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A review of high ideality factor in gallium nitride-based light-emitting diode

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Abstract. Theory concerning the high ideality factor of gallium nitride (GaN) based light-emitting diode (LED) has been reviewed. The presence of a high ideality factor indicates a large forward voltage that results in efficiency reduction. The paper suggests that tunneling is the main reason defining the exponential behaviour of current-voltage measurements, which leads to a high ideality factor. However, there is also a paper that suggests that the design of current geometry in the LED chip defines the value of ideality factor. An effective current spreading geometry in the LED chip will minimize the ideality factor and make it fall between the ideal range of 1 to 2. Besides, how the ideality factor is calculated will also play a major role in defining its value. By calculating the ideality factor based solely on the radiative recombination current formula, the value of ideality factor can result in an ideal ideality factor of 1.08.

Keywords: gallium nitride, ideality factor, light-emitting diode, tunneling.

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1. Introduction

The ideality factor of a *p-n* junction is a measure of how close the diode follows the ideal diode equation and it is also a parameter that defines the types of dominant recombination mechanism, when the diode operates under the forward bias. The *p-n* junction diode has two types of recombination current, which are the recombination current and diffusion current. According to the Shockley–Read–Hall (SRH) theory, the ideality factor should be ranging between 1 and 2, where 1 indicates the dominance of diffusion current and 2 indicates the dominance of recombination current [1-3]. In the context of an ideal diode with the ideality factor close to unity, free electron from the conduction band will directly recombine with free hole in the valence band and release energy in the form of photons. Based on the SRH theory, the recombination of free electron and hole *via* a defect in the bandgap region has the ideality factor close to 2. This recombination is non-radiative. There are various non-radiative recombination mechanisms under the forward bias, which is known to correspond to the factor of high ideality. Apart from SRH recombination *via* a defect level, tunneling leakage assisted by defects is also considered as one of the contributors in non-radiative recombination in LEDs. The value of the ideality factor can be also used as an index for the crystal quality of the LED material as the ideality factor that is close to 2 marks the dominance of recombination current through defect levels at the particular current.

However, in the case of the gallium nitride (GaN) LED, its ideality factor is usually higher than 2. It has been reported that the ideality factor for GaN can reach up to 7 [3-9]. GaN has attracted a great deal of interest due to its application to optoelectronic and micro-electronic devices, such as blue light emitting diode, blue lasers, ultraviolet Schottky barrier photodetectors, solar-blind Schottky photodiodes, metal–semiconductor (MS) field effect transistors, and high electron mobility transistors [10-18]. GaN is an interesting material to study due to its several advantages over other conventional III-V materials. Its high thermal stability, high breakdown electric field, high robustness, excellent lifetime (several 10 000 h), and great mechanical strength have to make GaN LED as an effective device with many applications. Further research stated that GaN LED is one of the promising candidates for the next generation lighting source in the field of domestic and commercial applications. The development of the field of III-nitride semiconductor technology has been spectacular in recent years. There are mainly two explanations for choosing III-nitride for source of blue light. The key explanation for this is that AIN, GaN, and InN have direct bandgap energies of 6.2, 3.4, and 0.7 eV, respectively, at room temperature [19-22], spanning the spectra from ultraviolet to the entire visible spectrum. The other advantage of III-nitride over other wideband semiconductor is the stronger chemical bond, which make the nitride very stable and have high resistant against strong electric current and high temperature.

Research related to GaN LED has resulted in many groundbreaking progresses towards the solution of material- and device-related problems. However, the high ideality factor in GaN LED that is ranging between 2.0 up to 7.0 is still not fully understood by many researchers. It is our interest in this article to review the most common theory that previous researcher related with the high ideality factor of GaN LED.

