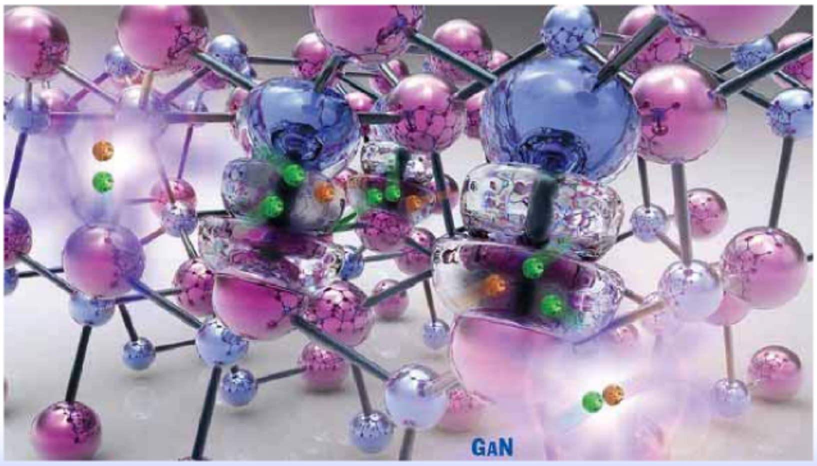
GaN基发光二极管Droop现象研究的一点体会

陆海

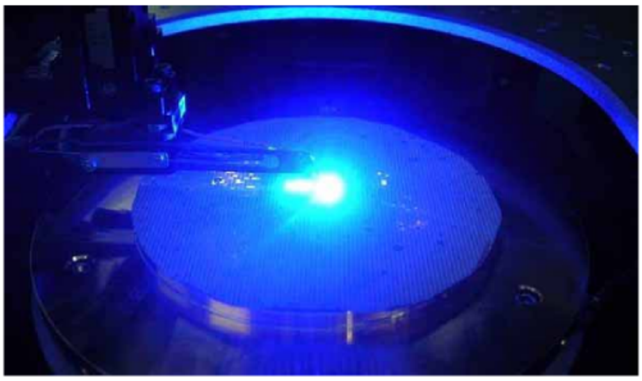
南京大学电子科学与工程学院



2011年8月11日

Outline

- Leading explanations for efficiency droop
- Problems found in past efficiency droop study
- Droop behavior in reliability study

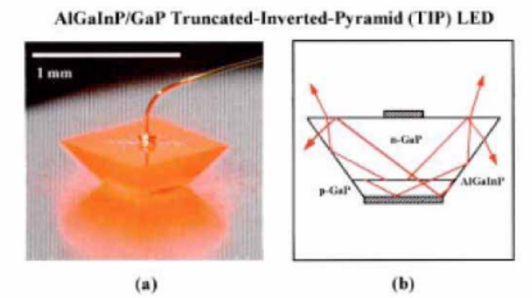


Why is "droop" so important? → Cost

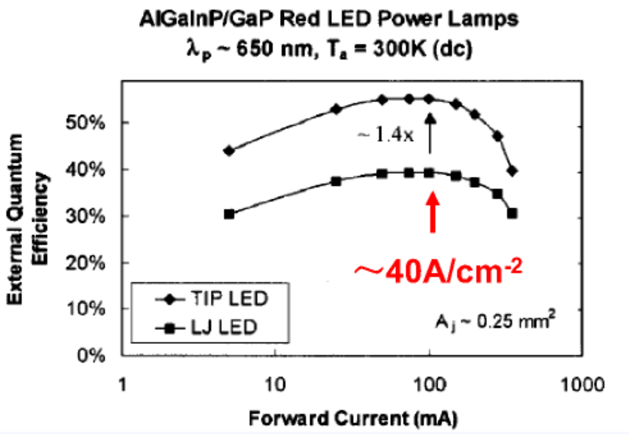
Is droop a high current phenomenon? Yes or No !

Peak IQE of GaN-based LEDs normally occurs at relatively low current densities < 10 A/cm^2.

If compared to:



Lumileds, APL 75, 2365 (1999)



Droop effect occurs not only in blue LEDs, but also in green and UV LEDs.

Leading explanations for efficiency droop

What Causes Droop?

- Simple answer: **We don't know yet**
- Several competing theories/explanations

1) Electron overflow at high current densities due to inadequate electrical confinement or polarization fields (UCSB, RPI, and others)

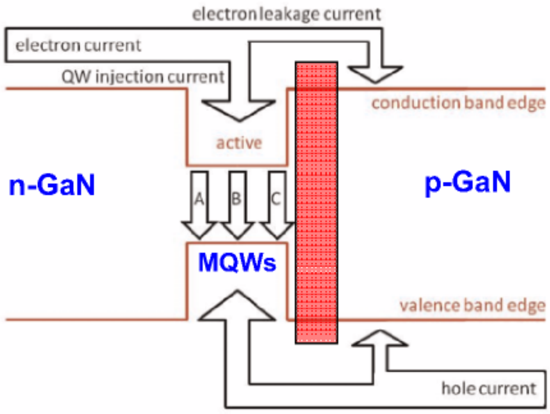
2) Auger recombination due to high carrier density, direct or defect-assisted (Lumileds and others)

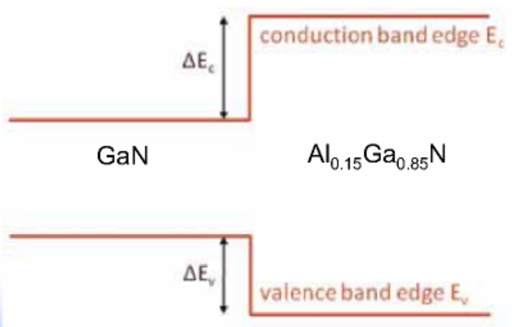
3) Poor hole transport in MQWs (Virginia Commonwealth Univ.)

4) Carrier overflow from localized states, that is, defect-related (West Virginia Univ.)

(1) Electron overflow

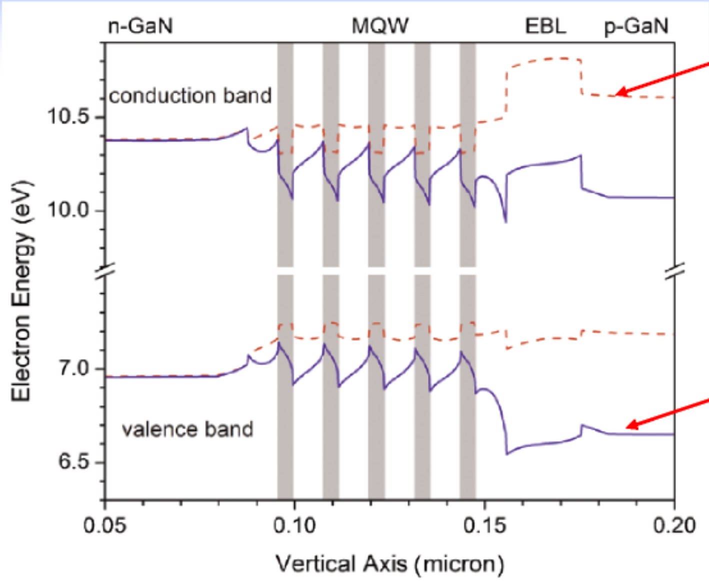
It is expected that the electron blocking layer (EBL) is unable to completely stop flow of electrons beyond the MQWs at high injection current levels, leading to strong non-radiative recombinations in the p-GaN layer.





However, a high band offset ratio of $\Delta Ec/\Delta Ev$ = 70:30 is usually assumed between GaN and AlN, then earlier numerical LED simulations did not show an efficiency droop despite the inclusion of electron leakage current.

