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Study on the effect of high magnetic field on electron transport in lattice mismatched n-GaN grown on sapphire based on two-layer model

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ABSTRACT

GaN for its wide band gap has gained popularity for its use in semiconductor devices. To this date there have been no successful techniques devised for production of bulk GaN of technologically suitable size. The mostly closed lattice matched substrate of reasonable cost is sapphire. SiC is more closely matched but it is very costly. Due to lattice mismatch, large number of dislocations develop near the interface which reduces sharply in the bulk layer. So the bulk n-GaN may be considered to be consisting of two layers, one being the thin interfacial layer where dislocations are very high. The layer above the interfacial layer just above the substrate is another layer, the bulk layer where the dislocation is less and negligible. With two layers in consideration, we have calculated the various transport parameters such as mobility, Seebeck coefficient and conductivity under the extreme quantum limit. In our model, the dislocation scattering and the ionized impurity scattering mechanisms are considered in the interfacial layer and in the bulk layer other scattering mechanisms like the acoustic phonons via deformation potential and the piezoelectric potential, the ionized impurity scattering and the polar optical phonon scattering are considered. We have studied the transport parameters at high and low temperatures. For studies in the low temperatures, the polar optical phonon scattering is not considered. The study shows that combined conductivity decreases with increase in magnetic field at high temperatures whereas it increases at low temperatures. At all the situations the dislocation scattering affects the combined conductivity and the thermoelectric power of GaN and lowers the value of transport parameters.

1. Introduction

GaN has been attracting a considerable research interest for its potential for wide applications in various solid state devices. The semiconductor has direct band gap of 3.5 eV [1] and its bond strength is quite high. Therefore, it can be used for electronic and optoelectronic devices like laser diodes [2], light emitting diodes [3], photo detectors [4] and metal semiconductor field effect transistor (MESFETs) [5]. Since GaN has large peak velocities, they are suitable for high electron mobility transistors (HEMT) [6], heterojunction bipolar transistors (HBTs) [7] and high frequency applications [8].

The GaN materials are grown by epitaxy methods like the molecular beam epitaxy (MBE) or the metal-organic chemical vapor deposition (MOCVD) or the hybrid vapor phase epitaxy (HPVE) on the sapphire or SiC substrates.

Since SiC is very costly, sapphire is mainly used as a substrate. But there is 14% lattice mismatch between the sapphire and the GaN ($a_{\text{sapphire}} = 4.76\,\text{Å}$ and $a_{\text{GaN}} = 3.18\,\text{Å}$) [9] and the mismatch in the thermal expansion coefficient is about 34% [10]. The large lattice mismatch leads to high dislocation densities [11,12] of the order of $10^7-10^{11}\,\text{cm}^{-2}$. Transmission electron microscopy (TEM) investigations have shown high screw dislocation densities near the substrate as well as high edge dislocation densities, with the edge dislocation lines threading from the substrate to the epilayer surface [13].

The effect of dislocations on electron transport in GaN has been extensively studied [14,15]. Weimann and Eastman [14] and Ng et al. [15] have shown that mobility of electrons reduces due to the scattering of electrons by the charged threading dislocations which act as a Coulomb scattering center.

The interfacial layer is found to be highly degenerate and conducting [16]. The presence of such a conducting interfacial layer in the sample of n-GaN grown by HVPE has also been reported by Weimann and Eastman [14]. If the dislocation density exceeds $7 \times 10^{14}\,\text{m}^{-2}$ as in the interfacial layer [10], the dislocation scattering dominates over the other scattering mechanisms.

Look and Sizelove [10] and Look and Molnar [17] have developed a two-layer model for the electron transport in n-GaN considering the presence of a large dislocation density near the interface. In their model [17], data were fitted by solving the Boltzmann equation in the relaxation time approximation. According to Look and Molnar [17], the dislocations reduce very fast along the direction of growth of the film, Look, therefore,

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proposed that the bulk film may be considered to be consisted of two layers, the thin narrow layer just above the substrate called interfacial layer, where dislocation density is very high and above the interfacial layer is the bulk layer where dislocation density is much less. So the effect of dislocation is neglected in the bulk layer. The combined current passing through the layers is the sum of currents through these, and is similar to parallel resistors. This model is called two-layer model. Using this two-layer model, the authors studied electron transport in n-GaN [17]. This model has been useful in predicting the electrical conductivity in the lattice mismatched n-GaN which fairly matches with experimental data [17]. But this model [17] was not used to predict thermal transport properties of the lattice mismatched n-GaN.