2. Discussion

One of the most common methods used to determine the ideality factor of LEDs is through electrical characterizations of LEDs. A current-voltage measurement will be performed and from that measurement, the ideality factor can be calculated through the current-voltage curve [4, 7, 23-25]. H.C. Casey *et al.* used to plot a semi-logarithmic slope of the *I-V* curve from a commercial blue GaN LED to get its ideality factor. The ideality factor of the commercial LED is $n = 6.8$ as $I = I_S \exp\left(\frac{qV}{nkT}\right)$. From this exponential *I-V* behavior, it is believed that tunneling is the dominant mechanism that leads to a high ideality factor rather than the space-charge recombination mechanism [7, 26]. H.C. Casey *et al.* stated that tunneling can occur from a *p*-type AlGaN layer into localized states within the energy gap of the *n*-type InGaN active layer. Meanwhile, as the voltages approaching the built-in potential, tunneling can happen through the movement of holes from the valence band in *p*-type AlGaN into the valence band of a smaller energy gap of *n*-type InGaN active layer. C.L. Reynolds *et al.* also agreed that tunneling is the reason for the GaN high ideality factor, and he believed that the tunneling current should be expressed as:

$$I = B \exp\left(\alpha V\right), \tag{1}$$

where B is a constant, V – applied forward bias voltage, and α is interpreted as follows:

$$\alpha = \pi \frac{m_T^{1/2} \varepsilon^{1/2}}{4hD^{1/2}}. \tag{2}$$

Here, m_T is the effective mass of the tunneling entity, ε – relative permittivity, h – Planck's constant, and N_D – concentration of ionized donors. It is reported that InGaN LEDs grown on sapphire usually have the ideality factor ranging between 4 and 8, and this statement is supported by several authors [7, 9, 27, 28], which also conclude that tunneling is to be held responsible as the main reason for this unrealistically high ideality factor. The ideality factor of the InGaN based sapphire in C.L. Reynolds *et al.* is seen to decrease from 7.09 down to 2.96 with the forward bias voltage increase from 1.5 up to 2.4 V. Despite experience of this huge drop, the ideality factor still unable to fall inside the normal range 1 to 2. Since the amount of forward voltage increase beyond 2.4 V, the device current behavior will be defined by the series resistance, hence it is not accurate to relate the result with subsequent discussion.

In this paper, the author relates specifically the type of entity that responsible for tunneling that leads to a high ideality factor according to their respective forward bias range. By taking the ratio of the slopes in low (0.3…1.5 V) and medium (1.9…2.4 V) forward bias regime and by comparing it with the relative effective masses, m^*/m_0, the dominant tunneling entity can be determined. The relative effective masses, m^*/m_0, for electron, heavy hole, and light hole in GaN are 0.2, 1.4, 0.3, respectively [23, 29]. In these articles, the authors associate electrons as the tunneling entities in the low forward bias regime and heavy holes – in the medium regime. The electron tunneling to the deep level is being related to the defects that exist at the *p*-side of the *p-n* junction. It is also proposed that electron tunneling is related to the deep level mixed/screw dislocations. This statement is supported by Cao *et al.* [27] that the stated dislocations *via* electron tunneling are responsible for high ideality factors. Specific characteristics of defects that are being related to tunneling are not discussed in this paper, since they focus only on electrical characterizations. Due to this, there is no structural characterization that has been done. Meanwhile, for the medium bias regime, heavy hole is the tunneling entity, and it is believed that it undergoes interband tunneling at the intermediate states.

Besides, the paper by Sang Heon Han *et al.* also stated that tunneling is the reason defining the GaN high ideality factor. In this paper, the ideality factor is 5.2, when the forward voltage lies between 1.5 and 2.3 V. As the forward voltage increases from 2.3 up to 2.8 V, the ideality factor decreases down to 2.2, but it is still unable to fall below 2. Electron tunneling through dislocations is associated with a high ideality factor. In this paper, there are 2 different models of LED under investigation. InGaN/GaN LEDs grown on a sapphire substrate (LED A) is the one that experienced 5.2 and 2.2 ideality factor according to their respective forward bias range. Meanwhile, for InGaN/GaN LEDs with intentionally formed V-shaped pits grown on a sapphire substrate (LED B), the ideality factor is only 1.6 for forward bias ranging from 2.2 up to 2.6 V. In LED B, the dislocations are electrically passivated due to a highly resistive *p*-AlGaN and *p*-GaN that were grown on the semi-polar plane which formed around the V-shaped pits. Due to this, it prevents electron from moving to the dislocations and, hence, results in a lower ideality factor value [25].