南京大学　陆海 (hailu@nju.edu.cn)



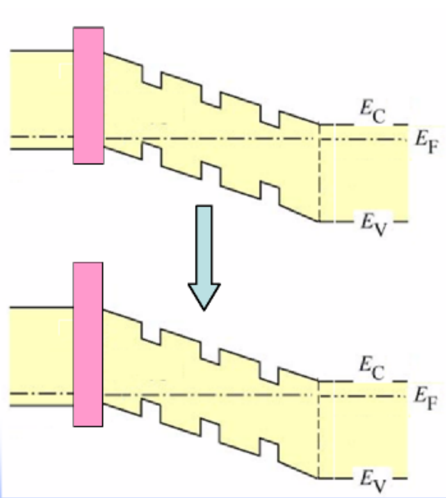
One of the possible reasons for electron leakage is **the energy barrier reduction by built-in nitride polarization**. That is, with the typical Ga-polar growth of nitride LEDs, the polarization charges at the MQW-EBL interface are positive, which leads to electron accumulation at this interface and strong negative band bending.

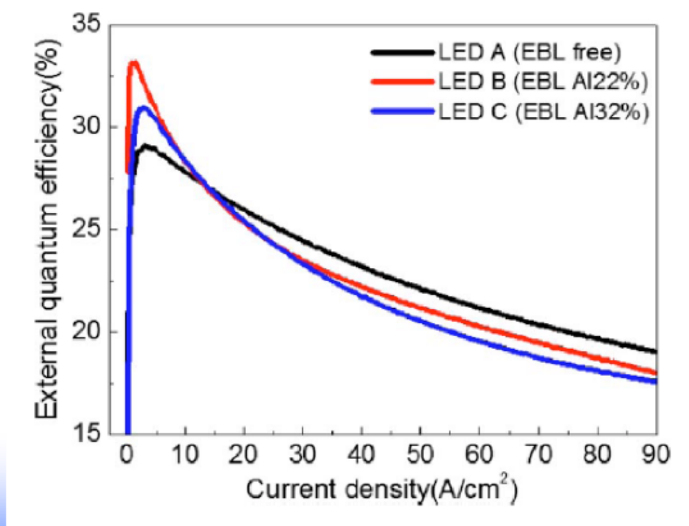
Ways to enhance the electron confinement

1. EBL layer with higher Al content

Seems not successful, however, one should remember that higher Al content in EBL also adds more polarization.

(Samsung, APL 94, 231123, 2009)

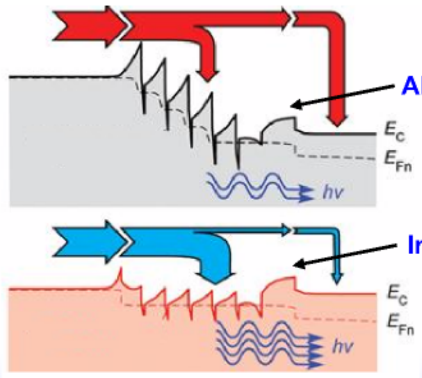


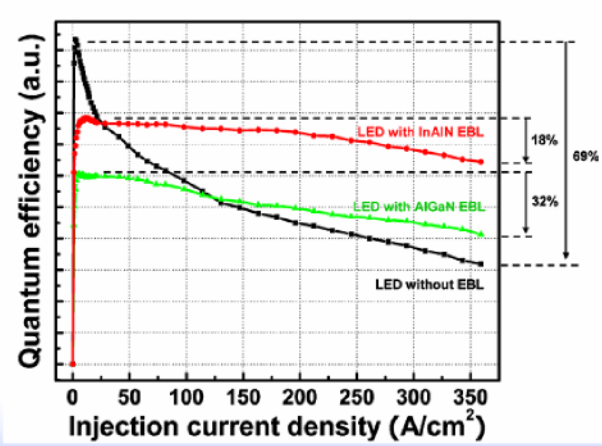


2. Polarization engineering

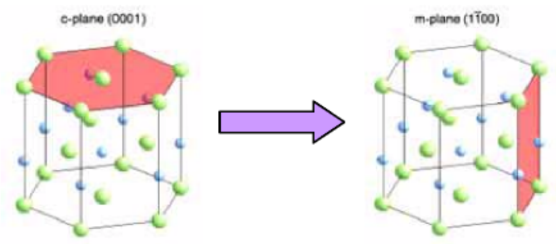
Several layer sequence combinations have been tried, such as InAlN EBL (GIT, APL 96, 221105, 2010), GaInN/AlGaInN MQWs (RPI, APL 93, 041102, 2008), GaInN/GaInN MQWs (RPI, APL 94, 011113, 2009)

The approach seems effective. People can see improvements.

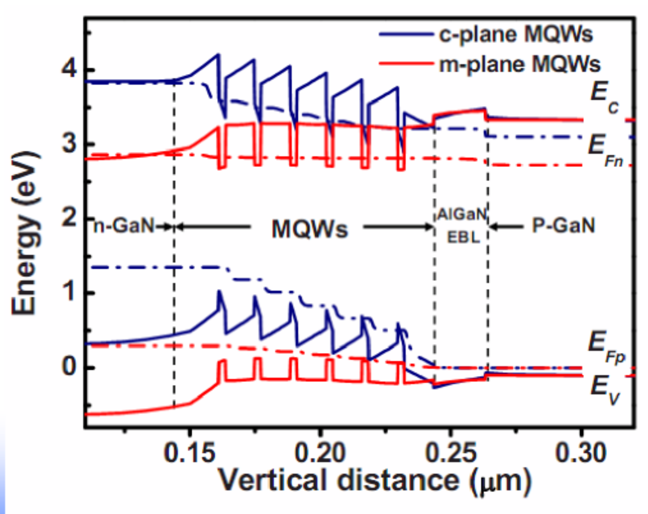




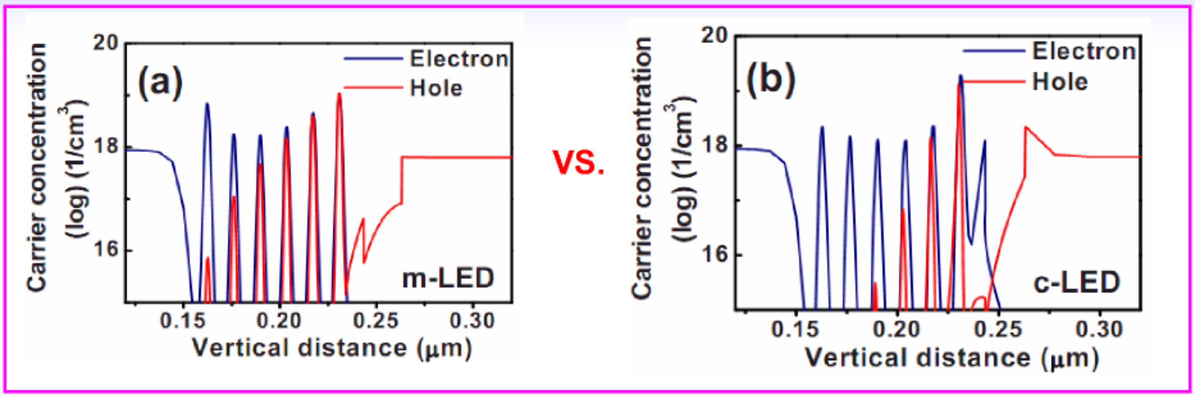
3. Non-polar LED approach

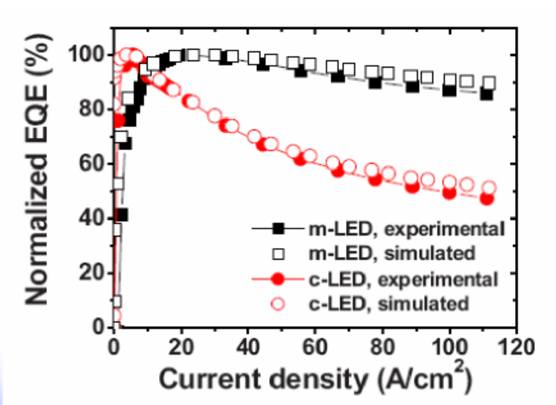


By fabricating LEDs on non-polar GaN plane to completely eliminate polarization-induced EBL lowering.