Srethsta et al. [18] calculated transport coefficients such as ac/dc mobilities, Seebeck coefficient, thermal conductivity and thermoelectric figure of merit of n-GaN using two-layer model. In the model, various low and high temperature scattering mechanisms in the bulk layer and only the dislocation scattering mechanism in the interfacial layer were considered to calculate the above transport parameters. Our results of conductivity and Seebeck coefficient are also found to agree reasonably well with the experimental data when we consider the interfacial layer having equal thickness as equal to that of bulk layer, i.e., the thickness ratio of the bulk layer to the interfacial layer is 1:1.

The transport properties undergo dramatic changes under the influence of a high magnetic field. This is mainly due to the profound changes in the density of states of the conduction electrons in presence of a magnetic field due to Landau quantization. Such high magnetic field effects are also important to probe the system by making a detailed study of transport coefficients in the high magnetic field since these systems' behavior is quite different compared to the behavior without magnetic field due to change in position of E_F, the Fermi energy.

Not many references on the effect of magnetic field on dislocation scattering are found in the literature to our knowledge. However, the effects of high magnetic field on the dislocation scattering have been studied by a few authors [19,20].

Vinokur [19] calculated the dislocation contribution to the transport collision time under the influence of a high magnetic field which enters into the Dingle factor assuming the quasi-classical condition that $\hbar\Omega/E_F \ll 1$ where Ω is the cyclotron frequency and E_F is the Fermi energy. He used the quasi-classical asymptotic form of Laguere polynomial in the wave function changing it to Bessel function.

Mann [20] calculated relaxation time for dislocation scattering in high magnetic field for metals. For metals, the number of states occupied are considered to be very high and that transforms the Laguere polynomial in the wave function to Bessel function. He also considered a different form of potential for the edge dislocation scattering. In the above case, the effect of screening was ignored in the dislocation potential considered.

We have formulated the relaxation time for the edge dislocation scattering in a high magnetic field considering the dislocation potential including the screening as given by Bonch-Bruevich and Glasko [21].

In our work, we have calculated the conductivity and Seebeck coefficient of n-GaN under extreme quantum limit at low and high temperatures, considering two-layer model of Look [17]. We assumed that all the electrons of the semiconductor, n-GaN are in the lowest Landau level as the magnetic field is assumed to be quite high, i.e. the electrons are in the extreme quantum limit including the screening effect in nondegenerate case. It is well established of the effect of large magnetic field that makes the system less degenerate.

We have derived a simple expression for the relaxation time for the dislocation scattering under the extreme quantum limit.

We have calculated the mobility and the Seebeck coefficient of the interfacial layer of n-GaN considering the dislocation scattering and the ionized impurity scattering. For the bulk layer, the ionized impurity scattering and the acoustic phonon scattering via acoustic potential and the piezoelectric scattering and the polar optical phonon scattering mechanisms are considered. In case of low temperatures, the polar optical phonon scattering mechanism is not taken into consideration.

No study of transport parameters of n-GaN in high magnetic field using two-layer model has been made so far. So we used the formulation of two-layer model for calculation of conductivity and Seebeck coefficient of the combined bulk n-GaN under extreme quantum limit extending the model developed for n-GaN in the absence of high magnetic field [18].

2. Theory

The schematic presentation of the two-layer model is shown in Fig. 1. The threading dislocations are along x-direction whereas the longitudinal magnetic and the electric fields are applied along z-direction (longitudinal configuration). The edge dislocations introduce acceptor centers along the dislocation lines which capture electrons from the conduction band in a n-type semiconductor [22,23]. The dislocation lines become negatively charged and a space charge is formed around it. The resulting potential field scatters the electrons and reduces the mobility of the electrons [23].

The screened potential at a large distance from a charged dislocation was given by Bonch-Bruevich and Glasko [21] as

$$V(r) = \frac{e}{2\pi\varepsilon c} K_o(r/\lambda) \tag{1}$$

Here c—the lattice parameter along the (0 0 0 1) direction, e—the electronic charge, ε—the static dielectric constant, K_o—zero order modified Bessel function, λ—the screening parameter, r is the distance from the dislocation line in the z–y plane.

