大功率GaN基发光二极管Droop现象中的科学问题

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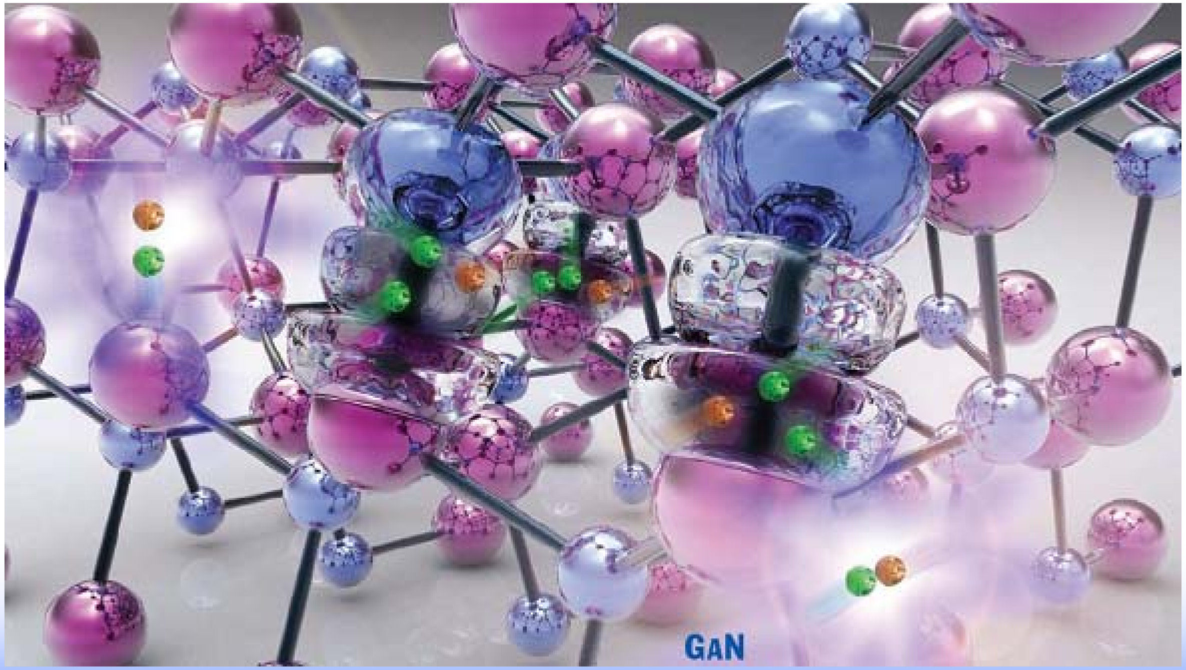
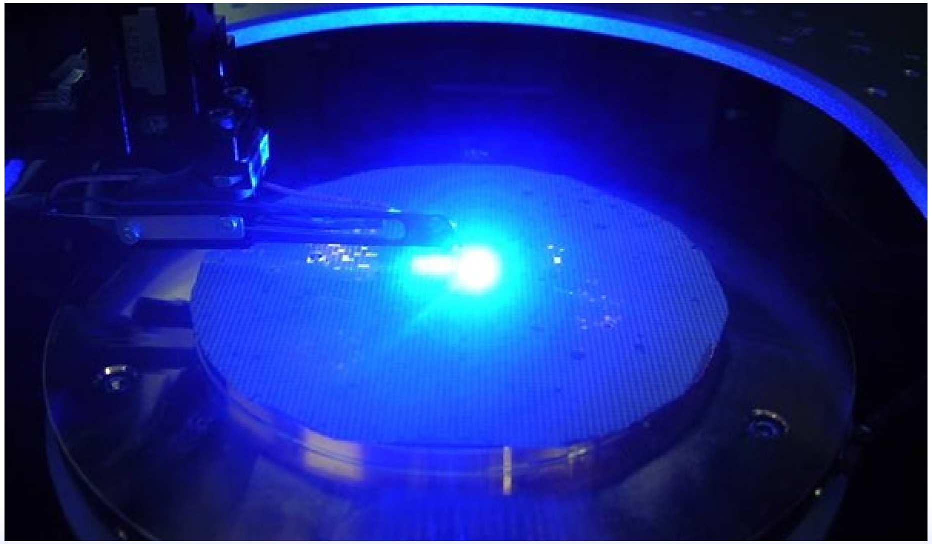


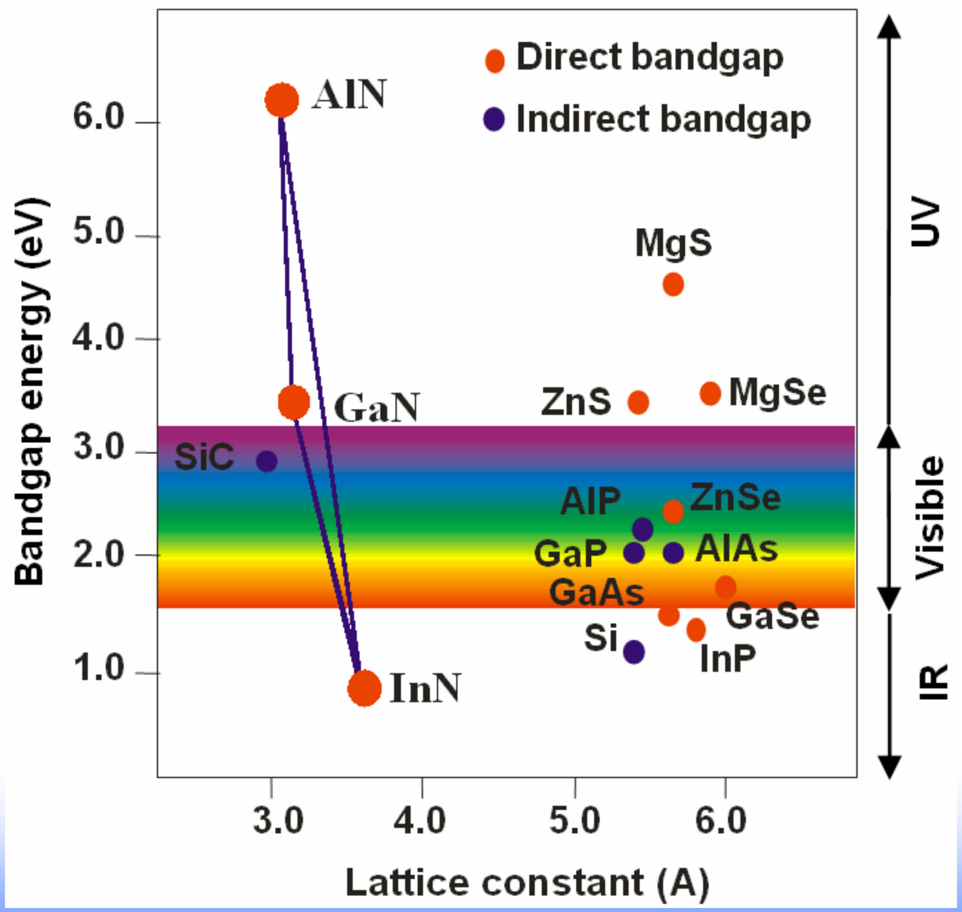
Outline

- III-nitride basics
- Some unique properties of GaN-based LEDs
- Leading explanations for efficiency droop
- Summary

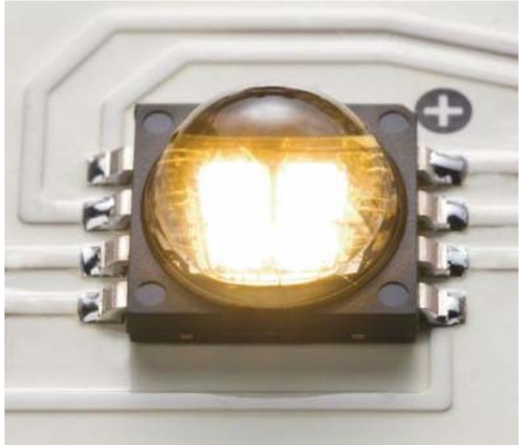


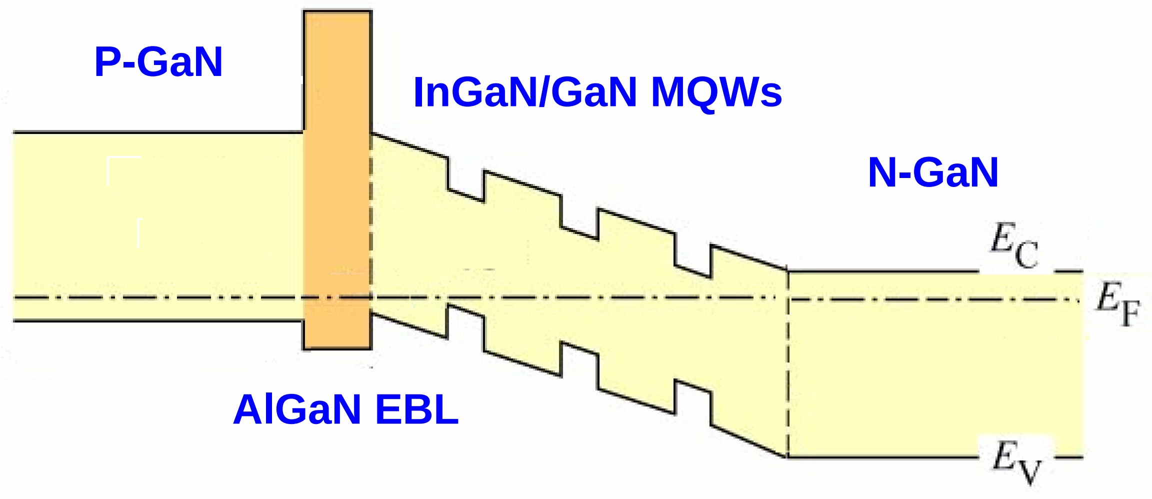
宽禁带III族氮化物半导体

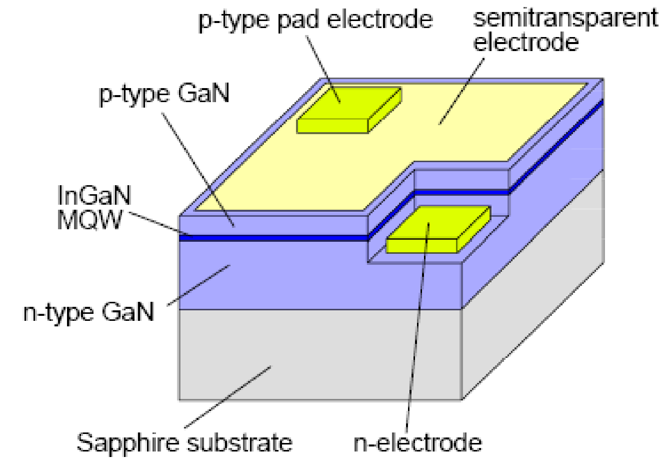
以III族氮化物为代表的宽禁带半导体材料被称为第三代半导体材料。在固态照明、功率电子器件、微波功率器件、紫外探测等领域有重要应用。



