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Spatially Resolved Study of the EQE Droop in InGaN QW LEDs: Interplay of Point Defects, Extended Defects, and Carrier Localization

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We offer a concise overview for the mechanisms on the external quantum efficiency (EQE) droop in InGaN QW LEDs. We believe that non-radiative recombination due to extended defects and the deficiency in the electron blocking layer are most likely two primary mechanisms responsible for the droop. We perform spatially resolved electroluminescence (EL) measurements with varying injection current on an InGaN QW LED. The analyses of the EL mapping data reveal a correlation between carrier delocalization and EQE droop. In addition, we observe that at very low current, there is virtually no correlation between the local EL intensity and peak energy, reflecting very low carrier mobility; whereas with increasing current, an anti-correlation between the intensity and energy is eventually established, indicating substantial changes in the carrier mobility and diffusion length with increasing current. The results suggest the material inhomogeneity occur in different scales.

Introduction

Mechanisms for quantum efficiency droop

The issue of external quantum efficiency (EQE) droop, particularly in InGaN quantum well (QW) based LEDs, is pertinent to the application of solid-state lighting for general illumination. It is a very complicated issue that involves from fundamental understanding of the electronic structure of a semiconductor alloy, intrinsic and extrinsic non-radiative recombination in semiconductors, specifically Auger process for the former and defects (both point and extended) for the latter, to device physics related to the complicated heterostructure in the device, and further to the engineering issues such as thermal management and electrical contact. Despite more than one decade intensive study and debate, there is still not yet a generally accepted droop mechanism. The possible droop mechanisms have recently been reviewed by Cho et al.[1] The potential mechanisms proposed in the literature are grouped into three categories: (1) Defect-related mechanisms, (2) Auger recombination, and (3) Electron leakage. Given the large number of variables in the problem and the wide variation in the device quality, it is practically impossible to identify one unique droop mechanism for all the devices reported in the literature. It is worth mentioning that there have been a few reports in the literature showing not only high peak EQEs but also low droop rates, for instance, $\eta_{EQE,max}$ = 54.4% at ~6 A/cm^2 and τ_{EQE} ~ 0.15%/(A cm^{-2}), up to ~ 40A/cm^2 with flat sapphire substrate by Narukawa et al.,[2] and ~53% at ~ 10A/cm^2 and ~ 0.04%/(A cm^{-2}), up to ~ 200A/cm^2 (under pulsed injection) with roughened semi-polar (20-2-1) GaN substrate by Zhao et al.[3] These exceptional high performance devices can be taken as an indication that the efficiency droop is not necessarily associated with any intrinsic loss mechanism, such as Auger recombination. In fact, if Auger recombination were indeed significant, the impact would be larger for such high performance devices, because the carrier concentration is likely to be higher in such devices than in average devices under the same injection current level. In fact, if a droop rate in the order of 0.1% A/cm^2 is readily achievable under the expected DC operation condition up to 100 A/cm^2, the droop rate might not remain as a critical issue. Note that these high performance devices had a small active area of ~ 0.1 mm^2, and used an ITO current spreading layer to achieve uniform current injection. Apparently, the study of the droop mechanism is most needed for and relevant to a category of devices that are most commonly seen and can offer a reasonable good EQE (e.g., > 40% without applying any special light extraction structure, such as using a patterned substrate) but typically exhibit a rapid EQE droop after the efficiency peak. These devices are usually known to show prominent carrier localization effects. We would like to point out a subtle difference between these devices and the high performance devices mentioned above, that is, the peak EQE current tends to be somewhat lower for the former category, usually close to or a little more than 1 A/cm^2. The low peak EQE current has often been suggested as undesirable, which is not necessarily correct. The initial rising portion of the EQE ~ I curve reflects essentially how quickly some inevitable point defects can be saturated, therefore, in general one would like to see a fast rise in the curve. However, for those devices with strong carrier localization, the localization suppresses the effectiveness of the defects, which accelerates the initial rise of the curve. Once the function of the localization is maximized, other material quality and device structure related issues take over, leading to a rapid efficiency droop. Fundamentally, the high performance devices likely have higher material quality, for instance, with lower defect densities. Surprisingly, less detailed and in-depth material research has been found for the materials used for those high performance devices compared to a large body of work for the materials used in less good devices.