When a magnetic field is applied along the z-direction, electron performs orbital motion in the plane perpendicular to magnetic field. The motion becomes quantized when the magnetic field is, such that the de-Broglie wavelength, associated with carriers become comparable to the radius of the orbit. This gives rise to equally spaced ladder of energy levels called Landau levels. The electron motion in the plane perpendicular to the magnetic field is quantized in the Landau states. If the magnetic field is so high that electrons occupy only the lowest Landau level, i.e. level corresponding to $n = 0$, the condition is the called the extreme quantum limit. However, the motion of the electron along the direction of the magnetic field is not affected by the magnetic field. The situation is quasi-one dimensional. We have considered here the electrons in the extreme quantum limit.

The expression for relaxation time for dislocation scattering under extreme quantum limit has been arrived at

$$\frac{1}{\tau_{disl}} = \frac{L_x n_{disl}^{2d} e^4 \lambda^4 m}{4\pi^2 \hbar^3 \varepsilon^2 c^2 k_z} \times \left[\int_0^{2K_\perp} \frac{\mathrm{e}^{-A^2 q_y^2}\, d^2 q}{(1 + q_y^2 \lambda^2)^2} + \int_0^{2k_\perp} \frac{\mathrm{e}^{-A^2 q_y^2}\, d^2 q}{(1 + q_y^2 \lambda^2 + 4k_z^2 \lambda^2)^2} \right] \tag{2}$$

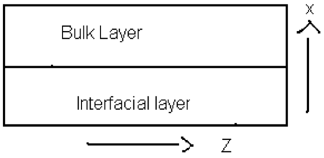

Fig. 1.

The detailed calculation is shown in Appendix A. The mobility $\mu = (e/m^*)\langle\tau\rangle$ is calculated considering the dislocation scattering and the ionized impurity scattering mechanisms for the interfacial layer and for the bulk layer, the acoustic phonon scattering via deformation potential and the piezoelectric scattering, the ionized impurity scattering and the polar optical scattering are considered [24].

The relaxation time for various scattering mechanisms under the extreme quantum limit is taken from Ref. [24]. The expressions are

$$\frac{1}{\tau_{ac}} = \frac{C_{ac}(m^* a_o)^{1/2}}{2\sqrt{\pi}\hbar^2 l^3} F_{ac}\left[\frac{N_q}{\sqrt{E+\hbar\omega_q}} + \frac{N_q+1}{\sqrt{E+\hbar\omega_q}}\right] \tag{3}$$

$$\frac{1}{\tau_{pz}} = \frac{C_{pz}(m^* a_o)^{1/2}}{2\sqrt{\pi}\hbar^2 l} F_{pz}\left[\frac{N_q}{\sqrt{E+\hbar\omega_q}} + \frac{N_q+1}{\sqrt{E+\hbar\omega_q}}\right] \tag{4}$$

$$\frac{1}{\tau_{imp}} = \frac{n_i e^4}{4\pi(2m^* a_o)^{1/2}\varepsilon^2\varepsilon_o^2 E^{1/2}(\varepsilon_d + 4E)} \tag{5}$$

$$\frac{1}{\tau_{pop}} = \frac{1}{2}\left[\left(1+\frac{\alpha}{2}\right)e^{x\theta}E_1(x\theta) - \frac{\alpha}{2x\theta}\right] \times C_{pop}x \times \left[\frac{N_q}{\sqrt{E+\hbar\omega_q}} + \frac{N_q}{\sqrt{E+\hbar\omega_q}}\right] \tag{6}$$

where τ_{ac}, τ_{pz}, τ_{imp} and τ_{pop} are relaxation time for acoustic, piezo electric, impurity and polar optical phonon scattering, respectively.