GaN基发光二极管的基本结构







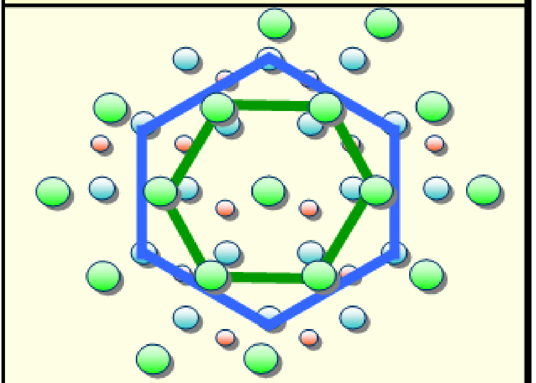
2010年初，美国CREE公司报导GaN基大功率芯片光效已达 208 lm/W @ 350 mA，这无疑是对功率芯片性能的重大突破。

Electrical Efficiency	90%
Internal Quantum Efficiency	90%
Extraction Efficiency	95%
White Conversion Efficiency	75%
Target (K×η total)	200 lm/W

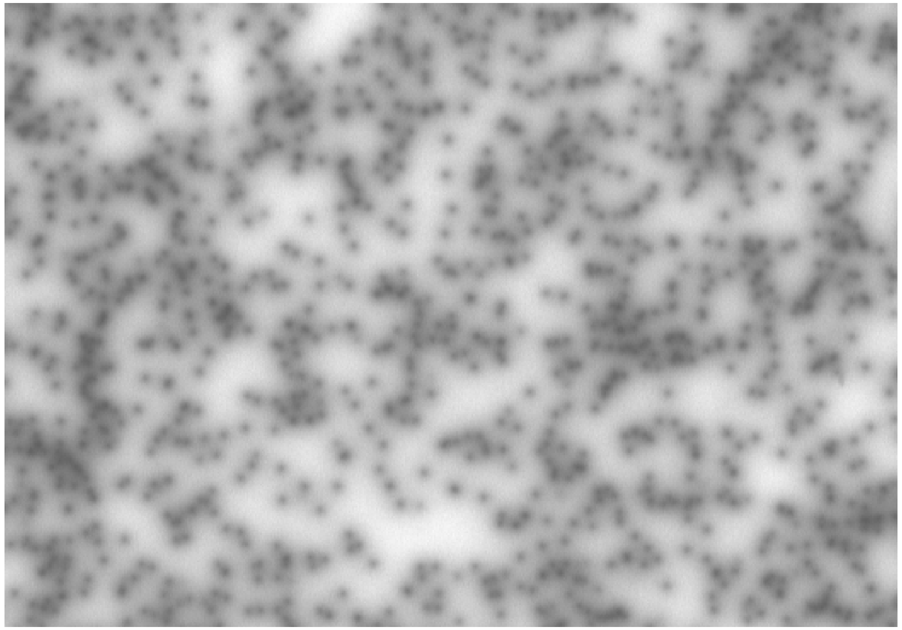
Some unique properties of GaN-based LEDs

(1) Highly dislocative materials

Due to the hetero-epitaxial growth commonly used, the material system has very high dislocation density

	$[11\text{-}20]_{III\text{-}N}//[10\text{-}10]_{Sap}$ 30 ° Rotation
Atomic arrangement	
GaN a=3.189 Å	+16.1%

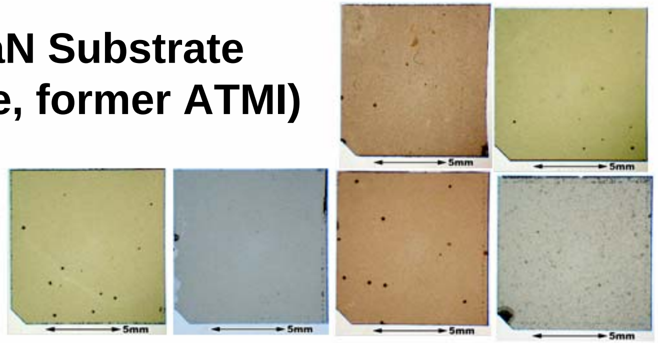
Large lattice mismatch between GaN and sapphire



A BEST MOCVD GaN on sapphire

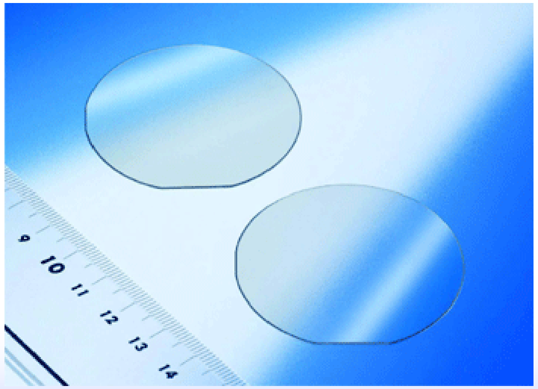
DD ~ 5e8 cm^{-2}

As a result, bulk GaN substrate has been being intensively developed worldwide with more or less success.



GaN Substrate (Cree, former ATMI)

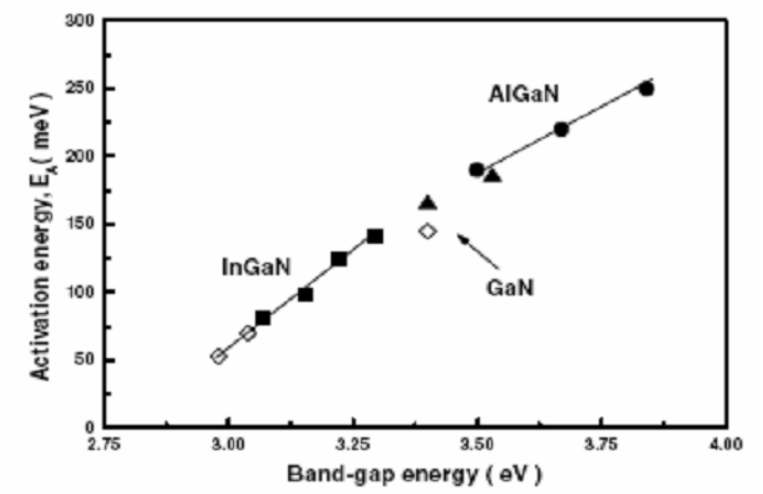
HVPE GaN template (Nanjing Univ.)



Sumitomo Electric's bulk GaN

(2) Low P-type conductivity

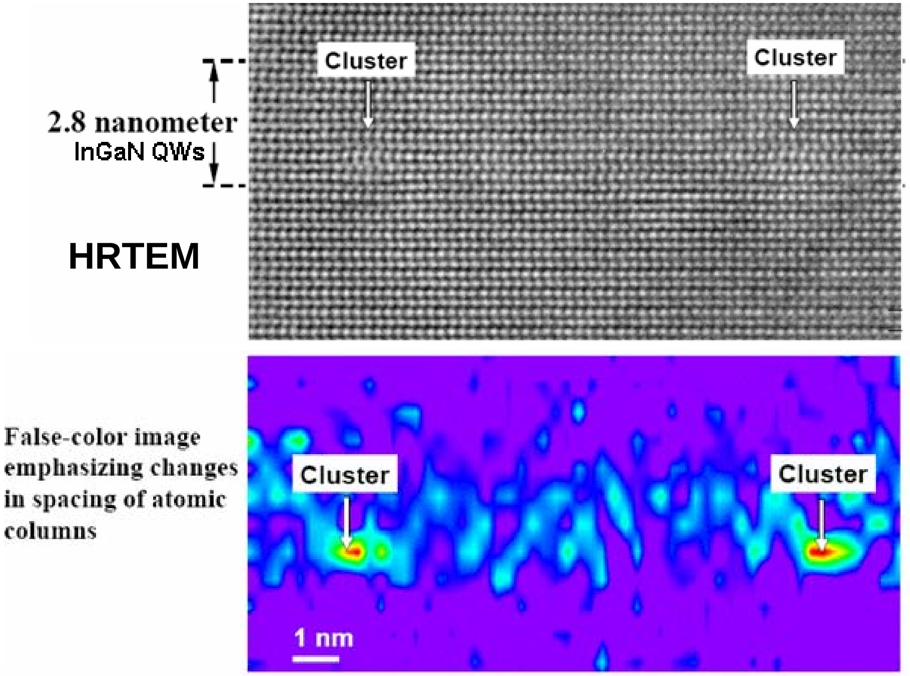
Mg is the most commonly used p dopant in GaN with a high ionization energy around 150-200 meV. At RT, only around 1% Mg atoms are ionized. For example, 5e17 hole concentration is already a good number.