Simulation of carrier distribution in the MQWs



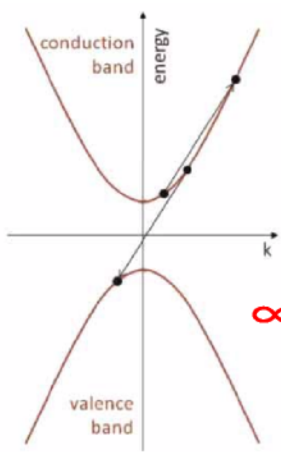


However, UCSB group reported that m-plane GaN LEDs also such suffer from strong droop. (J. Phys. D 41, 082001, 2008)

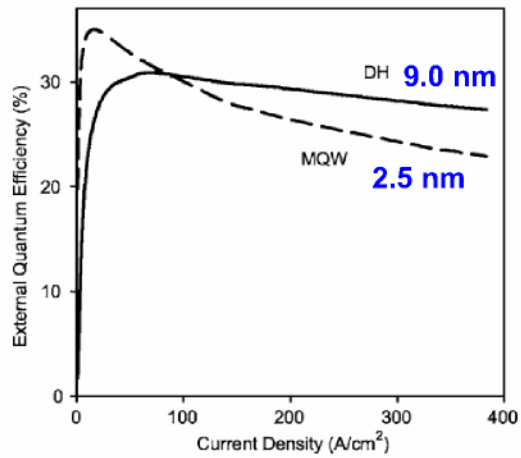
NCTU APL 96, 231101, 2010

(2) Auger recombination

Non-radiative electron–hole recombination processes transfer the excess electron energy to other particles. In case of Auger recombination, these other particles are electrons or holes that are excited into higher energy levels within the same band.

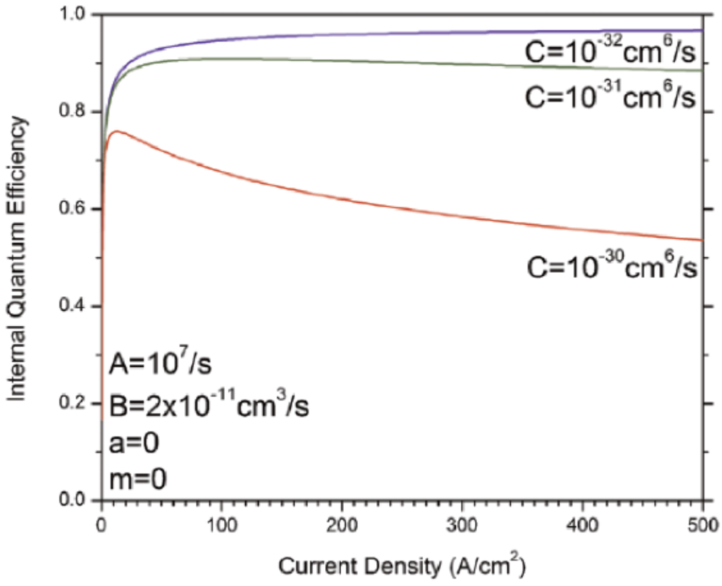


$\propto Cn^3$



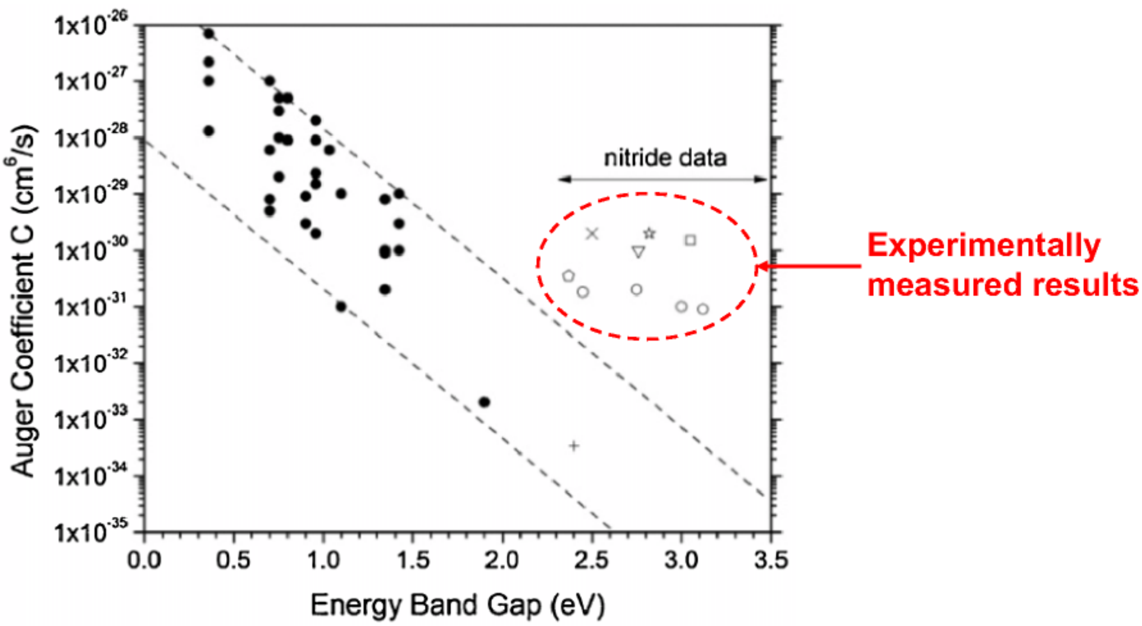
The hypnosis was firstly suggested by scientists in Phillips Lumileds and has been popular since then. APL 91, 141101; 91, 243506, 2007

The magnitude of the Auger coefficient of GaN is the key !

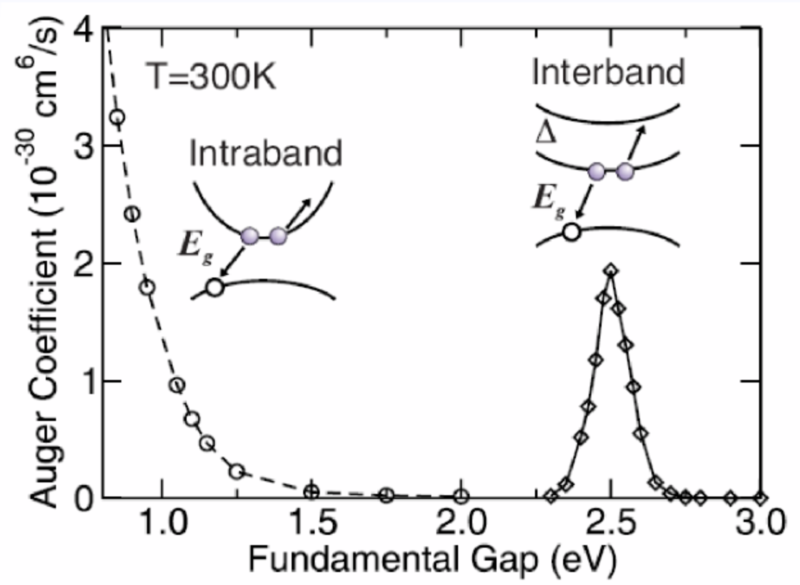


Simple rate equation analysis indicates that only Auger parameters of 10^{-31} cm^6 s^{-1} or higher could cause significant efficiency droop.

Auger process decreases strongly with increasing energy band gap and it is generally considered negligible in wide-gap materials.



Eq. direct measurement of Auger recombination in $In_{0.1}Ga_{0.9}N$/GaN quantum wells by using large signal modulation method. 1.5e-30 cm^6s^{-1} is determined for the Auger coefficient at RT. (UMich APL 95, 201108, 2009)

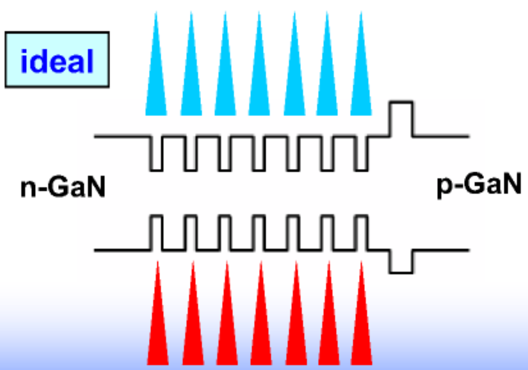


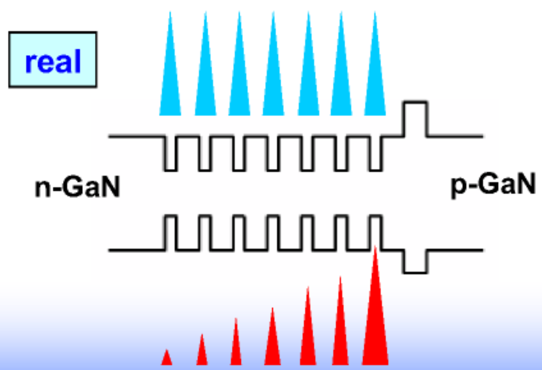
Theoretical analysis suggests defect-assisted Auger or interband Auger process could be the reason. (eq. First principle calculation by UCSB, APL 94, 191109, 2009) Sounds interesting ?!