According to the two-layer model, the combined current is the sum of the total currents through the layers, hence

$$I_{com} = I_{int} + I_{bulk} \tag{7}$$

where I_{int}, I_{bulk} are currents in the interfacial layer, bulk layers and I_{com} represents the combined current of the crystal as a whole. The combined conductivity σ_{com} is obtained as

$$\sigma_{com} = \frac{(a\sigma_1 + \sigma_2)}{(a+1)} \tag{8}$$

and the combined Seebeck coefficient is

$$S_{com} = \frac{(s_1\sigma_1 a + S_2\sigma_2)}{(\sigma_1 a + \sigma_2)} \tag{9}$$

where '*a*' is the ratio between width of layer 1 and layer 2. The formula for calculation of Seebeck coefficient is [25]

$$S = -\frac{k_B}{e}\left[\frac{-E_F}{K_B T} + \frac{\int \frac{E}{K_B T}\tau\frac{\partial f}{\partial E}k_Z^2\,\mathrm{d}k_Z}{\int \tau\frac{r\partial f}{\partial E}k_Z^2\,\mathrm{d}k}\right] \tag{10}$$

where E_F is the magnetic field dependent Fermi energy and f is the equilibrium distribution function and E represents the energy of the electron.

3. Results and discussions

A detailed theoretical study of various transport parameters under the extreme quantum limit of n-GaN grown on the sapphire has been made. We have calculated the transport parameters such as the combined conductivity (σ_{com}), the combined Seebeck coefficient (S_{com}) under the extreme quantum limit on the basis of two-layer model. Two ratios of thickness of the interfacial layer to that of the bulk layer at 1:1 and 1:24 have been considered. Apart from the scattering mechanisms such as the acoustic phonon via deformation potential and piezoelectric scattering and the ionized impurity mechanisms, the polar optical phonon scattering mechanism is considered for the bulk layer for temperatures ranging higher than 77 K. For temperature lower than 77 K, the polar optical scattering mechanism is not considered in the bulk layer. Due to the lower dislocation density in the bulk layer, the dislocation scattering is neglected in it.

In the high density of dislocations in the interfacial layer, the dislocation scattering dominates in the interfacial layer. At very low temperature, the effect of the ionized impurity scattering mechanism is also high. So both the ionized impurity scattering mechanism and the dislocation scattering mechanism are considered for the interfacial layer.

We have considered the data of the sample prepared by Huang Yan [26] where carrier concentration in the bulk layer is $9 \times 10^{22}\,\mathrm{m}^{-3}$. The fitting parameters for the donor concentration (N_D) and the compensated acceptor concentration (N_A) are taken as 19×10^{22} and $5 \times 10^{22}\,\mathrm{m}^{-3}$ and the dislocation density (n_{disl}) in the interfacial layer are considered to be $7 \times 10^{14}\,\mathrm{m}^{-2}$. The other various parameters taken from various sources are given in our earlier paper [18,27–30]. Here for parabolic semiconductor, a_o is taken as 1. The thickness of the interfacial layer is taken as 0.2 µm.

Fig. 2. shows the variation of electrical conductivity, $\sigma_{com,}$ of the combined layer with magnetic field under the extreme quantum limit for two ratios of the thickness of the interfacial layer to that of the bulk layer at 1:24 and 1:1. It is found that σ_{com} reduces with magnetic field in case of both ratios. From the expression of τ_{disl} in Eq. (2), it can be seen that the value of τ_{disl} decreases exponentially with increase in magnetic field. As in the case of τ_{disl}, the value of relaxation time for other scattering mechanisms like the acoustic, the peizo and the polar optical phonon scattering mechanisms reduces with increase in magnetic field, so the combined conductivity reduces with increasing magnetic field. The conductivity for the width ratio 1:1 is less than that of 1:24. It can be explained that the dislocation scattering in the interfacial layer reduces the conductivity in the bulk layer.

So the more the relative width of the interfacial layer compared to bulk layer, the less is the conductivity due to the adverse effect of dislocations in the interfacial layer. No experimental data of conductivity of n-GaN under the extreme quantum limit could be found in the literature. In our earlier work [18], the conductivity of some sample [31] is reported to be $260.52\,\Omega^{-1}\,\mathrm{m}^{-1}$ at 133 K. We find the value of conductivity is $100\,\Omega^{-1}\,\mathrm{m}^{-1}$ at 100 K at 8 T. Mobility and conductivity reduce with the increase of magnetic field. For a high magnetic field of 8 T, the conductivity is expected to reduce quite substantially. So the theoretical value of conductivity seems compatible and reasonable with the experimental data.