Regarding (1) defect-related mechanisms, the interplay of point defects, extended defects, and carrier localization is the primary topics of the discussion. Although carrier localization is not a necessity for having high radiative recombination efficiency, there has been overwhelm evidence supporting that carrier localization, due to either well width or In composition fluctuation, does help to achieve a relatively high peak efficiency by suppressing non-radiative recombination. The underlying physics is straightforward and the general idea has been known and tested in other material systems [4] before it was applied for InGaN.[5] Furthermore, it has been pointed out recently that even at very high injection current, the localization sites continue to yield high radiative recombination efficiency for the carriers trapped to these sites, and it is that the loss of those overfilled thus more mobile carriers leads to the efficiency droop.[6] Therefore, for these devices, the answer lies in that what happens to these more mobile carriers. One could probably agree that point defects most likely affect the efficiency at low current and the maximum efficiency but unlikely cause the droop at high current, because they are relatively easy to be saturated in a decent quality material.[1, 7] How about the role of the extended defects, such as threading dislocations? There is in fact unambiguous evidence that threading edge dislocations do act as effective non-radiative recombination centers.[8] The question would be to what extent they could impact the device performance. One might be impressed or puzzled by that an InGaN QW LED seems to perform well given the fact that it has a relatively high extended defect density in the order of 10^8 cm^{-2} or $1/\mu m^2$. The "good" performance is significantly benefited from the short minority carrier diffusion length due to energy fluctuation in the material.[9] In a 2-D system which is appropriate for the QW, the impact range of a defect under uniform injection can be measured by $\xi(\pi L^2)$, where L is the carrier diffusion length and ξ is a constant depending on the exact nature of the defect.[10] Taking L = 0.1 μm (a reasonable number of InGaN) and $\xi = 1$, the non-radiative recombination loss would be in the order of 3% based on the area ratio and thus negligible. However, with increasing carrier mobility, the impact of such defects can increase rapidly from this qualitative model.

Regarding (2) Auger recombination, its actual effectiveness seems to hinge on the accurate value for the Auger coefficient that is rather difficult to measure and calculate with high accuracy.[1] Given the existence of the above mentioned high performance devices with very weak droop, and that in the devices showing significant localization the droop started at rather low current density (e.g., 1-2 A/cm^2), it is logically difficult to envision that the Auger recombination would play an important role in the droop, because Auger process is supposed to be an intrinsic and high carrier density phenomenon.

Regarding (3) Electron leakage, it lumps a few potentially very difference mechanisms: (i) a poor hole-injection efficiency; (ii) an ineffective electron blocking layer (EBL); (iii) an incomplete capture of electrons by QWs; and (iv) electron escape from the QWs.[1] It was concluded that the asymmetry of a pn junction, specifically the large disparity in carrier concentration and mobility was the primary cause for the droop. We would like to make a few comments on these "leakage" related effects. Firstly, the poor hole injection efficiency might result in disparity between the electron and hole injection rates. However, in steady state, the current is determined by the lower rate of the two, which might reduce the energy efficiency (because of the current being reduced) but does not directly impact the EQE, unless the extra injected electrons meet the holes on the p-type GaN side and recombine there. Therefore, (i) is only effective with the co-existence of (ii) to have an impact on the droop. The effects of (iii) and (iv) are qualitatively the same as (ii). Localization can improve the electron capture at low current injection when the device structure design is not optimized (e.g., the electron blocking barrier is too low), but will not be as helpful to those electrons with higher energies. At the end, a deficient EBL would ultimately be responsible for those within the "electron leakage" category. The electron leakage of (ii) effectively provides a partial short-circuit or "shunt" to the injected current, which should yield an increase in the dI/dV slope at high bias. However, in contrast, usually a softening in the I-V curve has been observed.[11] The softening could be due to a number of possibilities: high injection effect of a p-n junction, the effect of the series resistance that is expected to become more significant at high current, an increased barrier height at one of the hetero-junctions, or enhanced non-radiative recombination.