(3) Poor hole transport

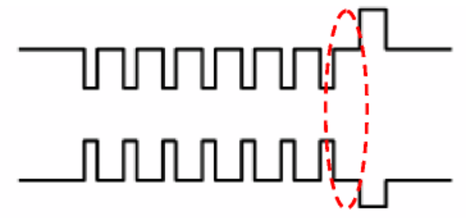
Two phenomena — escape of electrons form the active region and reduced hole injection — are components of any carrier leakage explanation for droop. However, it is not clear which is cause and which is effect; both have been proposed.

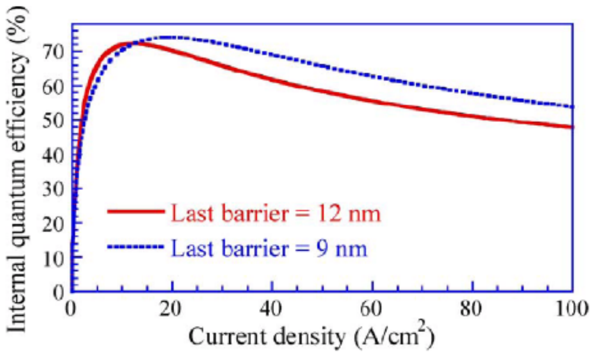
Poor hole transport and injection through the barrier due to large hole effective mass, low hole concentration, or the EBL also acting as a potential barrier for holes may lead to serious electron leakage without contributing to radiative recombinations.



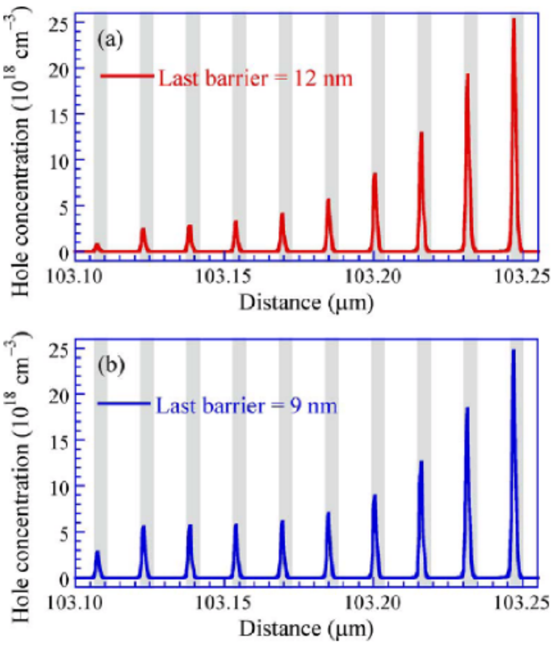


Reducing the last GaN barrier thickness within the MQWs to promote hole transport.



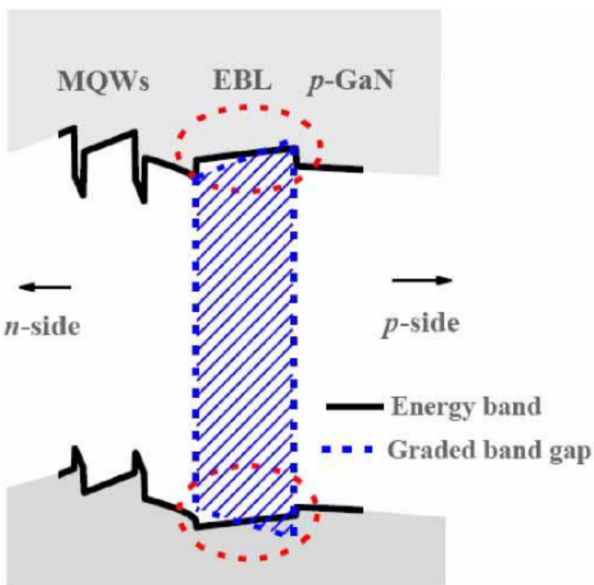


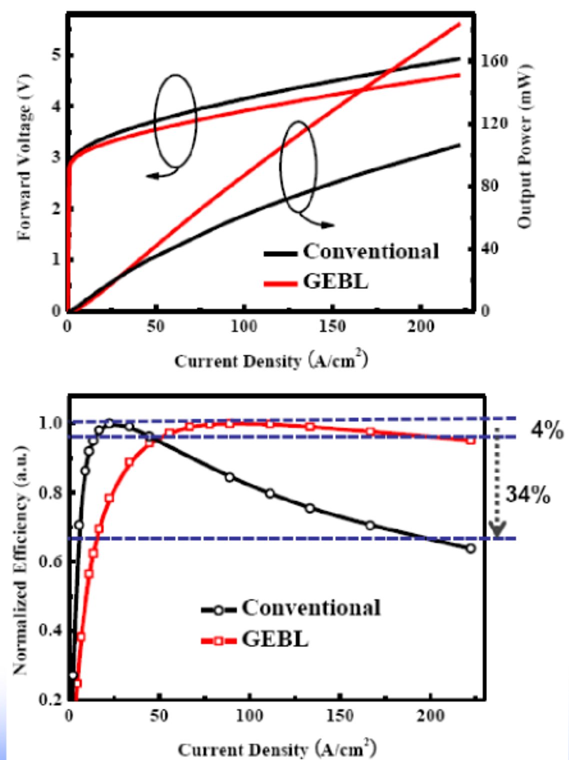
2/12 nm MQWs + 10 nm EBL



Epistar PTL 22, 1787, 2010

EBL engineering to promote hole transport

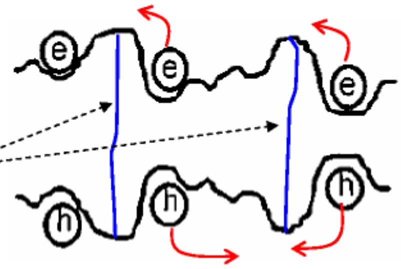




Graded-composition EBL

NCTU APL 97, 261103 (2010)

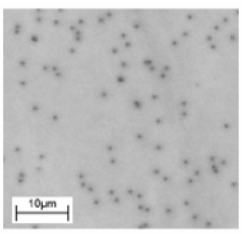
(4) Density-activated defect recombination



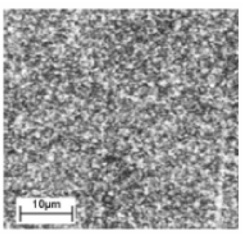
Indium-rich clusters are associated with a lower bandgap and therefore lead to carrier localization. At low current and low QW carrier density, indium-clusters then keep carriers away from structural defects that serve as SRH recombination centers. With higher current, more carriers accumulate inside the QWs so that the indium-clusters fill up. Carriers spill over into QW regions with lower indium concentration and increasingly recombine non-radiatively at defects, leading to a SRH lifetime reduction.

If the defect-assisted picture is correct, GaN LEDs with reduced dislocation density within the MQWs should have less droop.

