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The electron Hall mobility of n-GaN investigated using balance equation theory

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Abstract. The electron Hall mobility of n-GaN at 300 K has been investigated by using the balance equation theory. The calculated Hall mobility is in closer agreement with the experimental data than the data from the Boltzmann transport equation.

Although the first theoretical calculation of the electron transport properties of GaN was made 20 years ago [1, 2], GaN has again become the subject of extensive experimental and theoretical investigation because of its usage in optoelectronic devices operating in the blue-to-ultraviolet wavelength range, as well as in electronic devices operating at high temperatures and high power levels [3–6]. As summarized by Gaskill *et al* [7], however, the experimental electron Hall mobility for GaN falls generally by a factor of 2 or more below theoretically calculated values.

The recently published theoretical results of Rode and Gaskill [8] on cubic n-GaN are remarkable because they showed a good agreement between their results and the experimental results of Kim *et al* [9]. The agreement is demonstrated to be within 2.5% for low-doped samples. However, there is a significant disagreement for the heavily doped samples, with a disagreement of about 60% for the sample with the free-electron concentration $n = 1.51 \times 10^{20}$ cm^{-3}. In their calculation [8], the solution to the Boltzmann transport equation (BTE) in the presence of a magnetic field was cast into the form of a contrast mapping and solved iteratively. The BTE method is a semiclassical approach, and mainly adopted for studying systems with low doping concentrations, where electron–electron correlation is neglected. When the free-electron concentration of a system is as high as 10^{18} cm^{-3}, however, the electron–electron correlation may have a significant influence on the electron transport. On the other hand, the balance equation theory (BET) [10–12] considers systems where electron–electron interaction is large enough to induce rapid thermalization of the carriers around the drift transport state. The advantage of BET is that it can offer an accurate quasi-analytic picture of carrier transport, especially in cases including hot carriers and heavily doped systems. In this article we employ the BET in calculating the Hall mobility of n-GaN at 300 K, with energy band nonparabolicity taken into account.

Considering a sample under the influence of a crossed magnetic field and electric field, a Hall field is built up along the direction normal to the direction of the electric field

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Table 1. The Hall mobility of GaN at 300 K.

Free-electron concentration (10^{18} cm^{-3})	Experiment [9] (cm^2 V^{-1} s^{-1})	BTE [8] (cm^2 V^{-1} s^{-1})	BET (cm^2 V^{-1} s^{-1})
13.4	190	270	173.7
28.8	140	238	130.8
151.0	77.0	186.0	109.8

and normal to the direction of the magnetic field due to the charge accumulation. The steady-state force balance equations take the following forms [12] ($\hbar = K_B = 1$):

$$\frac{eE_x}{m^*_{xx}} + A_x = 0 \tag{1}$$

$$\frac{eE_y}{m^*_{yy}} - \frac{eBv_d}{m^*_{yy}}\gamma_{x,yy} = 0 \tag{2}$$

where e is the electron charge, E_x and E_y are the drift electron field and the Hall field respectively, and v_d is the drift velocity. Also $1/m^*_{xx}$ and $1/m^*_{yy}$ are components of the ensemble-averaged effective-mass inverse tensor along the x-direction and the y-direction, respectively. A_x is the frictional force due to the phonon scatterings (including deformation potential and piezoelectric acoustic phonon scatterings, and polar optical phonon scattering) which takes the same form as equation (60) in [11]. Also

$$\gamma_{x,yy} = \frac{\langle(\partial\varepsilon/\partial k_x)(\partial^2\varepsilon/\partial k^2_{yy})\rangle}{\langle\partial\varepsilon/\partial k_x\rangle\langle\partial^2\varepsilon/\partial k^2_{yy}\rangle} \tag{3}$$

is a dimensionless parameter used to describe the centre-of-mass motion in a crossed magnetic and electric field configuration. $\langle\ \rangle$ stands for the ensemble average:

$$\langle\cdots\rangle = \frac{2}{N}\sum_{\boldsymbol{k}}\cdots f(\varepsilon(\boldsymbol{k} - p_d), T_e) \tag{4}$$

with $f(\varepsilon(\boldsymbol{k} - p_d), T_e)$ the Fermi function and p_d the momentum of the centre of mass along the x-direction, and T_e the electron temperature. ε is the conduction energy of the electrons, which is determined by Kane's relation [13]

$$\varepsilon(1 + \varepsilon/E_g) = \frac{k^2}{2m^*} \tag{5}$$

with E_g the energy gap, m^* the effective mass of the conduction electrons and $\boldsymbol{k} = (k_x, k_y, 0)$ the wave-vector of the electrons.

Taking the same parameters as [8] and [9], we calculate the Hall mobility of GaN at 300 K by employing the frictional equations (1) and (2). The Hall field is determined to be $E_y = Bv_d\gamma_{x,yy}$ and the Hall mobility is then given as

$$\mu_H = \frac{1}{B}\frac{E_y}{E_x} = -\frac{ev_d}{m^*_{xx}A_x}\gamma_{x,yy}. \tag{6}$$

The calculated Hall mobility of GaN at 300 K is shown in table 1, along with the data from experiment [9] and from the BTE [8]. One can see that the BET data for the two low-doped samples are in excellent agreement with the experimental data. Even for the sample with $n = 151.0 \times 10^{18}$ cm^{-3}, the Hall mobility from the BET is much closer to the experimental value than to the BTE value.

In the theoretical study, the single-band model is employed. However, as the electron concentration is high enough, the electrons will occupy the satellite valleys. To fit the experimental data, one should take into account the effect of the satellite valleys.

In summary, by using the balance equation theory we find a Hall mobility in agreement with the experimental data for n-GaN at room temperature.

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