In short, the extended defects and ineffective electron blocking layer could both be important in the EQE droop. Given the existence of high performance devices with high peak EQE and low droop rate, the efficiency droop is not an effect intrinsic to the material system InGaN.

Spatially resolved study of EQE droop in InGaN QW LEDs

In the literature, the study of the droop effect was typically performed on a macroscopic size device, and thus yielded a spatially averaged effect over regions that may have very different EQE ~ I relationships. The conventional practice in the droop study is to compare devices with selective changes in the device structure, assuming that everything else remains the same. In contrast, the spatially resolved droop study, namely measuring the spatial variation of EQE ~ I relationship in electroluminescence (EL), would allow us to examine primarily the effect of the spatial variation or inhomogeneity of the active layer on the droop in the same device structure (such as substrate, contacts, light extraction efficiency), thus, minimize the potential ambiguity related to the variations in device structure and fabrication that involve a large number of layers and processes. Therefore, a spatially resolved study on the droop effect is expected to provide unique insights into the droop mechanism, and the directions for overcoming it. We have recently performed such study for two LEDs with distinctly different characteristics in spatial inhomogeneity:[6, 12] device A with different macroscopic regions exhibiting different degrees in carrier localization, thus very different droop behaviors; device B with different microscopic regions showing different EL efficiencies but similar overall droop behaviors. In the device A, for the strong localization region, the fast droop was found to occur (at ~ 2A/cm^2) concurrently with the blue shift in the emission peak energy, whereas the weak localization region showed much weaker droop (occurring at ~ 10 A/cm^2) and no blue shift, in fact red shift instead. In the device B, the EQE peaks occurred at similar currents (~ 2A/cm^2) for the bright and dark spots, and both showed blue shift in the emission peak energy. In this work, we perform more study on the device B, focusing on the injection current dependence of the spatial distribution of emission intensity, emission energy and their correlation.

Experiment

The device studied in this work is the device B mentioned above used in a previous publication.[12] It is an InGaN QW LED grown on a c-plane sapphire substrate with 1mm^2 active area and conventional grid electrode. The epilayer has a defect density of ~ 10^8 cm^{-2}. The details of the device structure and fabrication can be found elsewhere.[6, 12] The microscopic EL (μ-EL) spectra were measured using a Horiba LabRAM HR confocal optical system with a 40×/NA = 0.5 UV objective lens. A Keithley 2401 source unit was used as the excitation source. EL driving current varied from 0.1 to 750 mA or 0.01 to 75 A/cm^2, which corresponds to an average injection carrier flux of 6.3×10^{16} – 4.7×10^{20} cm^{-2}s^{-1}. The device had no encapsulation, because of using a short working distance microscope lens. The peak EQE of device is ~ 34%. [6] A nominally same chip was found to yield 44% EQE after encapsulation. Therefore, the devices investigated in this work fall into the category with better than average performance for the devices of similar device structures. Most droop studies have been performed on the devices of this category, and most improvement is needed for them.