Fig. 3 shows the variation of combined conductivity σ_{com} with magnetic field at very low temperatures. For the bulk n-GaN layer,

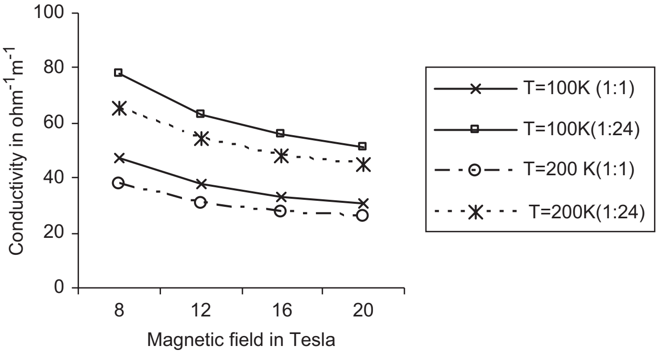

Fig. 2. Variation of combined conductivity in n-GaN with magnetic field at different temperatures.

the ionized impurity scattering, the acoustic phonon scattering via deformation potential and the piezo electric scattering mechanisms are considered. At low temperatures, the polar optical phonon scattering is not considered. For the interfacial layer, dislocation scattering as well as the ionized impurity scattering mechanisms are considered. It may be seen that the σ_{com} here increases with increase in magnetic field at low temperature whereas σ_{com} decreases with increase in magnetic field at high temperatures.

The relaxation time for the ionized impurity scattering increases with magnetic field whereas the relaxation time for other scattering mechanisms decreases with increase in magnetic field. At low temperatures, the ionized impurity scattering mechanism dominates over other scattering mechanisms as a result the combined relaxation time increases with magnetic field at low temperatures and there is corresponding increase in σ_{com} at low temperatures. However, the effect of dislocation in the interfacial layer is evident as we find that value of σ_{com} is higher for the bulk layer with width ratio 1:24 than that for the width ratio of 1:1.

Fig. 4 shows the variation of $\sigma_{\rm com}$ with temperature at magnetic fields of 8 and 12 T at the temperature range 100–250 K for the width ratios 1:1 and 1:24. In all the cases we find conductivity slowly decreases with temperature. Here also we have considered all the four scattering mechanisms like the acoustic phonon scattering through deformation potential and the piezo electric coupling, the ionized impurity scattering, and the poplar optical phonon scattering for the bulk layer and the dislocation scattering and the ionized impurity scattering for the interfacial layer. Except for the ionized impurity scattering, the relaxation time for other scattering mechanisms slowly reduces with increase in temperature, as the effect of ionized impurity scattering is less at this temperature range, conductivity slowly reduces with temperatures.

Fig. 5 shows the variation of σ_{com} with temperature at different magnetic fields at low temperature range. Here σ_{com} increases with temperature. At very low temperature the dominating scattering mechanisms are the ionized impurity scattering and neutral impurity scattering. We have only considered the ionized impurity scattering together with the acoustic and the piezo scattering mechanisms for the bulk layer and the ionized impurity scattering and the dislocation scattering for the interfacial layer. In the low temperature range conductivity of n-GaN increases sharply and after obtaining a peak value it decreases in the room temperature range. At low temperature the ionized impurity scattering dominates over the other scattering mechanisms. The relaxation time for ionized scattering increases with temperature. The combined relaxation time also increases with temperature and conductivity increases with temperature at the low temperature range. For our sample, the experimental value of mobility in absence of any magnetic field is reported to be 300 cm^{-2} (V s)$^{-1}$ at 50 K. The conductivity of the sample works out to be 1758 Ω^{-1} m^{-1} considering normalized carrier concentration of electrons at both interfacial and epilayer. The theoretical value of conductivity as per our model is 1200 Ω^{-1} m^{-1} under the influence of magnetic field of 12 T.

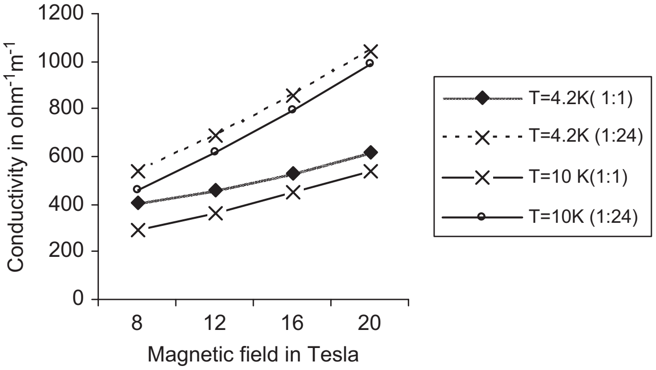

Fig. 3. Variation of the combined conductivity of the bulk layer of n-GaN with magnetic field at low temperatures.