- Akasaki and Hayashi: GaN by MBE (1974)
- Amano et al.: GaN heteroepitaxy by AlN buffer (1986)
- ★ Amano et al.: *p*-type GaN by Mg acceptor (1989)
- Nagamoto et al.: InGaN Epitaxy (1989)
- Nakamura et al.: GaN buffer by MOCVD (1991)
- ★ Nakamura et al.: Mg activation by thermal annealing (1992)
- Nakamura et al.: InGaN/AlGaN DH blue LEDs (1993)
- Nakamura et al.: InGaN-QW visible LEDs (1995)
- Nakamura et al.: Blue LD pulse operation (1995)

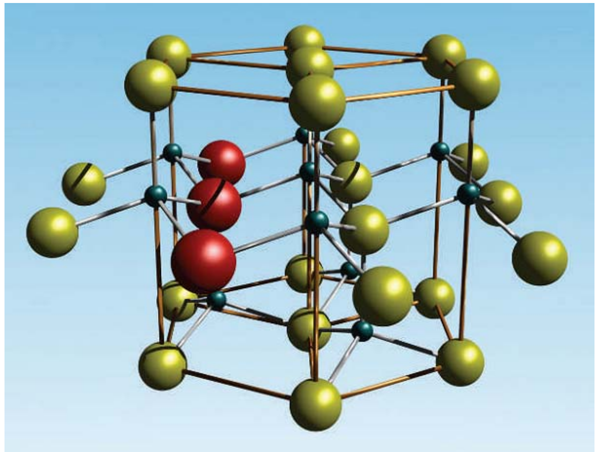
(3) Carrier localization

The internal quantum efficiency of GaN LEDs can easily reach 80% or higher. Then, a nature question arises how injected carriers (excitons) manage to escape from the detrimental effect of large number of nonradiative defects. The answer is "carrier localization".



In-rich clusters in InGaN

VS.

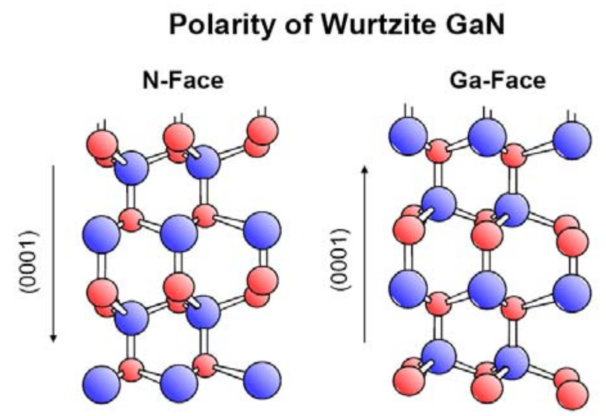


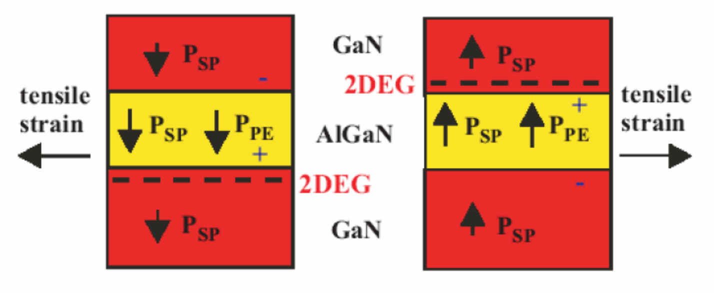
Local atomic configurations

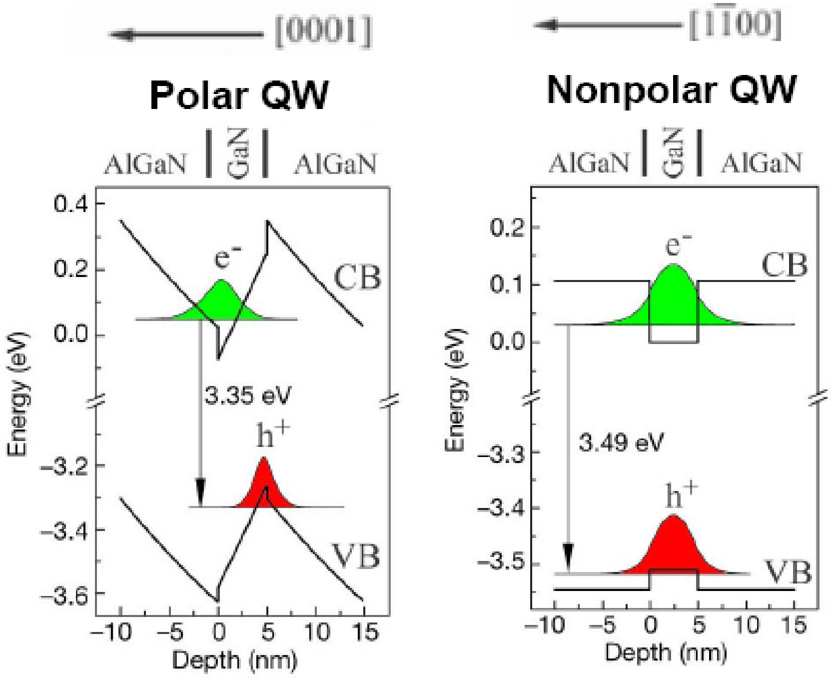
Chichibu et al, Nat. Mat. 5, 811, 2006

(4) Strong polarization effect

The possibility of inorganic crystals being polar (pyroelectric or piezoelectric) is strictly a function of their point group symmetry.





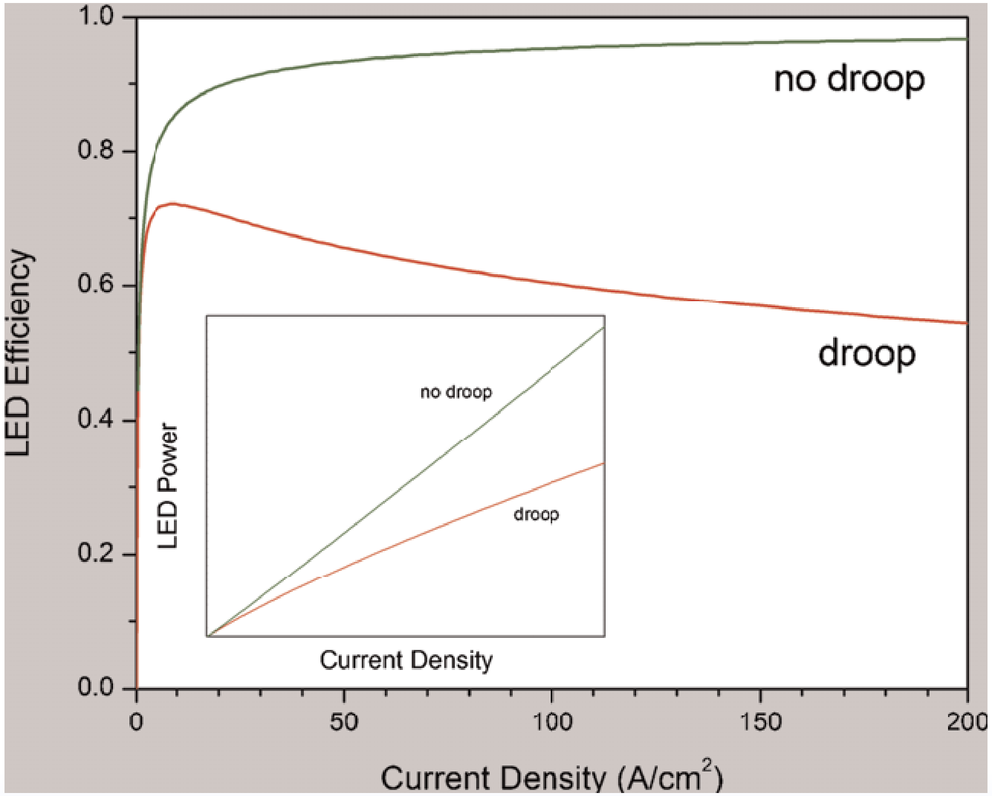


Commonly used **Under development**

Strong polarization field exists within the c-plane InGaN/GaN MQWs.

(5) Efficiency droop

Although the internal quantum efficiency of GaN-based LEDs is generally high at low currents, the efficiency gradually drops as the injection current increases. This well-known phenomenon is called as "efficiency droop"



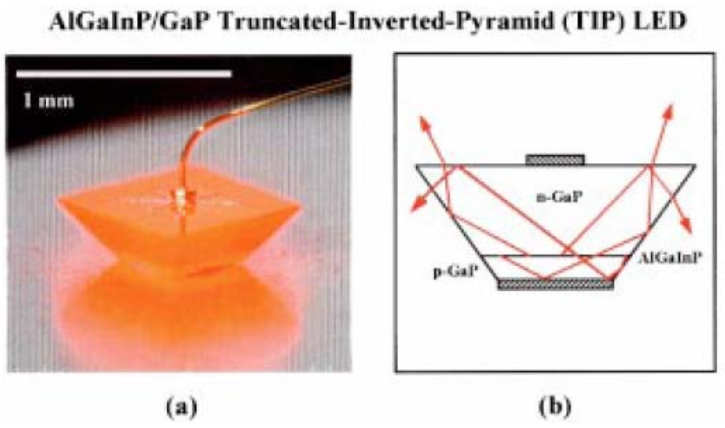
Such droop effect occurs not only in blue LEDs, but also in green and UV LEDs.

Why is “droop” so important? → Cost

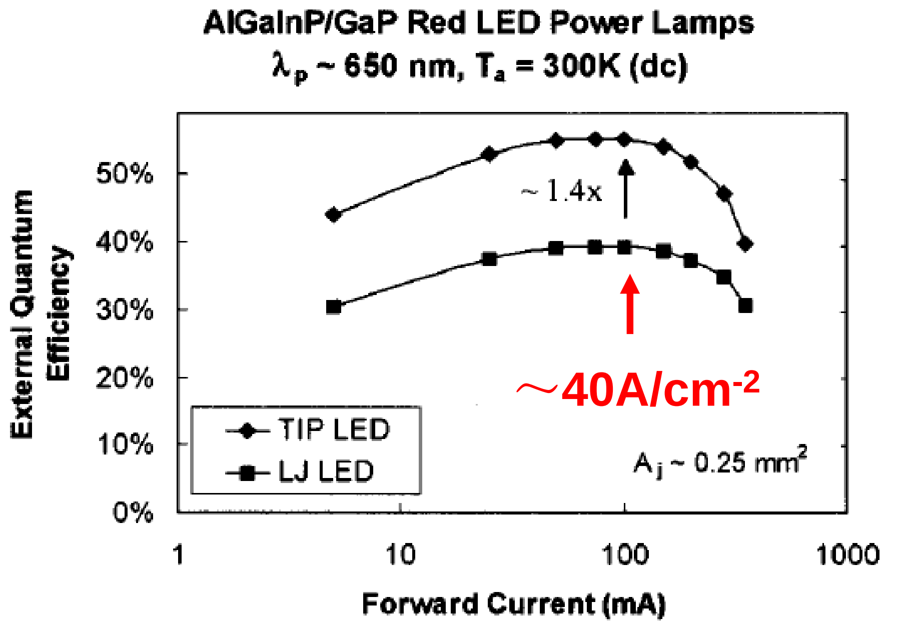
Is droop a high current phenomenon? Yes or No !

