Suggestions on Efficiency Droop of GaN-based LEDs

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Abstract. InGaN/GaN-based light-emitting diodes (LEDs) are widely used in modern society and industry among different areas. However, InGaN/GaN LEDs suffer from an efficiency droop issue: The internal efficiency decreases during high current injection. The efficiency droop significantly affects the development of GaN-based LEDs devices in efficiency and light-output areas. Therefore, the improvement of the droop phenomenon has become a significant topic. This paper introduces several possible mechanisms of droop phenomenon based on different hypotheses including Auger Recombination, Carrier Delocalization and Electron Leakage. Furthermore, some proposals to mitigate efficiency droop, including semipolar LEDs, electron blocking layer(EBL), quaternary alloy and chip design will be discussed and analyzed. Also, it will provide some suggestions for the further optimization of droop phenomenon in each proposal.

1. Introduction
In 1993, Nakamura et al. demonstrated InGaN/GaN light-emitting diodes (LEDs) [1] for the first time. After that, LED materials and devices ushered in a period of rapid development, so now GaN-based LED is entering the lighting application field. Despite significant advances in GaN-based LED, higher efficiencies and light-output are two areas that researchers are primarily working to enhance. In the field of efficiency, GaN-based LED is seriously plagued, which is called efficiency droop. Usually, the LED reaches the highest efficiency during low injection current, when the current increases, the efficiency drops drastically. Therefore, in order to further develop high-power and high-efficiency LED devices, careful consideration must be given to the efficiency droop. This paper will list and analyze some striking theories of droop mechanisms, including Auger Recombination, Carrier Delocalization and Electron Leakage. Despite the controversy of the basics behind droop phenomenon, the attempts of diminishing efficiency droop never stop. The next section of this paper introduces some solutions of efficiency droop including semipolar LED, electron blocking layer(EBL), quaternary alloy and chip design based on different models of droop phenomenon basics.

2. Overview of GaN-based LED and efficiency droop
Due to the promising advantages over traditional light sources, including the largely extended lifetime and greatly improved power efficiency, the commercialization of GaN-based LED lighting applications has become very rapid. Potentially, the use of blue and green InGaN/GaN LEDs on large TV screens or micro full colour panels should be promising because of their excellent brightness. As flashlights, GaN-based LEDs consume less power and provide longer lighting time, as a result, helping to improve the environment and save costs. Furthermore, GaN-based LEDs are ideal sources for data transmission, thanks to the two characteristics of LEDs: the capability of being modulated at
high speed and solid-state source. In addition, with the further development of the optical application of LEDs, more optimizations, such as increased chip and operation power, will help GaN-based LEDs to achieve a higher output power of LEDs in single unit.

As I mentioned, efficiency droop describes the phenomenon that the internal efficiency decreases significantly with the gradual increase of the current. Furthermore, even under short pulse, low duty cycle and constant temperature injection, it has been proven that the well-known efficiency droop phenomenon strongly affects GaN-based LEDs over a wide range of wavelength spectrum. Therefore, the efficiency droop can have a significant negative impact on the GaN-based LED applications and limit their basic functionality.

With the deepening of the understanding of droop phenomenon, different theories have been put forward to explain the droop phenomenon. Among them, auger recombination, carrier delocalization and electron leakage have gradually become mainstream.

The auger recombination can be discussed in the ABC model. Due to the SRH linear dependence and the radiation recombination square dependence, the radiation recombination becomes a controlling recombination when LEDs are working at higher currents. With this in mind, the auger recombination is likely to cause the droop phenomenon.

Another theory, the carrier delocalization, is demonstrated in both logic and experiments. The SRH model describes a typical non-radiative electron-hole recombination at crystal defects. The unified IQE droop formula is that if other carrier loss mechanisms are neglected (Ileak=0, C=0), the equation will be transformed into. In addition, the SRH carrier lifetime is equal to 1/2A. The carrier lifetime of SRH decreases as carrier density increases, and the continuous linear rise of parameter A leads to efficiency droop phenomenon. In addition, some experiments also support this theory, which will be discussed in more detail below.

According to the electron leakage theory, the droop phenomenon is mainly caused by the asymmetric distribution of holes and electrons. The increasing current will continuously weaken the electron trap of quantum wells and thus result in droop phenomenon.