Furthermore, this paper also stated that the presence of an energy barrier that is induced by the higher energy state of the InGaN well layer on the semi-polar plane makes it possible for electron tunneling to be suppressed through the existence of V-shaped pits at low forward bias. Hence, the value of the ideality factor is able to improve.

While Sang-Heon Han *et al*. purposely formed V-shaped pits defect in his InGaN/GaN LED to study its effect on the ideality factor, V.K. Malyutenko *et al*. on the other hand, purposely fabricate InGaN/GaN LED with current crowding geometry to determine whether current spreading play a vital role in GaN-based LED ideality factor. To understand more about the role of current crowding in determining the ideality factor of InGaN/GaN LED, two different models of LEDs with different contact patterns were tested. LED A was designed with an interdigitated contact structure where a bias current was applied through six contact wires (three *p*-contacts and three *n*-contacts) which allowed an effective current spreading across the entire emitting chip. For LED B, the only difference it has over LED A is that it contained only two contact wires at the center of the chip. Hence, for LED B, the current won't be able to spread effectively and result in current crowding.

The report in [4] uses the same method as in [25] to analyze the ideality factor, where the *I-V* behavior of both LEDs was separated into three different regions: low bias, medium bias, and high bias. The difference is analyzed in [25] in terms of applied voltage, while in [4] – in terms of applied current. The low current bias is ≤0.1 mA, medium current bias $0.1\text{ mA} < I \leq 10\text{ mA}$, and high current bias $I > 10\text{ mA}$. For the low current bias, the ideality factor extracted from the *I-V* curves is 8 for both LED A and LED B. As LEDs enter the medium bias range, the ideality factor decreases from 8 to 1.9 (LED A) and 2.4 (LED B). As we have seen, the ideality factor in low bias is extremely high and this is because at this stage the low current domain is not affected yet by the contact pattern due to high initial resistance of the *p-n* junction and the shunting nature of the current itself. However, as the LED enters medium bias current stage, the ideality is seen to decrease a lot for both LED A and B.

This fact shows that the way of the current spread in the LED chip does affect the ideality factor of the device. Chip with a better current spreading geometry will have lower ideality, and it is possible to achieve ideality factor below two for GaN-based LED with a better current spreading geometry in the device chip.

Aside from tunneling as the reason for the GaN high ideality factor, other reports suggest different theories. The paper by Mingsheng Xu *et al*. [24] claims that the high ideality factor originates from the InGaN/GaN heterojunctions. In this paper, the origin of the high ideality factor value is studied by analyzing the temperature-dependent *I-V* curves of InGaN/GaN MQW LED that was grown on a sapphire substrate. The *I-V* curves were separated into four regions: tunneling current (TC), recombination current (RC), diffusion current (DC), and series resistivity zone. When the forward injection current is below 1×10^{-7} A, the dominant carrier transport mechanism is TC. As the injection current increases from 1×10^{-7} A up to 1×10^{-3} A, an exponential relationship between voltage and injection current is observed. With account of this exponential relationship, the ideality factor and saturation currents can be fitted using Eq. (3) shown below,

$$J \propto J_S \exp\left(\frac{qV}{nkT}\right), \tag{3}$$

where J is the current density, J_S – saturation current, V – diode voltage, n – ideality factor, k – Boltzmann constant, q – elementary charge, and T – temperature. The ideality factor of LED at 300 K with the voltage ranging from 2 up to 2.4 V is 6.30. If the voltage increases from 2.4 up to 2.6 V, the ideality factor decreases down to 3.15. In this article, the reason for the high measured ideality factor as compared with the theoretical value is explained in terms of equation derivation. Mingsheng Xu *et al*. proposed the combination of heterojunction model that consists of *p-n* junction and InGaN/GaN MQWs (*p-n* MQW) to describe the way experimental ideality factor of GaN-based LED being identified. The injection current is exponentially dependent on the voltage drop of the InGaN/GaN heterojunction MQW according to the equation below:

$$J_{\mathrm{MQW}} = J_{\mathrm{DMQWS}} \exp\left(\frac{qU_{\mathrm{MQW}}}{n_{\mathrm{DMQW}}\, kT}\right) + J_{\mathrm{RMQWS}} \exp\left(\frac{qU_{\mathrm{MQW}}}{n_{\mathrm{RMQW}}\, kT}\right), \tag{4}$$

where J_{DMQWS} and J_{RMQWS} are the saturation currents for DC and RC in InGaN/GaN MQW, n_{DMQW} and n_{RMQW} – ideality factors of DC and RC, and U_{MQW} is the voltage drop of InGaN/GaN MQW. Eq. (4) can be further simplified as follows:

$$J_{\mathrm{MQW}} \propto J_{\mathrm{MQWS}} \exp\left(\frac{qU_{\mathrm{MQW}}}{n_{\mathrm{MQW}}\, kT}\right), \tag{5}$$

where J_{MQWS} is the saturation current of the heterojunction MQW and n_{MQW} – ideality factor of MQW. Meanwhile, the current-voltage relationship in the *p-n* junction can be expressed as:

$$J_{\mathrm{PN}} = J_{\mathrm{DPNS}} \exp\left(\frac{qU_{\mathrm{PN}}}{n_{\mathrm{DPNW}} kT}\right) + J_{\mathrm{RPNS}} \exp\left(\frac{qU_{\mathrm{PN}}}{n_{\mathrm{RPN}} kT}\right), \tag{6}$$

where J_{DPNS} and J_{RPNS} are the saturation currents for DC and RC of ideal *p-n* junction, n_{DPN} and n_{RPN} – ideality factors of DC and RC in the *p-n* junction, and U_{PN} is the voltage drop of the ideal *p-n* junction. Eq. (6) is further simplified as:

$$J_{\mathrm{PN}} \propto J_{\mathrm{PNS}} \exp\left(\frac{qU_{\mathrm{PN}}}{n_{\mathrm{PN}}kT}\right), \tag{7}$$

where J_{PNS} is the saturation current of *p-n* junction and n_{PN} is the ideality factor of the *p-n* junction. The total voltage drop of LED is the sum of MQW and *p-n* junction voltage drop as shown in Eq. (8):

$$U_{\mathrm{LED}} = U_{\mathrm{MQW}} + U_{\mathrm{PN}}. \tag{8}$$

Besides, in accord with the current continuity equation:

$$J_{\mathrm{LED}} = J_{\mathrm{PN}} = J_{\mathrm{MQW}}. \tag{9}$$

As the voltage drop goes down to zero, the values of U_{MQW} and n_{PN} will be close to zero. Hence, J_{PN}, J_{PNS}, U_{MQW}, and U_{MQWS} will all have the same value. Thereof, one can obtain the following relationship:

$$J_{\mathrm{PNS}} = J_{\mathrm{MQWS}} = J_{\mathrm{S}}. \tag{10}$$

According to Eqs. (3) to (10), it can be concluded that the true ideality factor of LED, n_{LED}, is the sum of n_{MQW} and n_{PN}. It can be seen in Eq. (11) shown below:

$$n_{\mathrm{LED}} = n_{\mathrm{MQW}} + n_{\mathrm{PN}}. \tag{11}$$

Mingsheng Xu *et al*. proposed that a combination of *p-n* MQW heterojunction model ideality factor is the reason for the GaN-based LED high ideality factor. It is believed that the value of high ideality factor depends, first of all, on the InGaN/GaN heterojunctions and not on tunneling. Besides, a different method of calculation to determine the ideality factor of GaN-based LED was used by Gyeong Won Lee *et al*. In this article [3], it is stated that most research articles use to calculate the ideality factor on the non-radiative region only and little attention has been given towards ideality factor on the radiative recombination region. Gyeong Won Lee *et al*. measured the temperature-dependent electroluminescence (TDEL) to obtain the data of internal quantum efficiency (IQE). Through this data, the radiative recombination current will be separated from the total current. Hence, the ideality factor of the GaN-based LED specifically in the radiative recombination region can be calculated. The radiative recombination rate R_r is shown below:

$$R_r = Bnp, \tag{12}$$

where B is the bimolecular radiative recombination coefficient, n – electron concentration and p – hole concentration. As the technology of LED evolves, multiple quantum well (QW) is commonly being used to enhance the carrier concentrations, which will result in an increasing value of radiative recombination rate. Due to this, Eq. (12) can be extended to:

$$R_r = \sum_l B_l n_l p_l, \tag{13}$$

where the index l is the parameter for the l-th quantum well. The current density due to the radiative recombination is obtained as follows:

$$J_R = qd_{qw} \sum_l B_l \left(n_l p_l - n_i^2\right). \tag{14}$$

In Eq. (14), q is the elementary charge, d_{qw} – thickness of each QW, and n_i – intrinsic carrier concentration. Since there is no current flow at thermal equilibrium, hence, n_i^2 is subtracted. In real life situations, the carrier concentration in each QW is different. Hence, we can introduce the effective active thickness d_{eff} as shown below:

$$J_r = qd_{eff} B\left(np - n_i^2\right), \tag{15}$$

where d_{eff} is the effective active thickness of QW; n and p in Eq. (15) are considered as the average electron and hole concentrations, respectively, while B – as the corresponding radiative recombination coefficient. Meanwhile, the carrier concentrations n and p should depend on the quasi-Fermi levels in the following way:

$$n = n_i e^{(E_{\mathrm{F}n} - E_{\mathrm{F}i})/kT}, \tag{16}$$

$$p = n_i e^{(E_{\mathrm{F}i} - E_{\mathrm{F}p})/kT}, \tag{17}$$

where $E_{\mathrm{F}i}$ is the intrinsic Fermi level, $E_{\mathrm{F}n}$ and $E_{\mathrm{F}p}$ are the quasi-Fermi levels for electron and hole, respectively, k is the Boltzmann constant and T – absolute temperature. The equation is further derived by putting Eqs. (16) and (17) into Eq. (15):

$$J_r = qd_{eff} Bn_i^2 \left[e^{(E_{\mathrm{F}n} - E_{\mathrm{F}p})/kT} - 1\right] = qd_{eff} Bn_i^2 \left[e^{qV_j/kT} - 1\right] \tag{18}$$

After this derivation, the final equation for the current density due to radiative recombination can be seen in Eq. (18). In the article [3], the ideality factor is obtained by fitting the slope of the linear portion of the $J_r - V$ graph. From this slope, m, the ideality factor can be obtained as

$$n_{ideal} = \left(\frac{q}{mkT}\right) \log e. \tag{19}$$

From Eq. (19), the ideality factor of blue LED in the article [3] is 1.08. This ideal value of ideality factor confirms that introducing the effective active thickness for MQW LED and focusing the ideality factor only on the radiative recombination current make it possible for GaN-based LED to achieve ideality ranging from 1 to 2. However, this theory is not valid for GaN-based LED that has major threading dislocations and transport peculiarities in MWQ. By reviewing multiple papers related to GaN-based LED ideality factor, we observed that different paper has their theory and approach. Table 1 summarizes the theory of the high ideality factor of GaN-based LED.