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)



$\sim$40A/cm^{-2}

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)

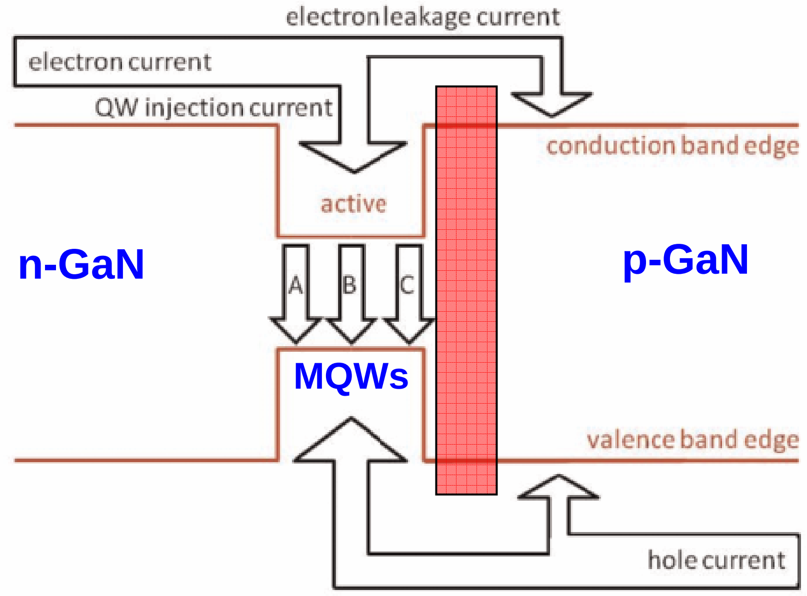
2) Auger recombination due to high carrier density, direct or defect-assisted (Lumileds and others)

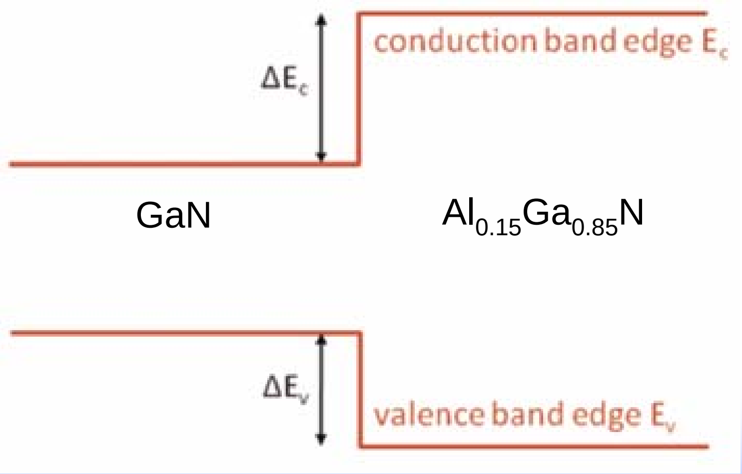
3) Poor hole transport in MQWs (Virginia Commonwealth Univ.)

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

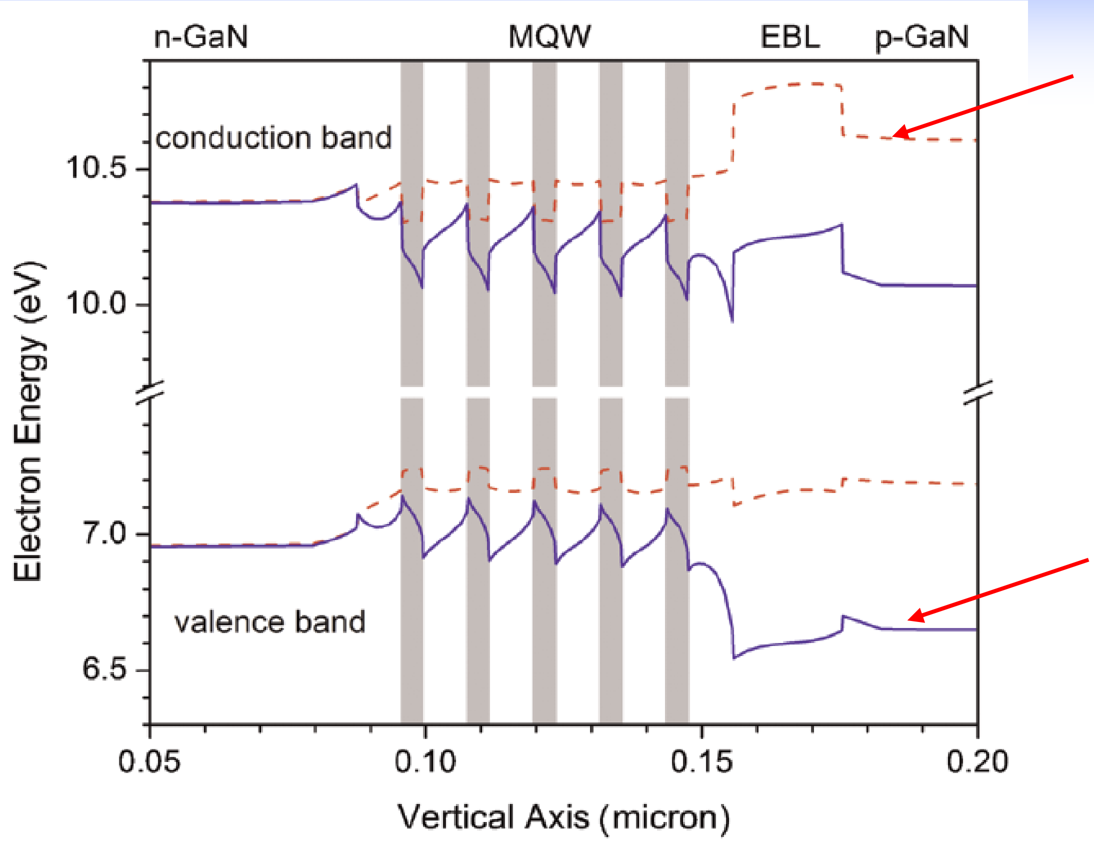
(1) Electron overflow

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.



W/O polarization

With polarization

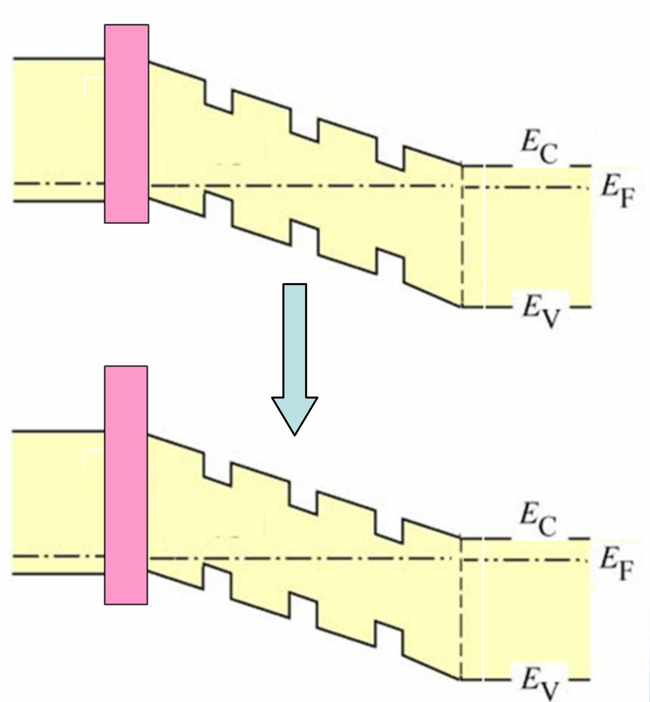
One of the possible reasons for electron leakage is the energy barrier reduction by built-in nitride polarization. That is, with the typical Ga-polar growth of nitride LEDs, the polarization charges at the MQW-EBL interface are positive, which leads to electron accumulation at this interface and strong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

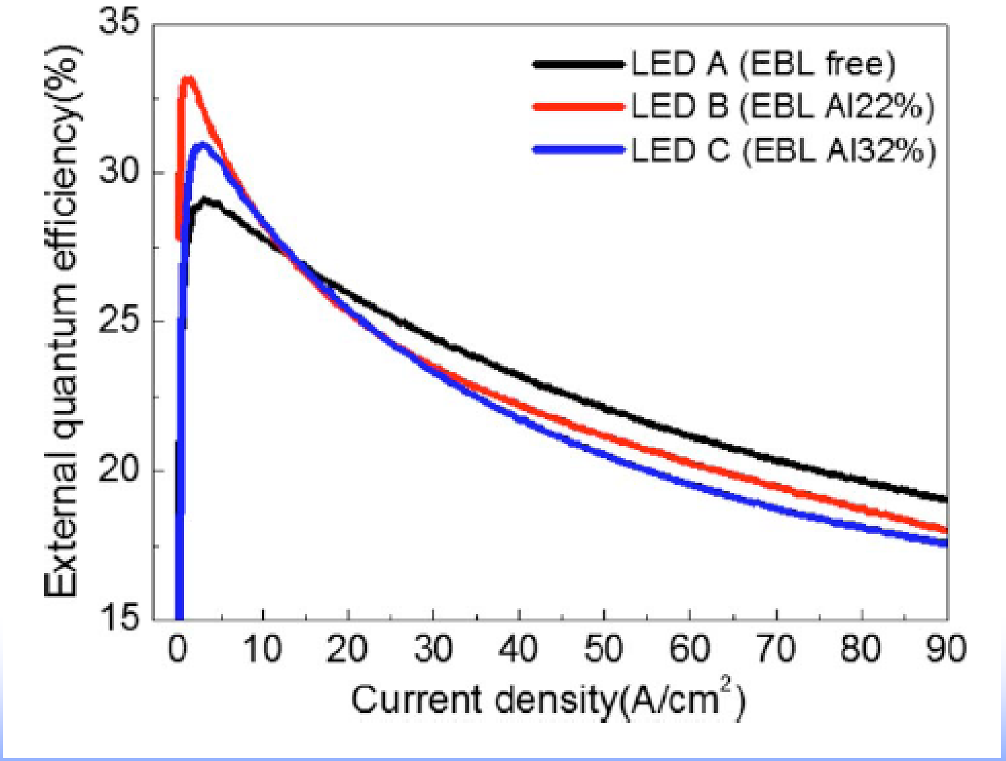
Ways to enhance the electron confinement