3. Droop mechanisms

3.1. Auger recombination

On account of the simplicity and flexibility of ABC model, researchers prefer taking it to briefly model the electron- hole recombination mechanism in LEDs[2].

\[ R = An + Bn^2 + Cn^3 \]

In the above formula, four variables, n, A, B, C in this equation, respectively represent the quantum wells (QWs) carrier density and Shockley - Read - Hall (SRH), radiative, nonradiative Auger-like recombination parameters. The radiative recombination turns into the governing recombination when LEDs work at higher current, attributed by the both SRH linear dependence and the radiative recombination square dependence. In addition, the domination of Auger contributions in recombination could be successfully predicted when LEDs are at a high current level by the ABC model.

Several researchers, based on some measurements and simulations, argued that the primary reason of the efficiency decrease with growing current and the basic nonradiative approach for carriers at LED working currents, is the Auger recombination. Shen et al. firstly published the measured result of InGaN Auger coefficient (ranging from 1.4*10\(^{-30}\) to 2.0*10\(^{-30}\) cm\(^6\) s\(^{-1}\)), which they claimed was large enough to diminish the internal quantum efficiency of the standard-operating-currents LEDs.
Following the first published experimental measured result of Auger coefficient [3], some other groups also published their experimental reports of Auger coefficient respectively within later few years and demonstrated the relevance between Augur coefficient and droop phenomenon.

After that, however, some theoretical groups calculated the nitride Auger coefficient directly, and in terms of these low theoretical value reports, several different variations and their theoretical reports to fortify the Auger recombination theory, including interband Auger recombination and indirect Auger recombination, have also been proposed.

However, the probability of the interband Auger recombination commonly drastically reduces with changing band gap, therefore it seems won’t literally become the unique reason for the efficiency droop across a wide wavelength range. In addition, all yielded values of theoretical calculation of the indirect Auger recombination coefficient vary from $1 \times 10^{-31}\text{cm}^6\cdot\text{s}^{-1}$ to $2 \times 10^{-31}\text{cm}^6\cdot\text{s}^{-1}$ [4], which is still not high enough to cover the discrepancy between experimental records and theoretical yielded values. Instead of the Band to band Auger recombination, it is likely that Phonon or defect-assisted Auger recombination are probable reasons for droop phenomenon according to the comparison of carrier density and temperature dependent electroluminescence and photoluminescence measurements.

| Method of calculation                      | Author                | Room temperature Auger coefficient ($\text{cm}^6\cdot\text{s}^{-1}$) |
|------------------------------------------|-----------------------|---------------------------------------------------------------|
| Direct Auger recombination               | Hader et al. (2008)   | $3.5 \times 10^{-34}$                                         |
| Indirect Auger recombination             | Kioupakis et al. (2011)| $0.5 \times 10^{-31} - 2.0 \times 10^{-31}$                  |
| Interband Auger recombination            | Delaney et al. (2009) | $2.0 \times 10^{-30}$                                         |
|                                          | Bertazzi et al. (2010)| $1.0 \times 10^{-32}$                                         |
| Experimental reports of Auger coefficient or C coefficient | Brendel et al. (2011) | $1.8 \times 10^{-31}$                                         |
|                                          | Shen et al. (2007)    | $1.4 \times 10^{-30} - 2.0 \times 10^{-30}$                  |
|                                          | Zhang et al. (2009)   | $1.5 \times 10^{-30}$                                         |
|                                          | David and Grundmann (2010) | $1.0 \times 10^{-29}$                                        |
|                                          | Dai et al. (2011)     | $8.6 \times 10^{-29}$                                         |
|                                          | Ryu et al. (2009)     | $1.0 \times 10^{-37} - 1.0 \times 10^{-34}$                  |

Figure 1. Theoretical and experimental reports of the Auger and C coefficients in the GaInN/GaN material system[5]

3.2. Carrier delocalization

Typical non-radiative electron–hole recombination at crystal defects is described by the SRH model. In the model, the primary unified IQE droop equation (1) could be transformed into equation (2), under the condition that other carrier loss mechanisms are neglected ($I_{\text{leak}}=0$, $C=0$). As a result, theoretical, if the SRH carrier lifetime falls down as carrier density grows, the continuous linear rise of parameter A will result in efficiency droop phenomenon.

$$
\eta_{\text{IQE}} = \frac{qV_{QW}Bn^{2}}{(I_{QW} + aT_{QW}^{m})^{1/2}}
$$

(1)
Primary unified IQE droop equation (1) and transformed IQE droop equation (2) with the electron charge $q$, carrier recombination current inside the QWs $I_{QW}$, the active volume $V_{QW}$ of all QWs, the QW carrier density $n$, the SRH parameter $A$, the radiative coefficient $B$.