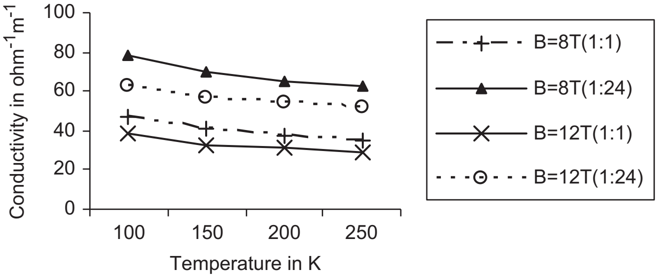

Fig. 4. Variation of the combined conductivity of n-GaN for temperature at different magnetic fields and different width ratios.

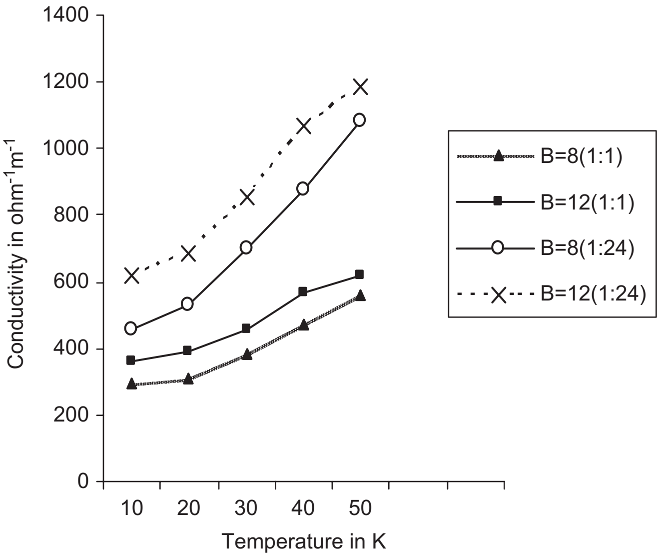

Fig. 5. Variation of combined conductivity of n-GaN with temperatures at different magnetic fields at different width ratios.

Fig. 6 shows the variation of absolute value of combined Seebeck coefficient with magnetic field at different temperatures. As the temperatures range from 100 to 200 K, we have considered the ionized impurity scattering, the acoustic phonon scattering via deformation potential, the piezo electric scattering and the polar optical phonon scattering for the bulk layer and the dislocation scattering and the ionized impurity scattering for the interfacial layer. The combined layer for two different width ratio of 1:1 and 1:24 of the interfacial layer and the bulk layer are considered. We find the absolute value of the Seebeck coefficient increases in all the situations with increase in the magnetic field. From the expression of Seebeck coefficient as given in Eq. (10) it can be seen that reduction of τ_{disl} with magnetic field will not have much effect on the Seebeck coefficient as the term appears both in numerator and denominator of the formula. But the Fermi energy decreases while the energy of the electrons increases with increase in the magnetic field. As a result, the first term decreases and the second term increases. So their differences also increase with increase in the magnetic field. In Fig. 5 we find that absolute value of Seebeck coefficient increases with magnetic field. No experimental data of Seebeck coefficient under the extreme

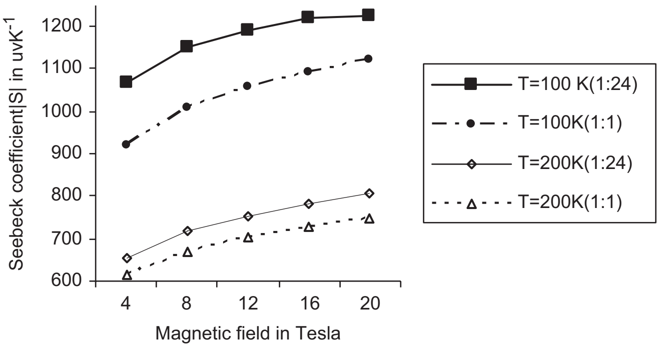

Fig. 6. Variation of combined Seebeck coefficient of n-GaN with magnetic field.