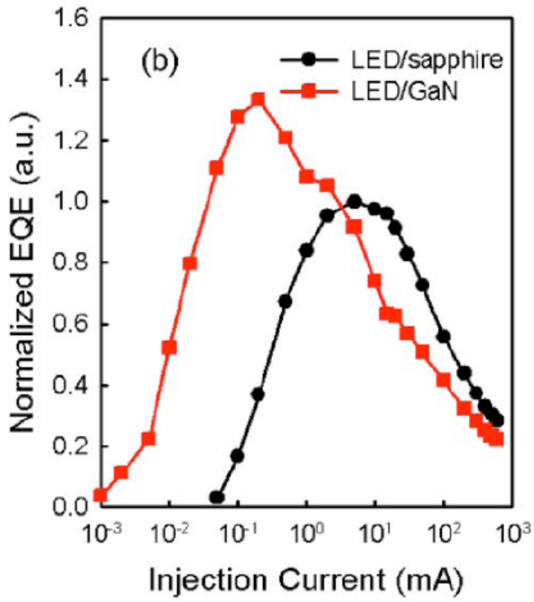
However, experimentally GaN LEDs made on bulk GaN substrate still suffer from strong droop.



GaN homoepilayer



GaN on sapphire



WVU, APL 94, 041117, 2009

南京大学　陆海 (hailu@nju.edu.cn)

Problems found in past efficiency droop study

We still don't know what causes droop yet !

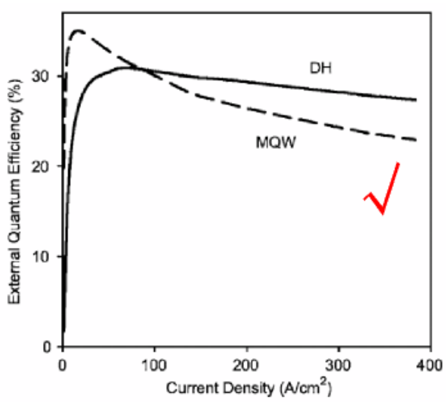
The problem itself:

Droop is quite complex. Multiple mechanisms might be involved simultaneously.

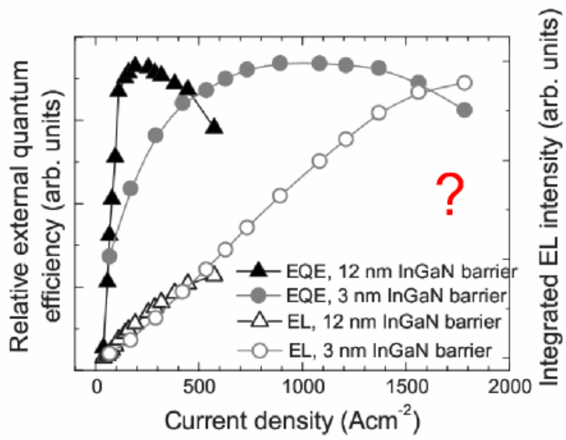
The problem of scientists themselves……

(1) Normalized/relative EQE instead of absolute EQE is frequently used

Droop normally happens at quite low current density in 1-20 A/cm² range. However, in some past studies, peak-efficiency-currents up to 100-200 A/cm², or even 1000-2000 A/cm², were reported and sometimes claimed as an achievement. Do these results all make sense?

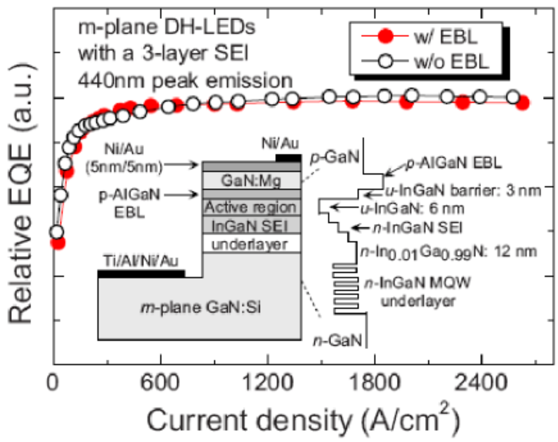


Lumileds, APL 91, 243506, 2007

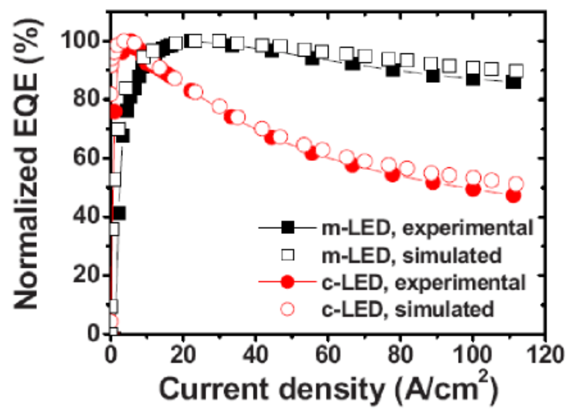


VCU, APL, 93, 171113, 2008

More examples

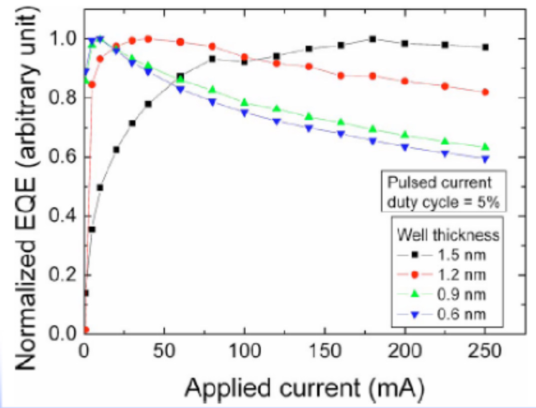


VCU, APL 97, 131110, 2010



NCTU APL 96, 231101, 2010

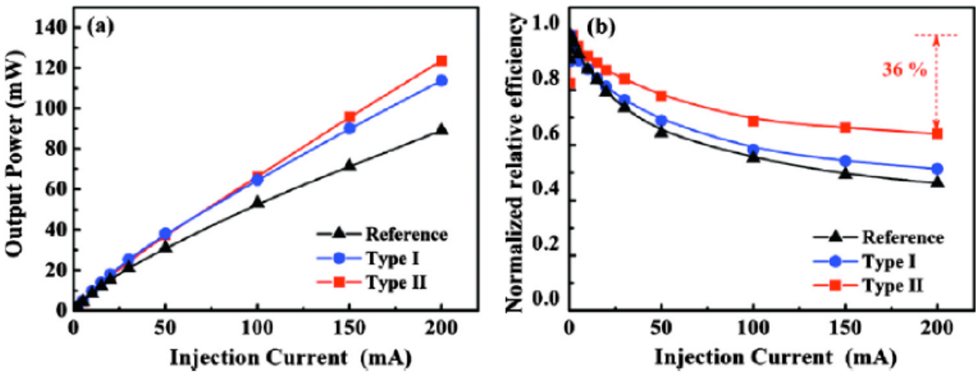
At present, the normal working current density of power LED chips is only about 35 A/cm².



NTU APL 91, 181113, 2010

南京大学　陆海 (hailu@nju.edu.cn)

How to fairly compare your data?



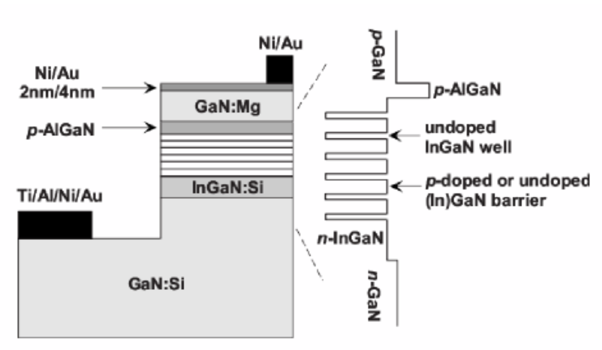
NCTU APL 97, 251114 (2010)

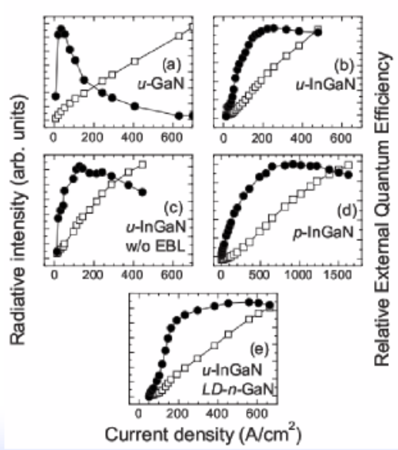
Besides absolute power and peak efficiency current, how much efficiency remains at high currents compared with peak efficiency is also a very helpful performance parameter.