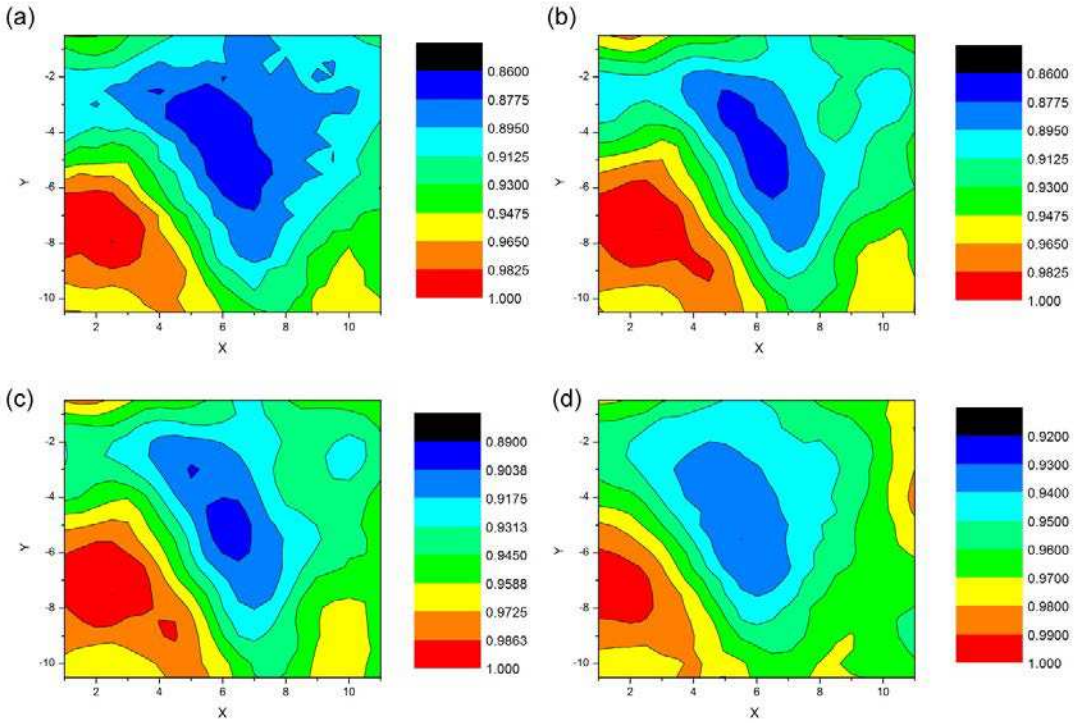

Figure 1. The EL mapping results of an InGaN QW LED at (a) 0.1 mA; (b) 100 mA; (c) 350 mA; and (d) 650 mA.

Results and Discussions

Fig. 1 shows EL mapping data for a 10 µm×10 µm area containing one bright and one dark region at 4 representative current levels: 0.1, 100, 350, and 650 mA. In contrast to the cases involving dislocation type defects where strong quenching in emission intensity is typically observed at the defect site with an impact range in the order of the diffusion length,[7, 8] here the intensity variation between the bright and dark sites is fairly small, only approximately 20%, and the impact range is much larger than the expected diffusion length in this type of material (e.g., 200nm or smaller).[8, 9] Therefore, the dark region is not very likely to be associated with an isolated dislocation type defect but a region of small well width, and the bright region is likely a region of large well width, although one cannot exclude the possibility of In composition fluctuation. A correlated structural characterization is apparently much needed. Interestingly, we find that the sizes of the dark and bright regions vary with the current. With increasing current till about 350 mA, the bright site expands and the dark site shrinks, which can be qualitatively understood as that added carriers continuously fill the potential well of the bright site and invade the potential barrier of the dark site. In the meantime, with increasing carrier density, the carrier diffusion length might also increase to some extent, which also contributes to the size changes. More interestingly, after 350 mA, both bright and dark region expand more rapidly, compared to the initial slower rates of size change. These observations can be more clearly seen in Fig. 2(a) that shows the effective widths of the bright and dark region. The effective width W_{eff} is defined through $\Delta I = W_{eff}^2 \times \delta I_{max}$, where δI_{max} is the intensity gain or loss at the center of the region with respect to the general area, and ΔI is the integrated intensity change over the “whole” area of the bright or dark region. For the bright region, the mapping data were incomplete, so only a partial area was used. These data are only meant to offer some qualitatively insight to the evolution. Fig 2(b) depicts the peak energy shifts for the central spots of the two regions. Both regions show a fairly large blue shift and almost in parallel, and as expected, throughout the whole current range, the peak energy of the dark spot is somewhat higher than that of the bright spot. The red shifts observed at the highest current levels (> 500 mA) are likely due to junction heating.[6, 12] It appears that they are both relatively large regions of a few µm in size with finer scale internal energy fluctuations. The accelerated size expansion at high current, shown in Fig. 2(a), might reflect increased carrier diffusion within each region, which could potentially lead to more non-radiative loss. In Fig. 2(b), the EQE ~ I curves are included to compare with the blue shifts in peak energy. The onset of the droop appears to roughly correlate with the blue shift.