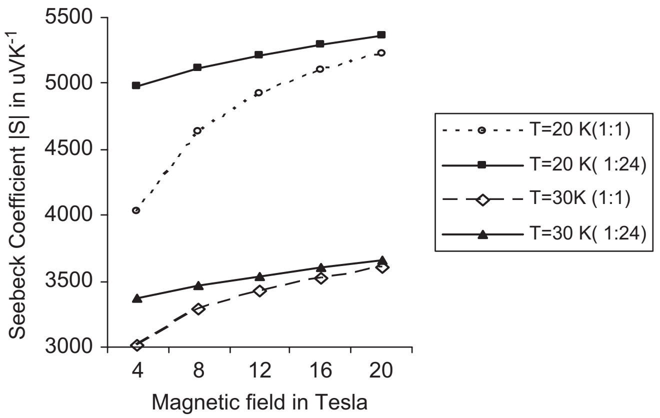

Fig. 7. Variation of Seebeck coefficient with magnetic field at low temperature in n-GaN for different width ratios.

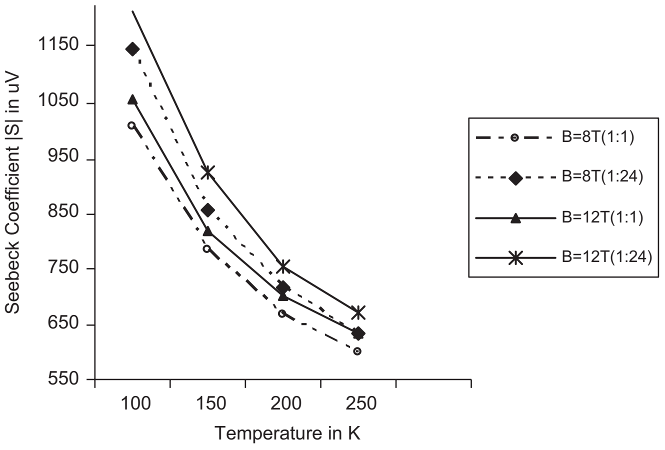

Fig. 8. Variation of combined Seebeck coeff |S|of n-GaN with temperature at different magnetic field and different width ratios.

quantum limit was available in the literature. In our earlier paper [18] we referred the experimental data on Seebeck coefficient of n-GaN [31] wherein Seebeck coefficient of the sample is reported to be $-300\,\mu\text{VK}^{-1}$ at 200 K. In our calculation we find at 200 K Seebeck coefficient at 4 T is $-600\,\mu\text{V}\,\text{K}^{-1}$. As magnetic field causes increase in value of Seebeck coefficient, so experimental value of absolute Seebeck coefficient is expected to be much higher at 4 T. It may be mentioned that samples are different and carrier densities are also different in the samples. Moreover we have not considered the nitrogen vacancy scattering mechanism. However, we find that Seebeck coefficient for width ratio 1:24 is higher for width ratio 1:1 which implies that the dislocation scattering reduces the combined Seebeck coefficient in n-GaN.

In Fig. 7, the variation of Seebeck coefficient with magnetic field at very low temperatures like at 20 and 30 K are shown. For low temperatures we have no experimental data of Seebeck coefficient. At low temperature, absolute value of Seebeck coefficient increases with change in magnetic field. The nature of curves for variation of Seebeck coefficient with magnetic field are more or less same at low temperature as well as high temperature. Here also we find that the dislocation scattering lowers the absolute value of Seebeck effect. Since Seebeck coefficient is lower for width ratio 1:1.

Fig. 8 shows the variation of combined Seebeck coefficient with temperature at different magnetic fields. For the bulk layer, the ionized impurity scattering, the acoustic phonon scattering via deformation potential, the piezo electric scattering and the polar optical phonon scattering have been considered for the bulk layer and dislocation scattering and ionized impurity scattering have considered for the interfacial layer for two width ratios, 1:1 and 1:24.

In the formula for Seebeck coefficient, both the terms reduce with increase in temperature, while the first term varies inversely with logarithm of temperature whereas the second term inversely varies with temperature. So the second term plays more important role in variation of Seebeck coefficient with temperature. While the first term reduces slowly with increase in temperature whereas the value of second term decreases much faster with increase in temperature. Consequently their differences decrease resulting in decrease in absolute value of Seebeck coefficient.