南京大学　陆海 (hailu@nju.edu.cn)

(2) Sample variations between labs or even within one experimental study

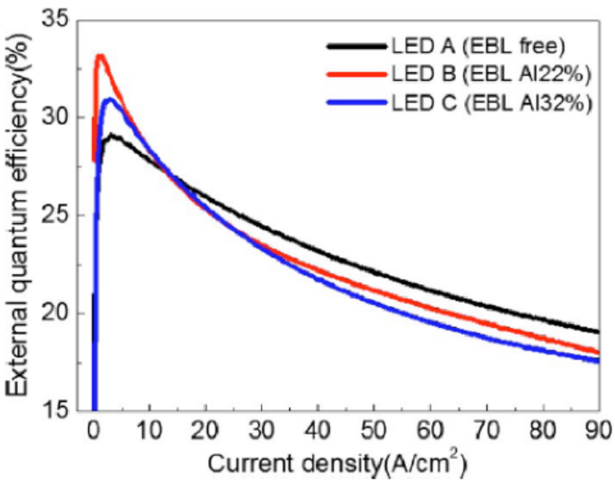
When well-thickness, doping level, layer sequence, polar orientation and etc. vary, other structural parameters, especially material quality, may also change ! The change in efficiency and peak-efficiency-current can be caused by unexpected side effects.





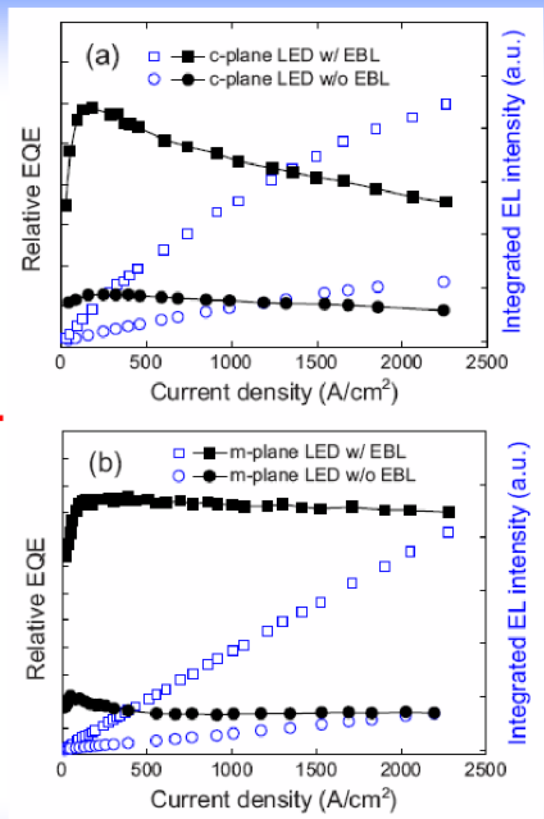
VCU, APL, 93, 121107, 2008

What's the effect of the EBL layer?



Samsung, APL 94, 231123, 2009

VS.

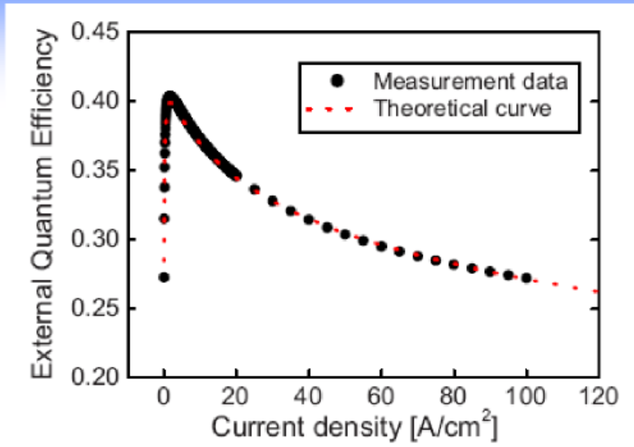


VCU, APL 95, 201113, 2009

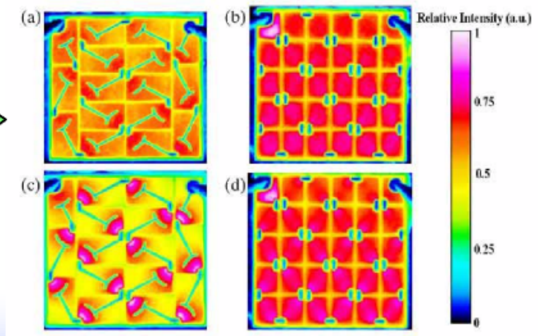
(3) Unreliable fitting

Questions:

1. **Each leading explanation could cause droop. It is easy to get a droop-shape curve. There are just too many parameters involved.**
2. **Some mechanisms have no mature analytical expression yet. There are just so many unknowns in the epi-structure. Carriers are not evenly distributed laterally as well as vertically.**
3. **Are you sure you get the right curve with precise details? (thermal droop excluded?)**



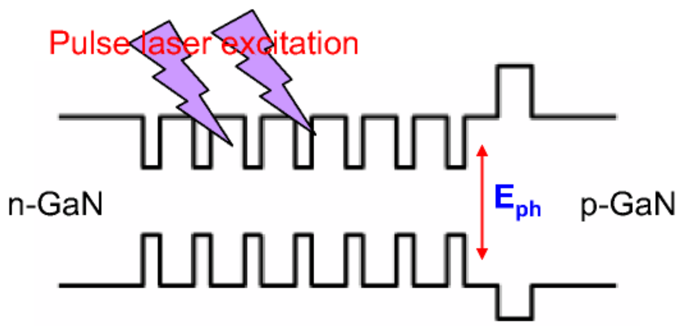
Korea group, APL 95, 081114 (2009)



NCTU, IEEE EDL 32, 1098 (2011)

(4) Variations in testing methods

A good example: efficiency droop in PL analysis

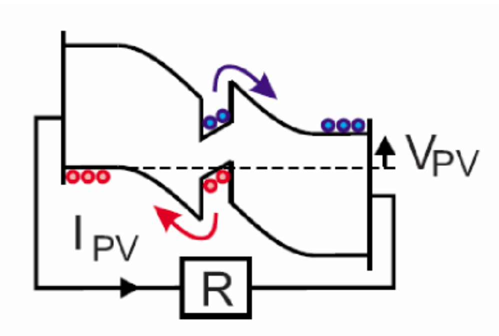


$E_{InGaN} < E_{ph} < E_{GaN}$

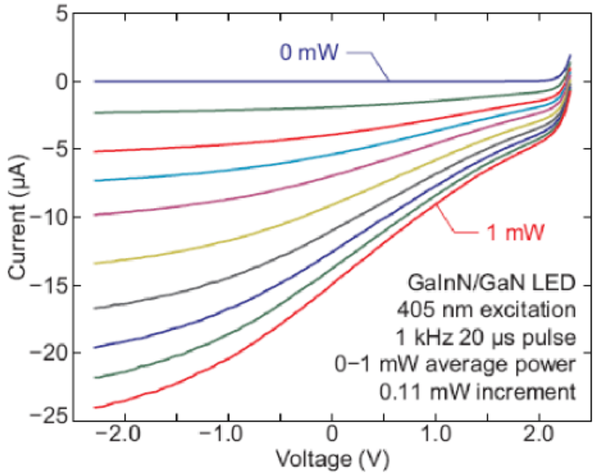
Since all photo-carriers are purposed to stay and recombine within the MQWs, the oginal idea is:

- **If there is no droop, droop is carrier transport related, like electron overflow;**
- **If there is droop, droop is caused by process occuring within the MQWs, like Auger.**

Recent study suggests that the PL analysis method itself might be problematic.



PV effect is observed !