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)

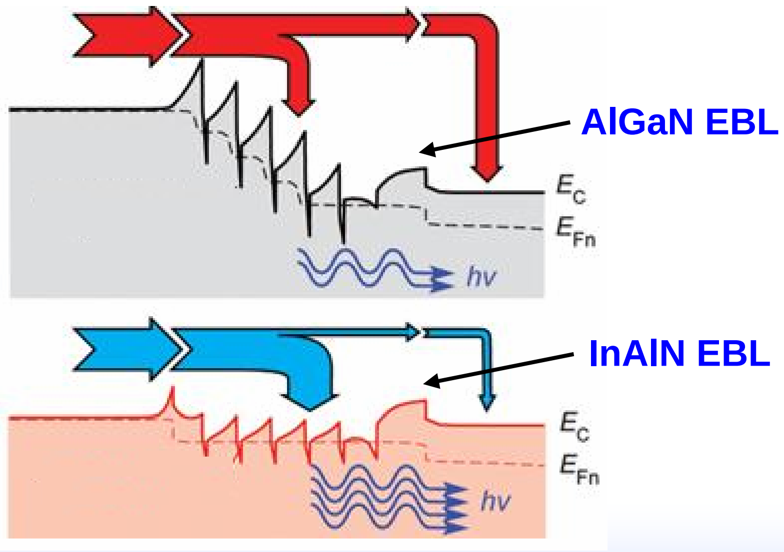


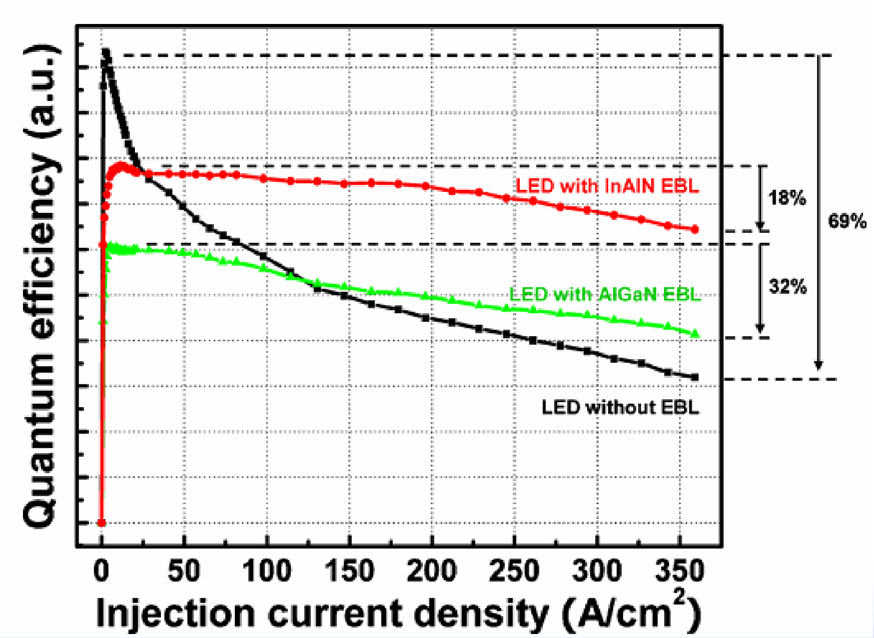


2. Polarization engineering

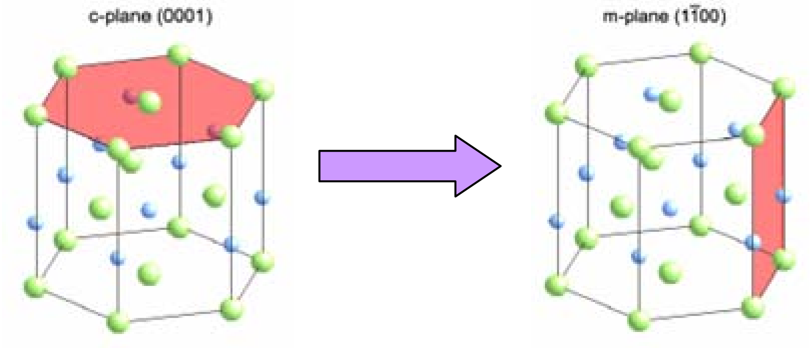
Several layer sequence combinations have been tried, such as InAlN EBL (GIT, APL 96, 221105, 2010), GaInN/AlGaInN MQWs (RPI, APL 93, 041102, 2008), GaInN/GaInN MQWs (RPI, APL 94, 011113, 2009)

The approach seems effective. People can see improvements.

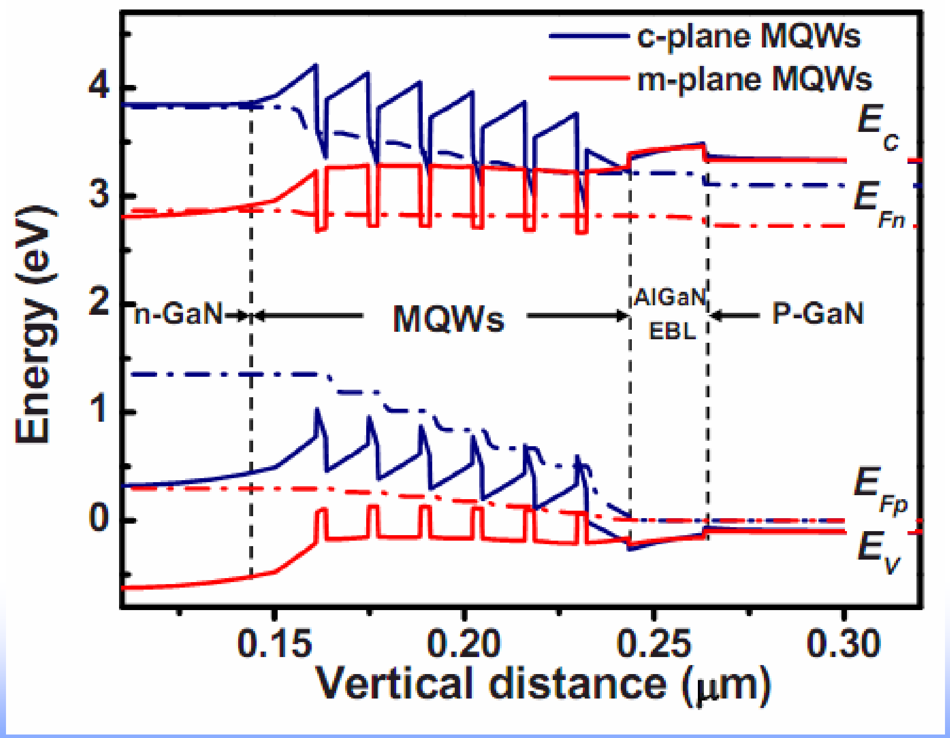




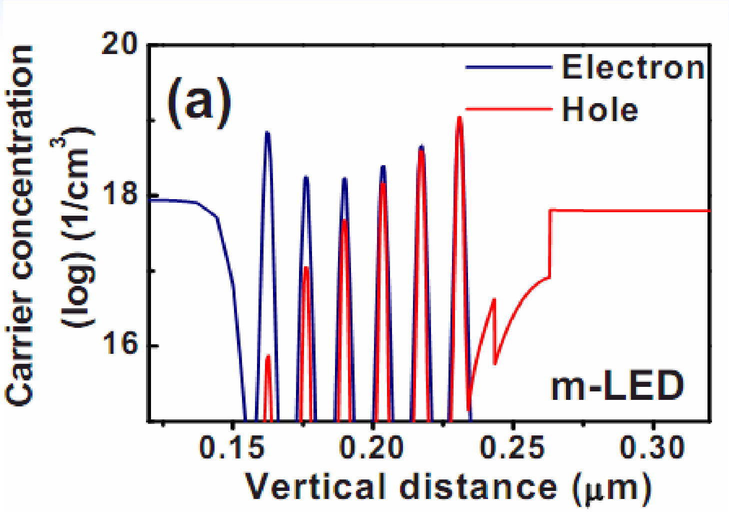
3. Non-polar LED approach



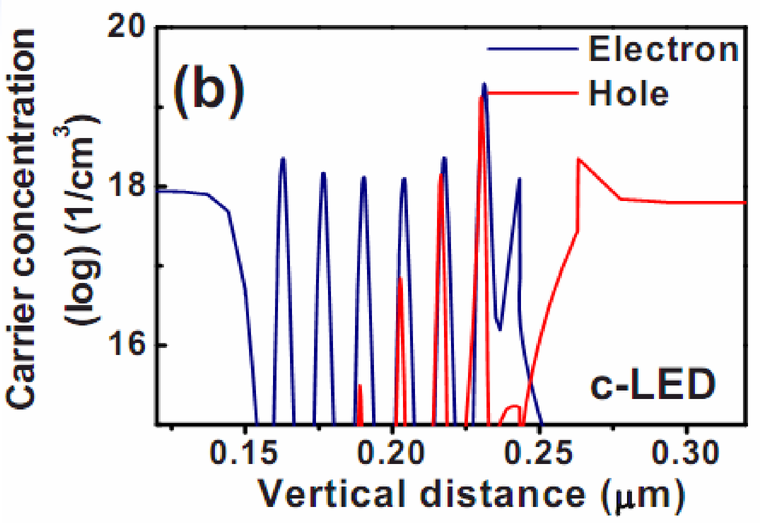
By fabricating LEDs on non-polar GaN plane to completely eliminate polarization-induced EBL lowering.