4. Conclusion

With the help of two-layer model in GaN, the effect of dislocation scattering on transport parameters like conductivity and Seebeck coefficient under the extreme quantum limit have been studied. The magnetic field dependence arising out of the present model can provide better understanding of the transport parameters and new physical processes. There are other nitride semiconductors where the density of dislocations is quite high. Our model can be used to study the effect of dislocations on transport parameters of those semiconductors under extreme quantum limit.

Appendix A

$$V(r) = \frac{e}{2\pi\varepsilon c} K_o(r/\lambda)$$

The Fourier transform of the potential in two dimension is $A(q) = e^2\lambda^2/(\varepsilon c(1+q^2\lambda^2))$ where $q = \vec{k}'_\perp - \vec{k}_\perp$ in the y–z plane. The relaxation time under Born approximation

$$\frac{1}{\tau_{disl}} = \frac{2\pi}{\hbar}\sum_{\alpha'} \left|\langle\alpha'|V(r)|\alpha\rangle\right|^2 \delta(E_{\alpha'} - E_\alpha) \tag{A.1}$$

$|\alpha\rangle$ is the electron wave function in a magnetic field and E_α is the corresponding energy level, where

$$|\alpha\rangle = \frac{1}{(L_y L_z)^{1/2}} \frac{\mathrm{e}^{\mathrm{i}(k_z z + k_y y)}}{(2^n n! \sqrt{\pi} A)^{1/2}} \times \quad e^{-\frac{(x-X)^2}{2A^2}} H_\mathrm{n} \frac{(x-X)}{A} \tag{A.2}$$

$H_\mathrm{n}(x)$ is the Hermite polynomial and B is the magnetic field.

where L_x, L_y and L_z are the crystal dimensions along x, y and z directions, respectively.

$$A = \left(\frac{\hbar}{eB}\right)^{1/2}, \quad X = -A^2 k_y$$

The energy

$$E_\alpha = (n+1/2)\hbar\omega + \frac{\hbar_2 k_z^2}{2m} \quad \text{where } \omega = \left(\frac{eB}{m}\right)$$

$$\begin{aligned}\langle\alpha'\lfloor V(r)\rfloor\alpha\rangle = {} & \frac{1 \qquad 2\pi}{(L_yL_z)\hbar(2^{n'}n'!2^n n!)^{1/2}\sqrt{\pi}A} \\ & \times \int V(r)\mathrm{e}^{\mathrm{i}(k_z'z+k_y'y)}\mathrm{e}^{-(x-X')^2/(2A^2)}H_{n'}\frac{(x-X')}{A}\mathrm{e}^{-\mathrm{i}(k_zz+k_yy')} \\ & \times \mathrm{e}^{(x-X)^2/(2A^2)}H_n\frac{(x-X)}{A}\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z \qquad \text{(A.3)}\end{aligned}$$

Using the integration given in Gradstyen and Ryzhik's book on Table of Integrals, Series and Product and putting $n = n' = 0$ under extreme quantum limit we get

$$\begin{aligned}\frac{1}{\tau_{disl}} = {} & \frac{L_yL_z}{(L_yL_z)^2}n_{disl}^{2D}\frac{2\pi}{\hbar} \\ & \times \frac{L_xL_yL_z}{(2\pi)^3}\int\frac{e^4\lambda^4\mathrm{e}^{-A^2q_y^2}}{\varepsilon^2c^2(1+\lambda^2(q_y^2+q_z^2)^2)}\mathrm{d}q_z\,\mathrm{d}q_x\,\mathrm{d}q_x \qquad \text{(A.4)} \\ = {} & \frac{L_xn_{disl}^{2d}e^4\lambda^4m}{4\pi^2\hbar^3\varepsilon^2c^2k_z} \\ & \times\left[\int_0^{2K_\perp}\frac{\mathrm{e}^{-A^2q_y^2}\,d^2q}{(1+q_y^2\lambda^2)^2}+\int_0^{2k_\perp}\frac{\mathrm{e}^{-A^2q_y^2}\,d^2q}{(1+q_y^2\lambda^2+4k_z^2\lambda^2)^2}\right] \qquad \text{(A.5)}\end{aligned}$$

here $d^2q = \mathrm{d}q_x\,\mathrm{d}q_y$ and $k_\perp$ represent the value of wave vector in x–y plane.

Under extreme quantum limit the q_z has two values either 0 or $2k_z$. d_{disl}^{2D} is the two dimensional dislocation density per unit area.

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