xx} with T is in agreement with the experimental results of magneto transport measurements on two-dimensional electron system in GaN [19].This also furnish the comparison of our theoretical results with the experimental ones. The overall Hall mobility due to combined effects of all scatterings , The individual contribution of acoustic scattering to the mobility is found to be almost same as that of the overall mobility value. It shows the Hall mobility for individual contribution of ionized impurity scattering. Referring to Fig. 2b, 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.

IV. CONCLUSION

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 Columbic nature of ionized impurity scattering. The decrease of ρ_{xx} with T is in agreement with the experimental results of magnetotransport measurements on two-dimensional electron system in GaN.

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