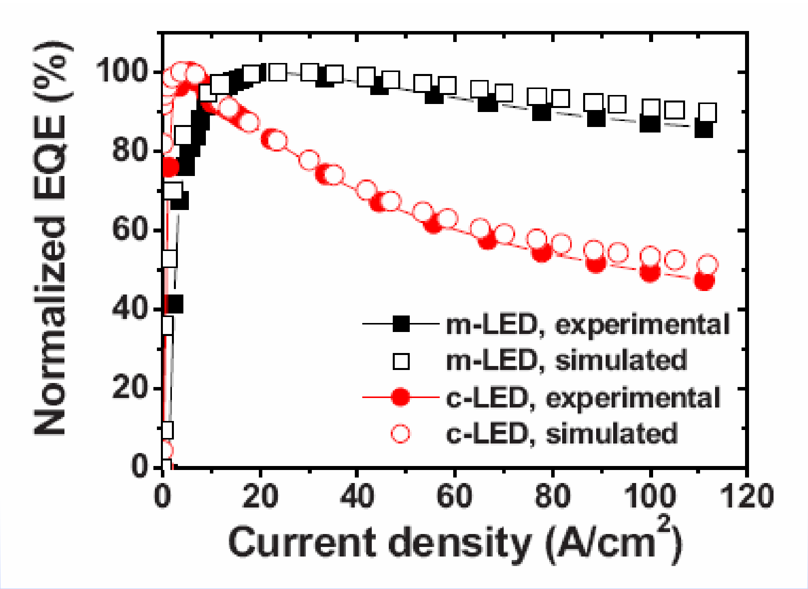


Simulation of carrier distribution in the MQWs



vs.



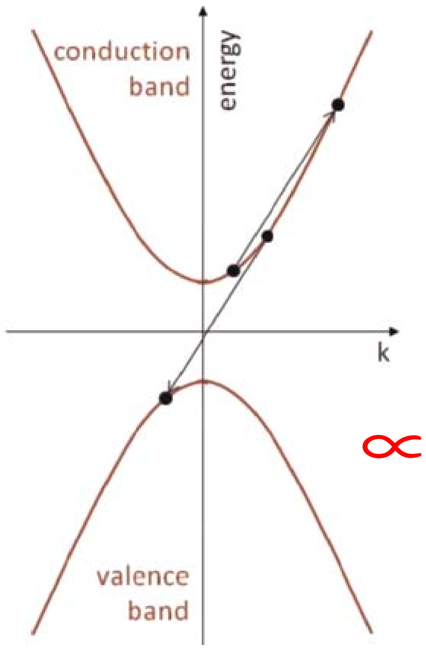


NCTU APL 96, 231101, 2010

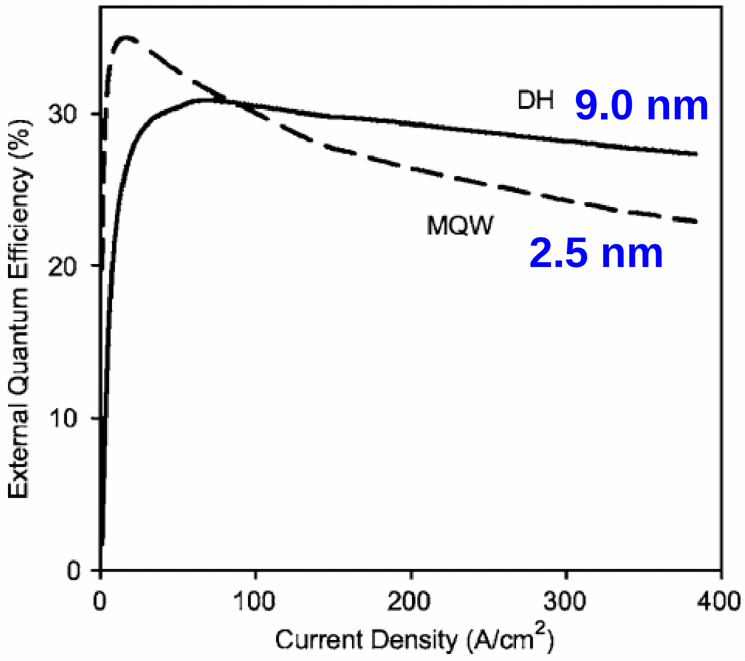
However, UCSB group reported that m-plane GaN LEDs also such suffer from strong droop. (J. Phys. D 41, 082001, 2008)

(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.

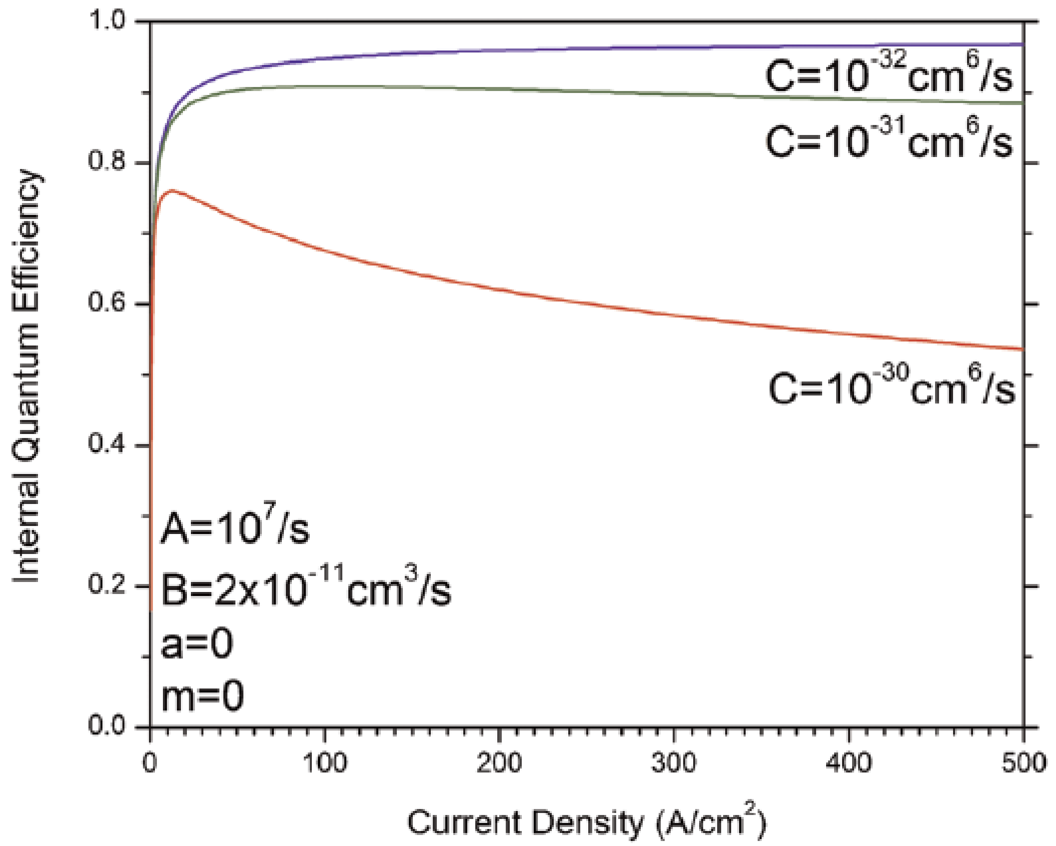


$\propto Cn^3$



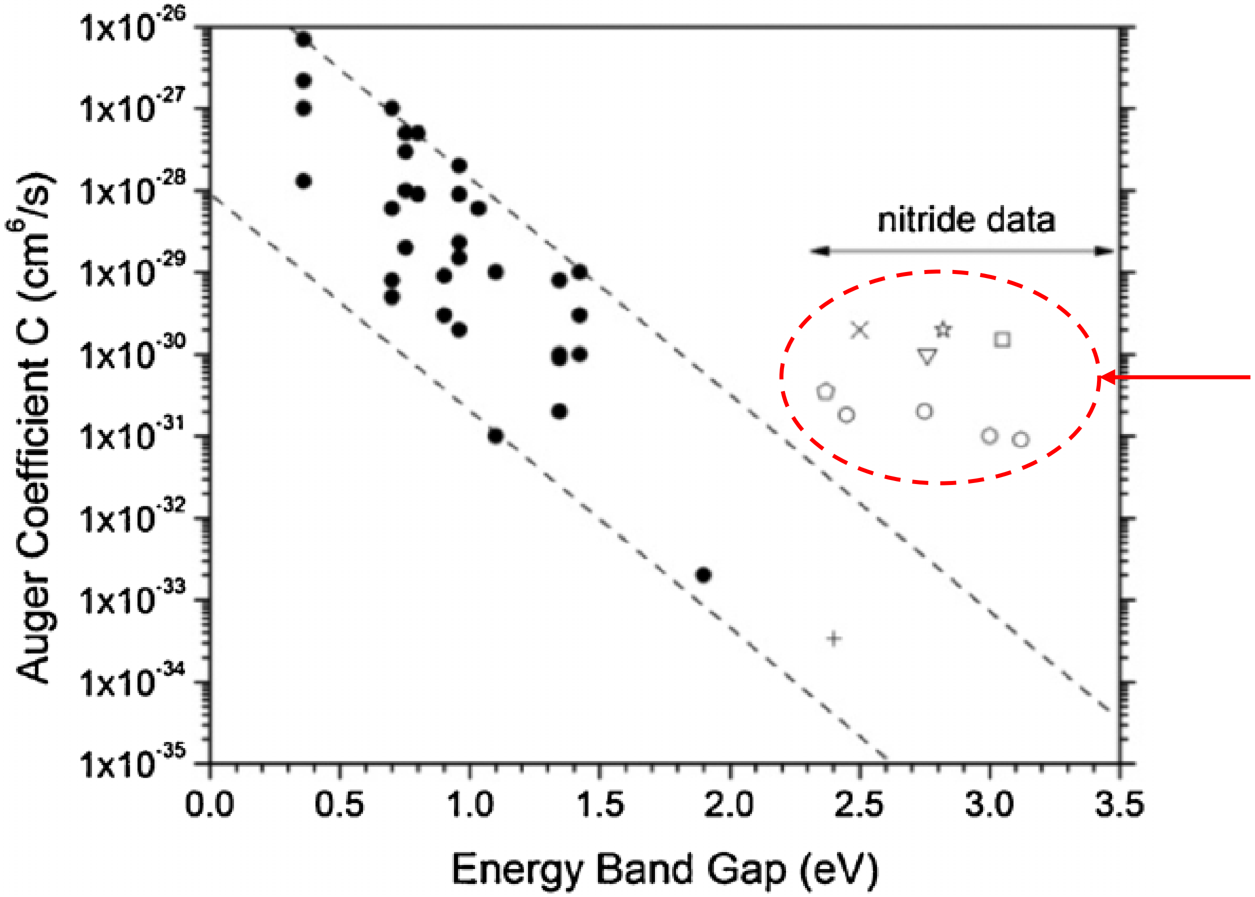
The hypnosis was firstly suggested by scientists in Phillips Lumileds and has been popular since then. APL 91, 141101; 91, 243506, 2007