The carrier delocalization is observed due to the non-uniform distribution of indium in the InGaN quantum wells. The random distribution of gallium and indium atoms results in indium and gallium-rich areas on crystal lattice sites. Usually, these indium-rich areas where carriers prefer to stay are with lower bandgap energy, while gallium-rich areas are with higher bandgap energy and tendency of repelling carriers. As a result, normally, this particular carriers localization effectively prevents the carriers diffusion and further taking advantage of dislocation and defects to recombine non-radiatively. With high injection current, however, quantum wells regions could not bear continuous increasing carriers and end up in a filled-up indium-clusters. Then more spilling out carriers will diffuse into quantum wells and recombine at defects non-radiatively and reduce SRH lifetime, then further cause droop phenomenon.

Although the theory seems reasonable and tenable, it might still be disputable. Firstly, the existence of indium-clusters turned into contentious later. Wang et al. [6] compared the external quantum efficiency and injection current of two light-emitting diode samples, and they concluded that although when at a low injection current, efficiency droop is dominated by the carriers delocalization, while at a higher injection current, efficiency droop is mainly account of the carrier leakage. Shen et al. [7] argued against Carrier delocalization theory. They argued the decrease would be apparent with a larger threading dislocation density if dislocations were indeed in charge of the efficiency decrease, while the actual observation didn’t literally reflect to the expectation.

Nevertheless, despite controversy, since the mechanism of low non-radiative recombination rate in InGaN quantum wells remains nearly mysterious, the carrier delocalization is still counted as reasons of efficiency droop.

3.3. Electron leakage

Another commonly discussed potential mechanism of efficiency droop is electron leakage. Theoretically, under a driving current, considering the large mobility difference between electrons and holes in GaN, the electron diffusion-drift distance between n-GaN and p-GaN is far longer than that of holes, resulting in the asymmetric distribution of holes and electrons. Hence, the increasing current will continue to weaken the electron trap of quantum wells. Finally, the recombination region moves from MQWs to the p-side of LED, which then prevents holes from reaching the active region. The conversion from kinetic energy to thermal energy leads to the efficiency droop phenomenon. The experimental evidence of electron leakage have been reported extensively.

The basic cause of electron leakage might be complicated. Some studies have shown that the electron leakage comes from the enhanced active region caused by sheet charges at hetero interfaces. The sheet charges might be further caused by severe polarization mismatch between different layers in the active region.

4. Suggestion

Although the mechanism of efficiency droop is still in dispute. However, based on different theoretical assumptions, some researchers have been working on the optimization of efficiency droop. In this part, several solutions have been listed, analyzed and reviewed.
4.1. Semipolar LEDs

Conventional LEDs ("polar" LEDs) typically grow on the c-plane substrates and are usually accompanied with large built-in electric fields caused by spontaneous polarization. Then, since the a/a-plane and the intermediate plane were applied to the second generation of bulk-GaN-substrate-based LED, the semipolar GaN-Based LED was invented and became a remarkable breakthrough, contributing to the reduction of efficiency droop.

The basic mechanism for overcoming droop for semipolar blue LEDs has been thoroughly studied. As previously discussed, it is believed that the reduction of the effective active region volume results in dense carriers in the active region, which then leads to severe Auger recombination and electron leakage, and finally causes droop phenomenon. Then, since polarization electric field, which mainly causes reduction of the effective active region volume, is significantly reduced in semipolar LEDs, a great decrease of efficiency droop could be observed. In addition, the SQW active region could eliminate carrier non-uniformity, mitigate the carrier density and electron leakage, and then assist LEDs in obtaining high efficiency. Furthermore, some observed phenomenon like narrow spectral width and a small blue shift with increased current density could vividly demonstrate that InGaN QWs grown on the semipolar (20-21) plane has relatively no potential fluctuation, therefore, the minimum band fill for localization degree and localization state of low carriers could be proved. [8]

4.2. Electron blocking layer (EBL)

Many efforts have been made to improve the efficiency of the the GaN emitters in the development of GaN-based LEDs, and EBL is nearly the most commonly used structures to prohibit electron leakage.