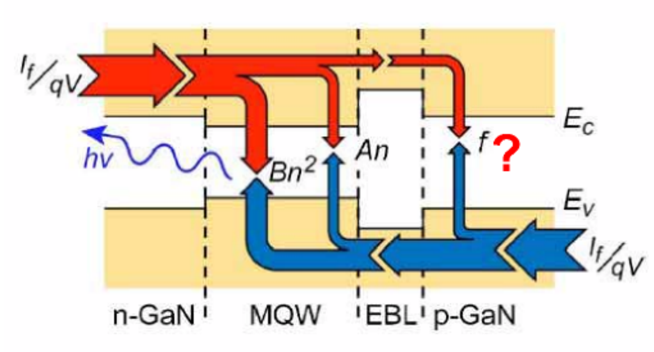


RPI APL 94, 081114, 2009

Droop behavior in reliability study

The effect of non-radiative recombinations on the onset point of efficiency droop

A basic rate equation



$$\mathrm{EQE} = \eta_e \mathrm{IQE} = \eta_e \frac{Bn^2}{An + Bn^2 + f(n)},$$

RPI APL 91, 231114, 2007

The injected current I_{inj} (=I_R+I_{NR}) is consumed by monomolecular non-radiative recombinations *An*, bimolecular radiative recombinations *Bn²*, and an additional carrier loss mechanism *f(n)~Cnᵐ* (m>2) approximated by neglecting even higher order effect.

Here the additional carrier loss mechanism *f(n)* is considered to be the cause of efficiency droop and is only important at high currents.

The effect of An to the onset point of droop

$$\eta_{IQE} = \frac{I_R}{I} = \frac{I_{inj}}{I}\frac{I_R}{I_R + I_{NR}} \approx \frac{Bn^2}{An + Bn^2 + Cn^m}$$ **at high currents**

With increasing injection current I_{inj}, the injection efficiency η_{inj} should quickly approach to unity, as leakage current I_L is much smaller than diffusion-recombination current when the LED is about to turn on.

Then efficiency droop should start to occur at the current density when

$$\partial \eta_{IQE} / \partial n = 0$$

Here we derive:

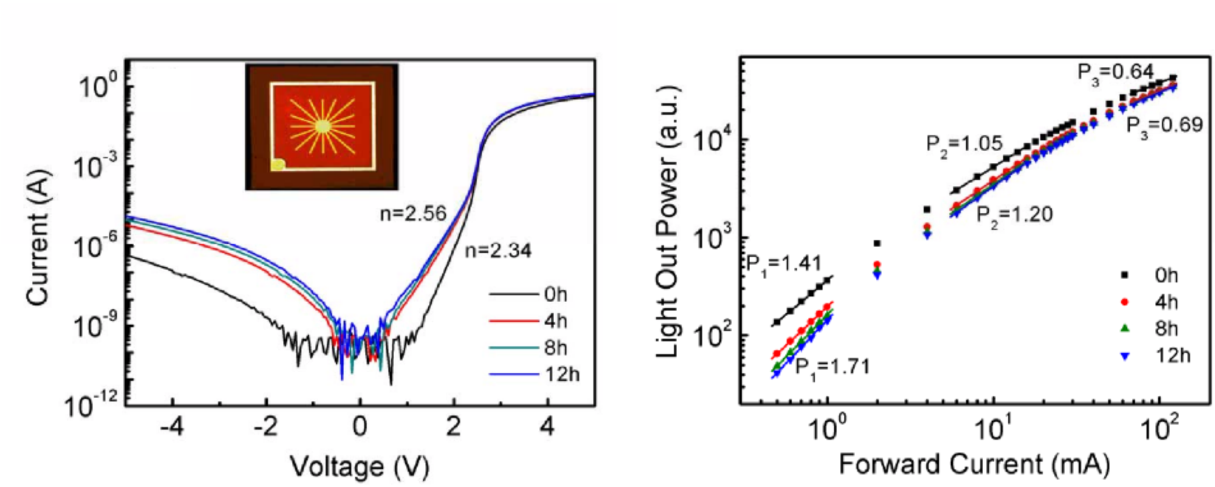
$$I_{peak} \propto n_{peak} = \left[\frac{A}{C(m-2)}\right]^{\frac{1}{m-1}}$$

Two reasons to study droop behaviors of aged LEDs

1. Since the reliability issue of LED chips is inherently an efficiency problem, the physics underlying efficiency droop and long-term efficiency decay could be highly related.

2. Aging process is a feasible way to prepare series of GaN LED samples with essentially same layer structure and distribution of localized states but with different defect densities. Many nitride researchers within the LED community start to believe that sample variations are root cause of the differences in opinion over the origin of efficiency droop.

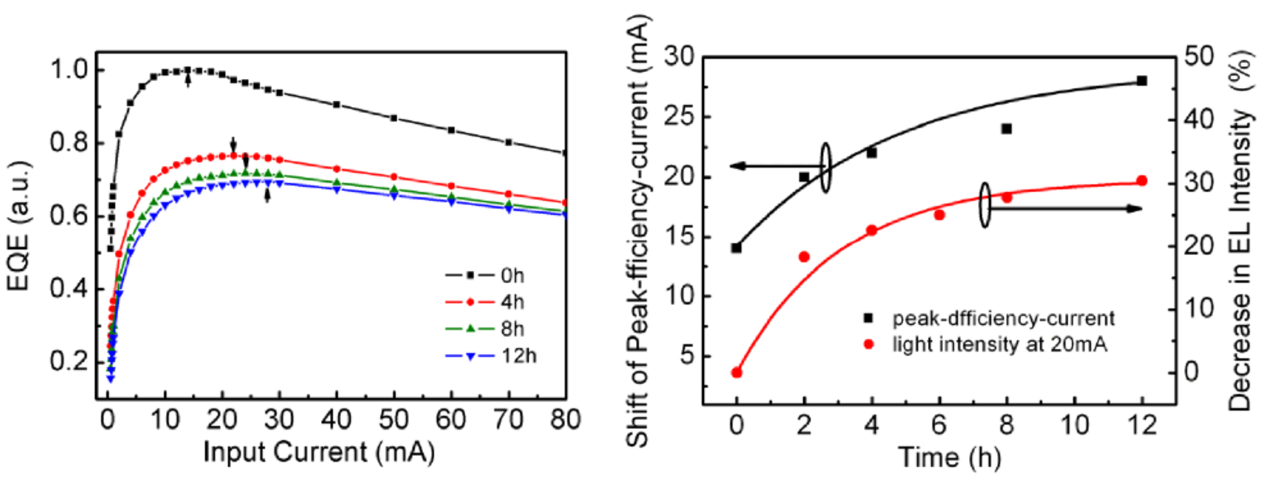
DC stress (RT, 60 A/cm^2)



DC stress can not only induce new parasitic leakage path throughout the epi-structure but also create new non-radiative recombination centers in the active region of the LEDs.

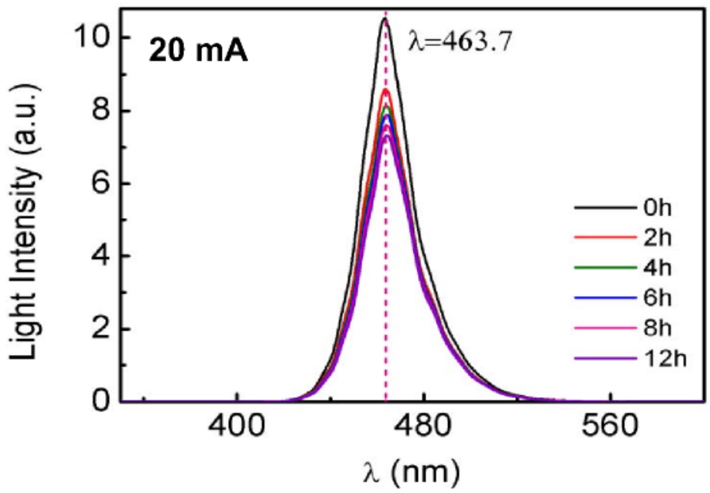
南京大学　陆海 (hailu@nju.edu.cn)

DC stress induced droop change



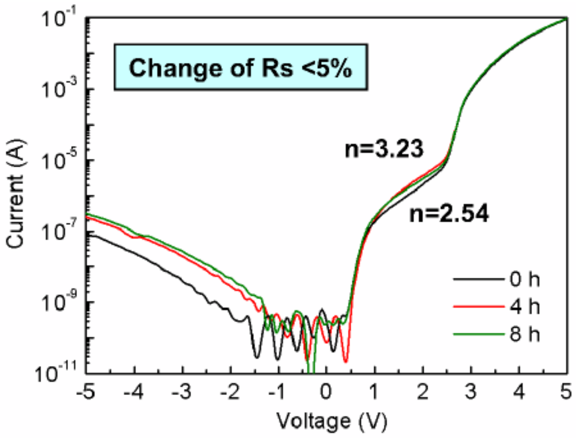
With increasing stress time, the overall quantum efficiency of the aged LEDs drops while the peak-efficiency-current shifts towards higher magnitude. The shift of peak-efficiency-current follows the same trend as the degree of luminescence decay.