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



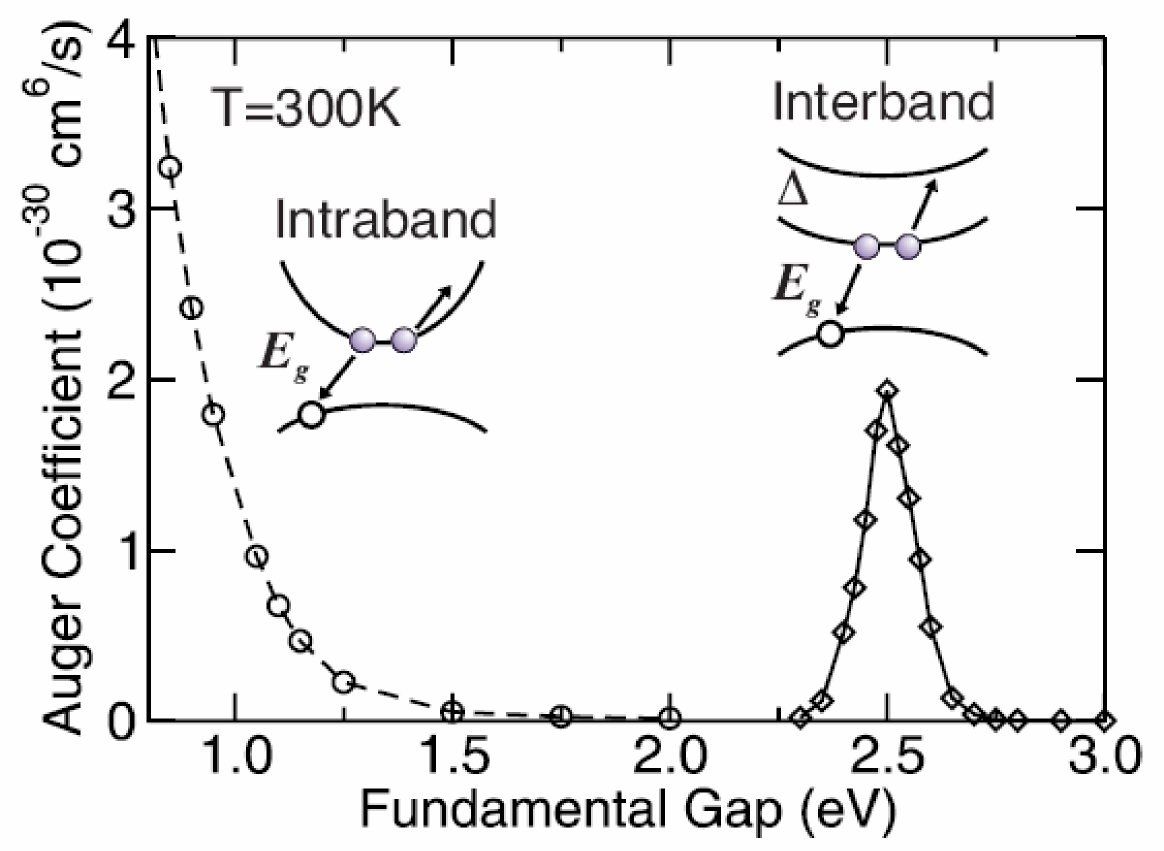
Simple rate equation analysis indicates that only Auger parameters of 10^{-31} cm^6 s^{-1} or higher could cause significant efficiency droop.

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



Experimentally measured results

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^{6}s^{-1} is determined for the Auger coefficient at RT. (UMich APL 95, 201108, 2009)

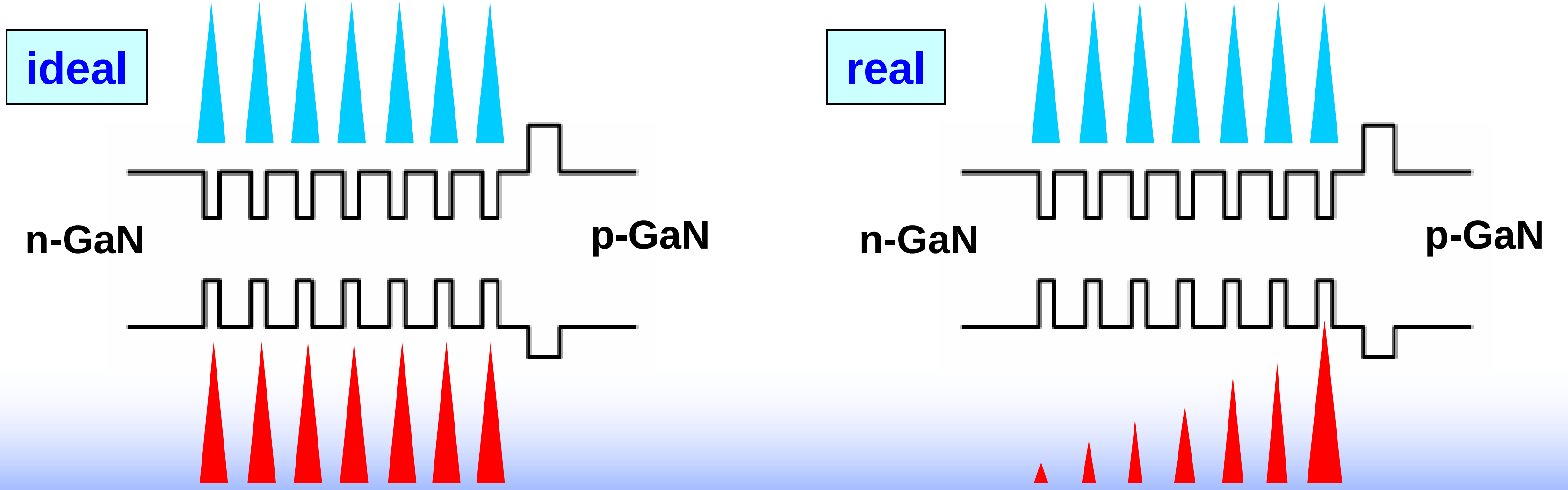


Theoretical analysis suggests defect-assisted Auger or interband Auger process could be the reason. (eq. First principle calculation by UCSB, APL 94, 191109, 2009) Sounds interesting ?!

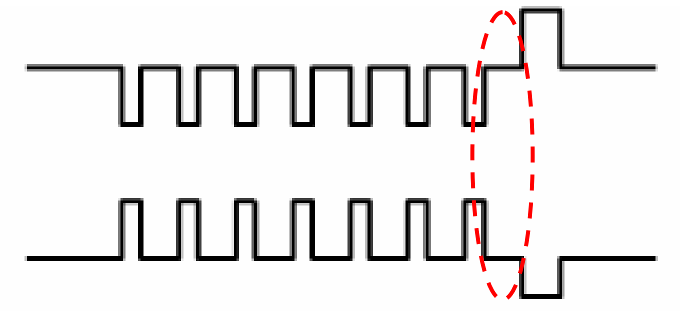
(3) Poor hole transport

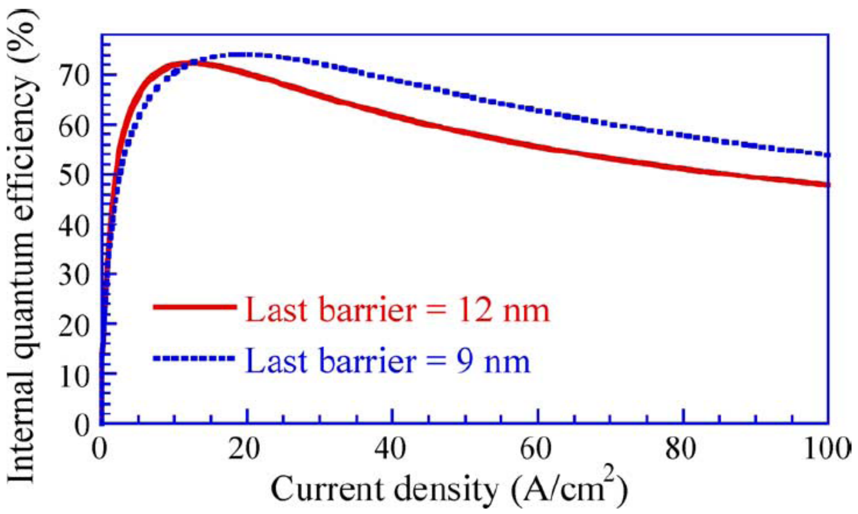
Two phenomena — escape of electrons form the active region and reduced hole injection — are components of any carrier leakage explanation for droop. However, it is not clear which is cause and which is effect; both have been proposed.

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.