The primary goal of a thin AlGaN cap as an EBL commonly grown over the MQWs of InGaN-based LEDs is to maintain electron overflow in the active region and prevent the InGaN active region from being damaged by the subsequent high-temperature growth of p-type layers. The EBL structure is still under development to improve the efficiency of LEDs. For instance, to overcome the inability of AlGaN layers in protecting the MQWs region from the high temperatures growth of the p-type GaN contact layers, Hansen et al. develop a Mg-doped AlGaN EBL grown at low temperatures directly above the final InGaN well of the InGaN QWs. Then R. C. Tu et al. [9] demonstrate that the growth method at low temperature can reduce the electron leakage current and improve the external efficiency[10].

Another example, in order to solve a severe issue that EBL acts as a barrier for holes impeding the holes transportation into the active region, alternatives of the Mg doped AlGaN EBL are proposed to enhance the hole injection with the electrons blocking capability. Later, graded AlGaN electron blocking layer (GEBL) LEDs were invented to optimize the efficiency droop.

In spite of the widespread use of EBL, due to the effect of EBL on the efficiency droop in InGaN/GaN MQWs LEDs, the EBL does not seem to be suitable for every situation. However, since they came to different conclusion and they mainly discussed the influence of different current magnitudes on the function of EBL, it seems that more researches in EBL field are required to provide specific answer.

4.3. Quaternary alloy

Recently, some researchers proposed the polarization matching theory to explain efficiency droop. To prevent polarization charge from enhancing the carrier’s non-capture and carrier escaping from the active region, quaternary alloys have been proposed by controlling interfacial polarization charges and bandgap to mitigate electron leakage from the active region and to reduce efficiency droop. Kim et al. demonstrated theoretically polarization-matched GaInN/AlGaN MQWs LEDs could exhibit high efficiency at large injection current and the quaternary alloys Al_{x}Ga_{1-x}N of an appropriate bandgap and lattice constant. After that, Schubert et al. [11] reported their LEDs with polarization-matched AlGaN barriers. The quaternary alloys enhances the illumination performance at high currents and reduces the forward voltages, which increases external quantum by 18.5% and reduces droop phenomenon.
Despite the encouraging features of quaternary InAlGaN in reducing droop phenomenon, it seems uneasy to utilize the common method of metal-organic-chemical-vapor deposition (MOCVD) to grow quaternary InAlGaN owning to tremendous discrepancies in the optimal growth temperatures of nitrides and the difficulty in balancing growth temperature and the diffusion length of Al adatoms. Hence, it is necessary to further study the optimization of quaternary InAlGaN growing methods.

4.4. Chip design
Lots of efforts have been put into the chip design of the GaN-based LEDs to improve LEDs light extraction efficiency. With the advent of conventional chip (CC) design and flip-chip (FC) approach, the current spreading problem and a tradeoff between current spreading and light extraction have been solved. Then as the droop phenomenon becomes a hot topic, the relationship between chip design and efficiency droop has been studied intensively. The picture of the relationship seems clear that magnifying the device chip areas could lead to the significant reduction of efficiency droop due to the current decrease. Hence, large-sized LED chip is usually employed.

In another way, efficiency droop might be related to overheating of the LED chip at high current density caused by the current crowding effect. The current crowding effect is mainly attributed to the non-uniform carrier mobility between holes and electrons in GaN-based materials, leading to carriers crowding near the electrode and then the efficiency droop. In order to mitigate the overheat problem, some researchers attempted to develop microchips due to the small chip area, high voltage and low operation current. Yen et al. reported that their multi-microchip design uses self-rectifier in alternating-current LEDs. Wang et al. studied the application of microchips on high-voltage LEDs and reported significant enhancement and reduction in luminous efficiency and droop phenomenon due to more uniform current distribution in LEDs. In the future, it is expected to conduct more researches to reduce the overheating problem.

5. Conclusion
In this paper, the well-known efficiency droop phenomenon is discussed in detail. The theoretical discussion and experimental evidence of the basis of efficiency droop are elaborated, including Auger recombination, carrier delocalization and electron leakage. In the future, more researches will be conducted on the correlation between different possible mechanisms causing efficiency droop. Since these mechanisms are often interrelated and cross-linked, some recent studies showed that efficiency droop might be caused by several different factors.

Several proposed solutions to efficiency droop problem are listed, and the basic structure, functions and technical problems that need to be paid attention to in the future, such as semipolar LEDs, electron blocking layer(EBL), quaternary alloy and chip design, are investigated. Despite these extraordinary achievements, some issues still need more thorough investigations, such as the applicable electrical current range of the EBL, the quaternary in AlGaN growth methods and more details on microchip improvements.

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