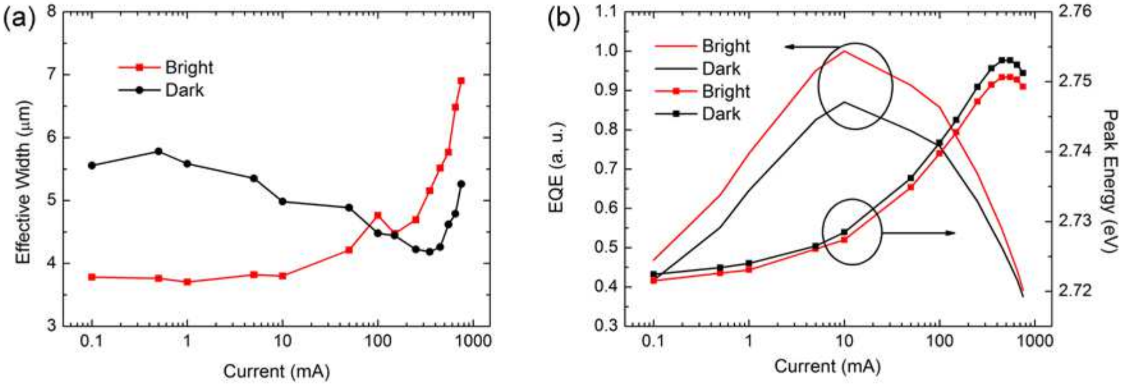

Figure 2. (a) The effective width of the bright and dark regions in Fig. 1 with varying current. (b) Comparison of EQE with blue shift in peak energy for the bright or dark spot at the center of the bright or dark region.

Fig. 3 depicts the emission intensity vs. peak energy for all the pixels of the spatial mapping data at different currents. At the lowest current of 0.1 mA, there is hardly any correlation between the emission intensity and peak energy. However, with increasing current, the anti-correlation between the emission intensity and peak energy gradually became apparent, and the intensity variation also reduced. The observed evolution is associated with the variation of the carrier mobility. At the lowest current, because the injected carriers preferentially went to the local energy minimums in the vicinity of the injection site and the presence of vacant point defect states, leading to very low carrier mobility or diffusion length, the carriers were not mobile enough to seek “global” energy minimums. With increasing current, those local energy traps were gradually filled and the point defects also saturated, the carrier mobility is increased, which eventually results in the well-defined anti-correlation at high current. There is also a general correlation between the enhancement in the carrier mobility – the establishment of the anti-correlation in Fig. 3 – and the EQE droop. Understandably, the mobile carriers are more susceptible to the extended defects. Unfortunately, this study alone could not determine if the failure of the electron blocking layer also occurs at the same current level.