3. Conclusion

In this paper, we presented a detailed analysis of the potential mechanism responsible for the existence of high ideality factor for GaN. The purpose of the study was to define the type of mechanism that is dominant under different parameters and the characteristics of each mechanism. These address key questions regarding the characteristics of the dominant mechanism responsible for GaN high ideality factor. Some peculiarities need to be addressed, such as the type of defects, which leads to the existence of a high ideality factor and a better understanding how to reduce the ideality factor value in GaN-based LEDs.

Table 1. Summary of the theory concerning the high ideality factor of GaN-based LED.

Ref.	Characteristics	Ideality factor	Theory
[7]	Commercial InGaN LED. Forward bias *I-V* with the voltage ranging from 1 up to 3.5 V at RT.	6.8	The *I-V* exponential behavior is the characteristic of tunneling.
[23]	InGaN LED grown on sapphire. Identify specific entity responsible for tunneling at specific forward bias regime	7.09 (0.3 – 1.5 V) and 2.96 (1.9 – 2.4 V)	Believed that tunneling is the dominant mechanism responsible for high ideality factor. Associates electron tunneling into the deep level as the cause for high ideality factor for voltage ranging from 0.3 up to 1.5 V. Heavy hole is believed to be the main tunneling entity for voltage ranging from 1.9 up to 2.4 V.
[25]	An *n*-GaN template of InGaN/GaN MQW LED was intentionally formed with V-shaped pits defects.	1.6 (2.2 – 2.6 V)	Existence of intentionally formed V-shaped pits can suppress electron tunneling from the InGaN well layer due to an energy barrier that is induced by a higher energy state of the InGaN well layer on the semipolar plane.
[4]	The LED chip was designed with a current crowding geometry and current spreading geometry in order to study the effects of current crowding on ideality factor.	(0 – 2.25 V): 8 (for both current crowding and current spreading geometry) (2.25 – 2.5V): 2.4 (current crowding geometry) 1.9 (current spreading geometry)	It is believed that current crowding the main reason for the GaN high ideality factor. A better current spreading geometry in the GaN-based LED chip will improve the ideality factor of the device.
[24]	A *p-n* MQW combination junction model is used to explain the high ideality factor.	6.3 (2 – 2.4V) 3.15 (2.4 – 2.6V)	The true ideality factor of GaN is believed to be the sum of *p-n* junction ideality factor and MQW ideality factor. Hence, this causes the ideality factor of GaN to be higher than the theoretical value.
[3]	Commercial blue InGaN/GaN LED. Perform temperature-dependent electroluminescence (TDEL) measurements	1.08	It is believed that the ideality factor of GaN-based LED is usually calculated from the non-radiative recombination process. Hence, the value is higher than the theoretical value. In this article, the ideality factor is calculated based on radiative recombination only, which results in an ideal value of ideality factor.

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Огляд теорії великих значень коефіцієнта ідеальності у світлодіоді на основі нітриду галію

A.S. Hedzir, N.F. Hasbullah

Анотація. Розглянуто теорію великих значень коефіцієнта ідеальності у світлодіоді на основі нітриду галію. Наявність великого коефіцієнта ідеальності свідчить про велику пряму напругу, що призводить до зниження ефективності. У статті висловлено думку, що тунелювання є основною причиною, яка визначає експоненціальну поведінку вольт-амперних характеристик, що приводить до великих значень коефіцієнта ідеальності. Однак є також стаття, яка передбачає, що дизайн геометрії струму світлодіодного чіпа визначає величину коефіцієнта ідеальності. Ефективна геометрія розподілу струму в світлодіодному чіпі дозволить мінімізувати коефіцієнт ідеальності та змусить його набувати значень в ідеальному діапазоні від 1 до 2. Крім того, спосіб розрахунку коефіцієнта ідеальності також відіграє важливу роль у визначенні його величини. Якщо обчислювати цей коефіцієнт, виходячи виключно з формули для струму випромінювальної рекомбінації, то величина коефіцієнта ідеальності може досягати ідеального значення 1,08.

Ключові слова: нітрид галію, коефіцієнт ідеальності, світлодіод, тунелювання.