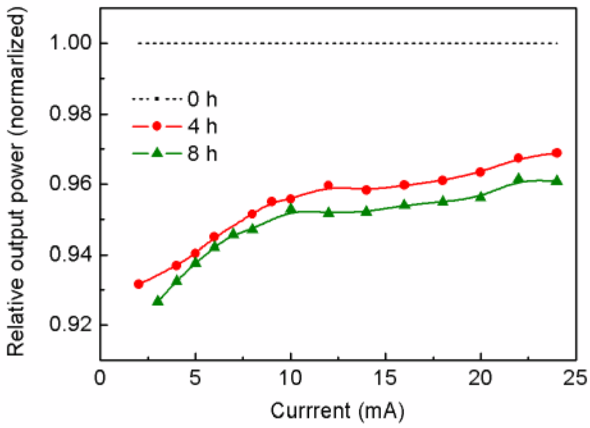
Evolution of EL spectra



The negligible change of EL peak wavelengths and their FWHMs indicates that the carrier filling status and the energy distribution of radiative recombinations in localized states should have very small change as well. Thus, the up-shift of efficiency roll-off point should not be caused by microscopic changes in layer structure or In-content redistribution within MQWs.

Reverse current stress (RT, -0.2 A/cm²)

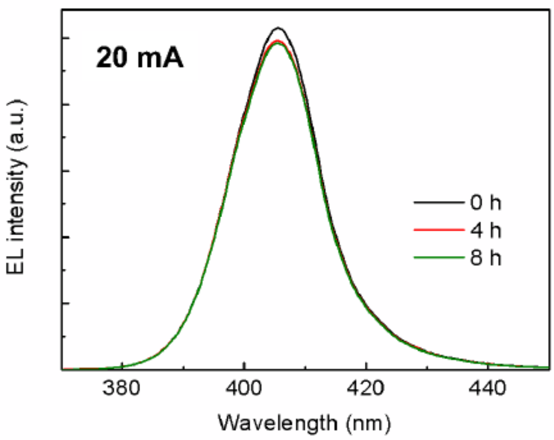


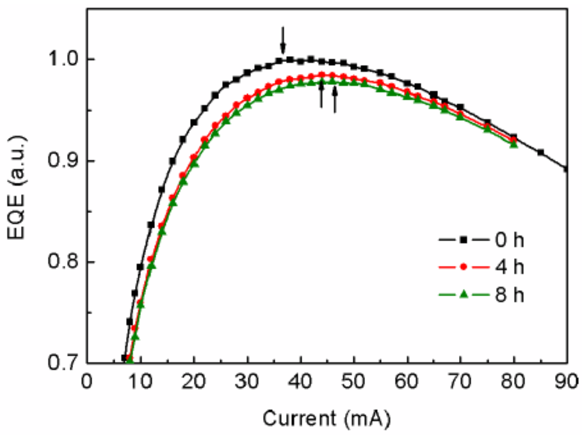


The effect of reverse current stress is quite similar to that of DC stress.

The non-radiative recombination centers generated within the InGaN/GaN MQWs can reduce the internal quantum efficiency of the LEDs, particularly at low current levels. While, at high currents, the non-radiative recombination paths can saturate, and their effect on overall light output is limited.

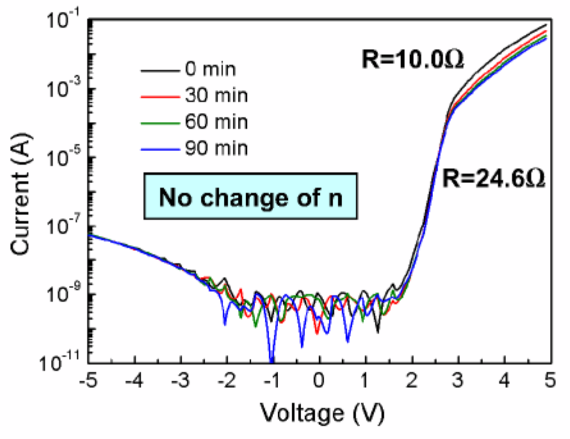
Reverse current stress induced droop change

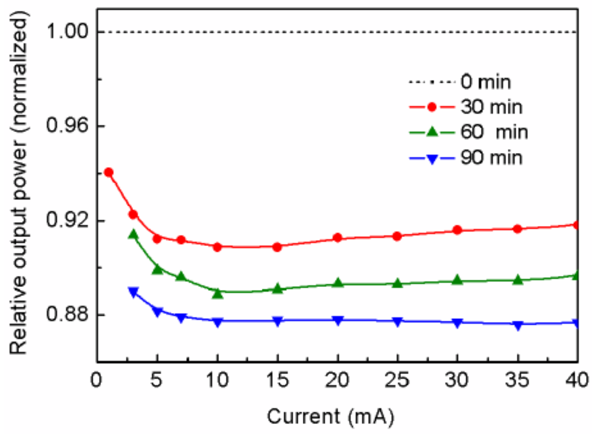




The up-shift of peak-efficiency-current upon reverse current stress can be explained by the same rate-equation model introduced in the study of DC stress. There should be no temperature effect at such a low current.

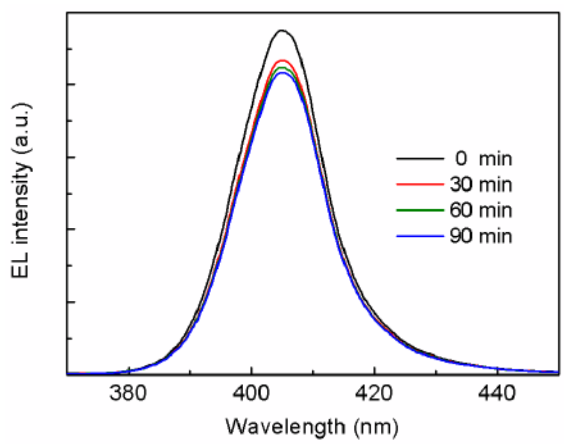
High temperature stress (220^{o}C storage)

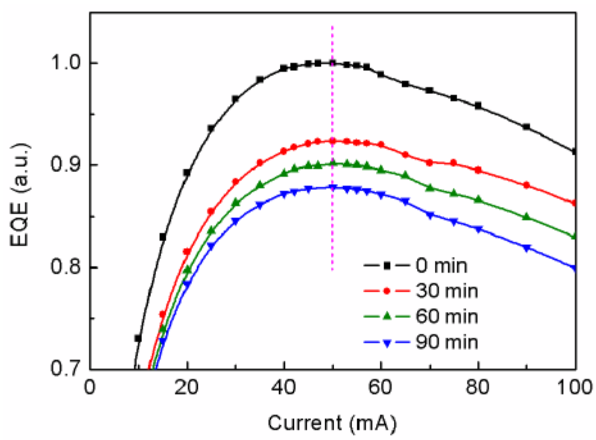




The increase of series resistance is mostly correlated to the OP decrease and to the enhanced influence of the so-called current and emission crowding, which is less severe at low input currents for a given device.

High temperature stress induced droop change





Based on the same rate-equation model introduced in the analysis of reverse-current stress, it is expected that there should be no shift of peak-efficiency-current for the GaN-based LEDs upon the high-temperature stress.

We still don't know what causes droop yet, but a common observation is…