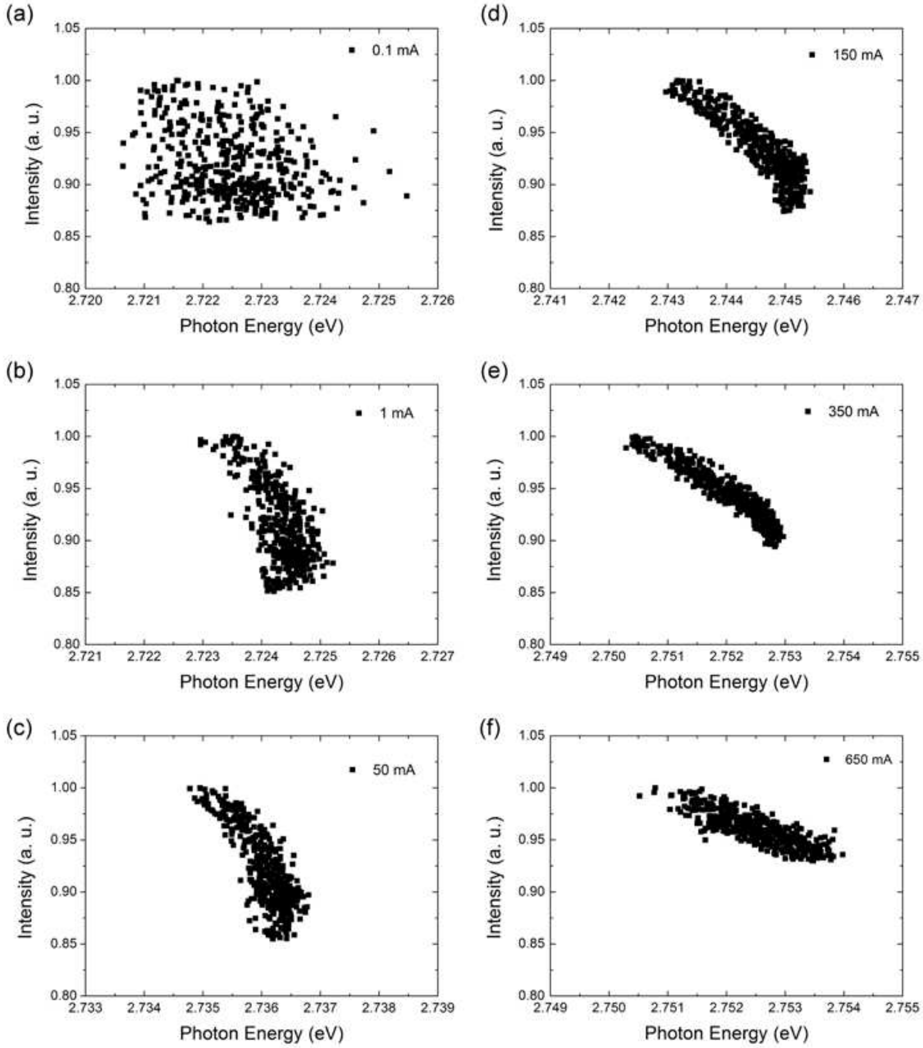

Figure 3. The peak intensity vs peak energy for all the pixels in EL mapping. (a) 0.1 mA; (b) 1 mA; (c) 50 mA; (d) 150 mA; (e) 350 mA; and (f) 650 mA. The horizontal ranges are the same (6 meV) for all the panels.

Conclusions

Spatially resolved EL study has revealed two different scales of inhomogeneity in InGaN QW LEDs. In the scale below the spatial resolution of the optical diffraction limit (typically of a few hundred nm), the local energy fluctuations in conjunction with the point defects leads to the very low carrier mobility or diffusion length. This scale of energy fluctuations may suppress the non-radiative recombination and improve the radiative recombination efficiency. A larger scale energy fluctuation occurs in the scale comparable or above the spatial resolution of the optical diffraction limit, leading to bright and dark regions of a few microns in size in the LED studied in this work. The variation of the EL spatial distribution suggests that the carrier mobility changes significantly with current. The efficiency droop is found to occur concurrently with the delocalization of the carriers. The loss of the delocalized carriers could be through non-radiative recombination of extended defects, but the failure of the electron blocking layer could incidentally occur in the same current level. The partition between the two mechanisms required further investigation.

Acknowledgments

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