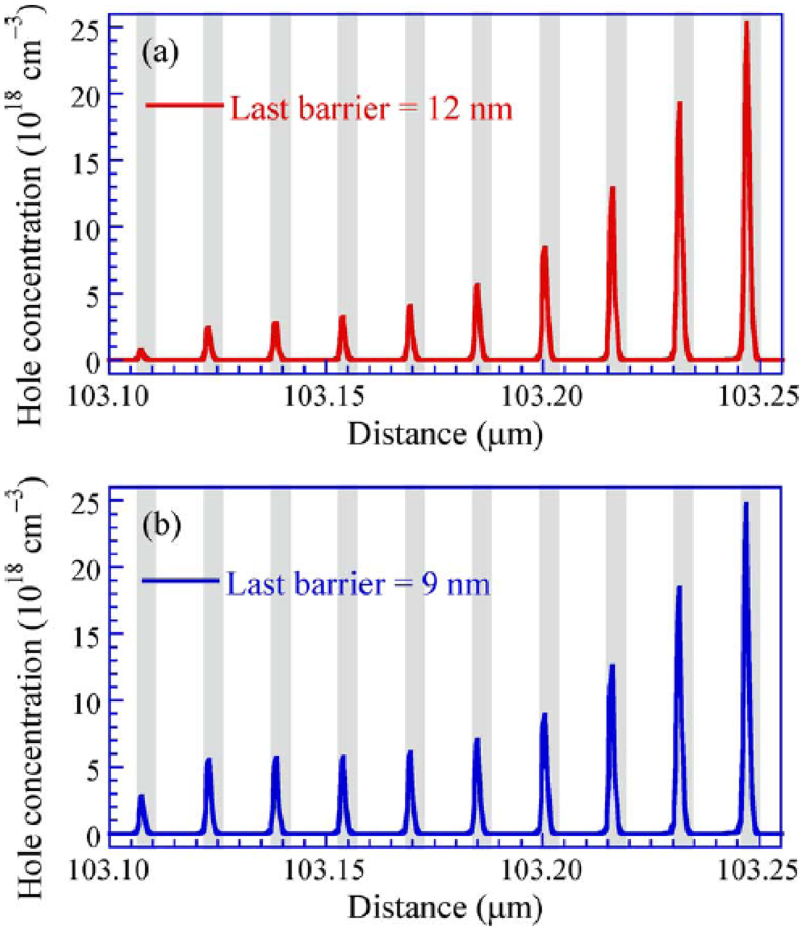
Reducing the last GaN barrier thickness within the MQWs to promote hole transport.



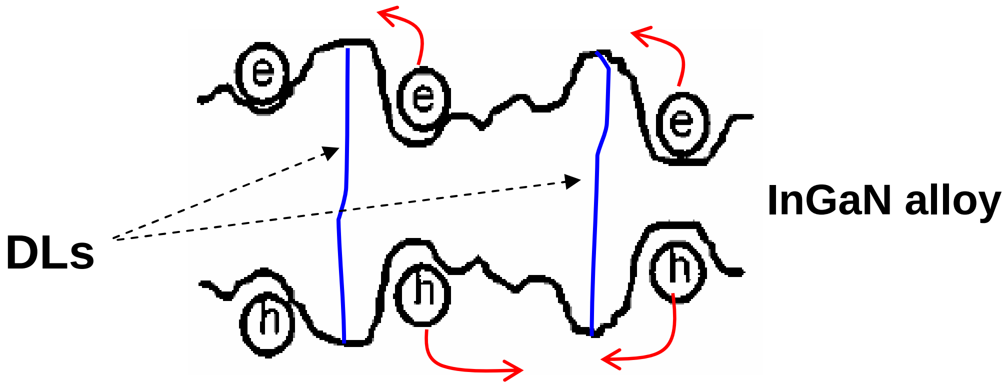


Epistar PTL 22, 1787, 2010

2/12 nm MQWs + 10 nm EBL



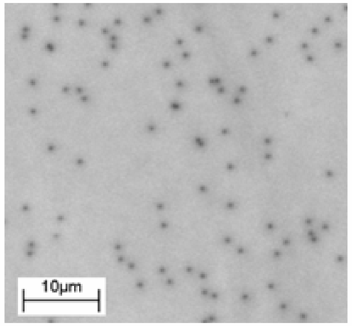
(4) Density-activated defect recombination



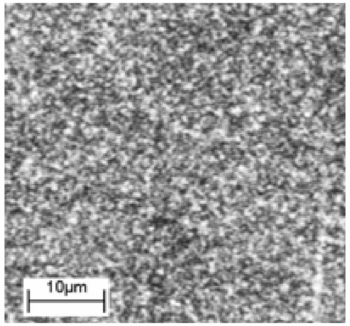
Indium-rich clusters are associated with a lower bandgap and therefore lead to carrier localization. At low current and low QW carrier density, indium-clusters then keep carriers away from structural defects that serve as SRH recombination centers. With higher current, more carriers accumulate inside 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.

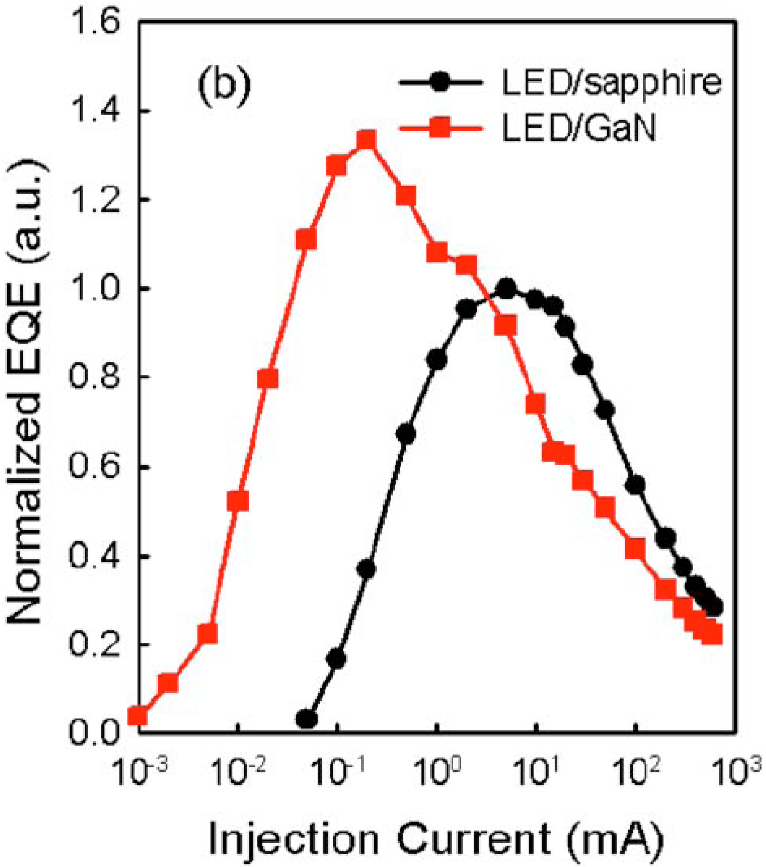
However, experimentally GaN LEDs made on bulk GaN substrate still suffer from strong droop.



GaN homoepilayer



GaN on sapphire



WVU, APL 94, 041117, 2009

Summary

We still don’t know what causes droop yet !

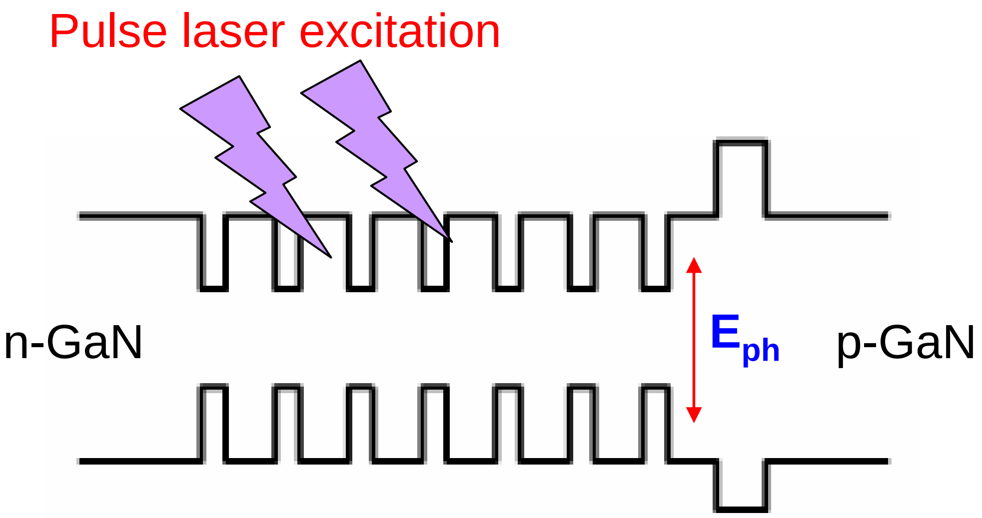
The problem itself:

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

The problem of scientists:

- **Absolute efficiency should be stressed when comparing droop characteristics;**
- **People should pay attention to the possibility of sample variations as well as the difference in testing methods.**

A good example: efficiency droop in PL analysis

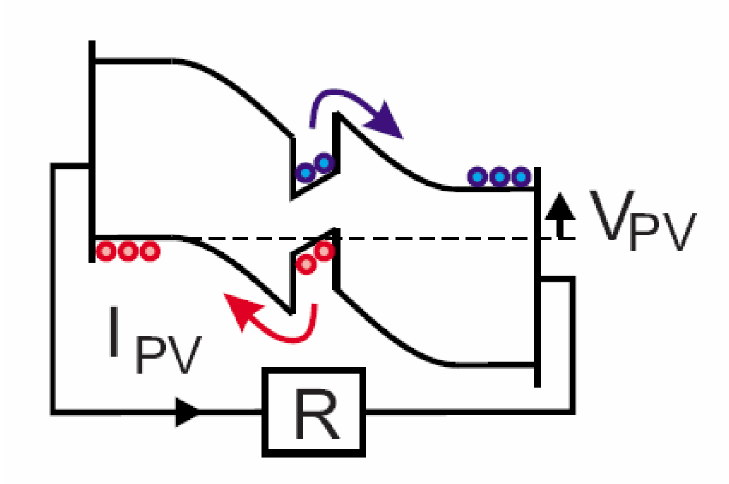


$E_{InGaN} < E_{ph} < E_{GaN}$

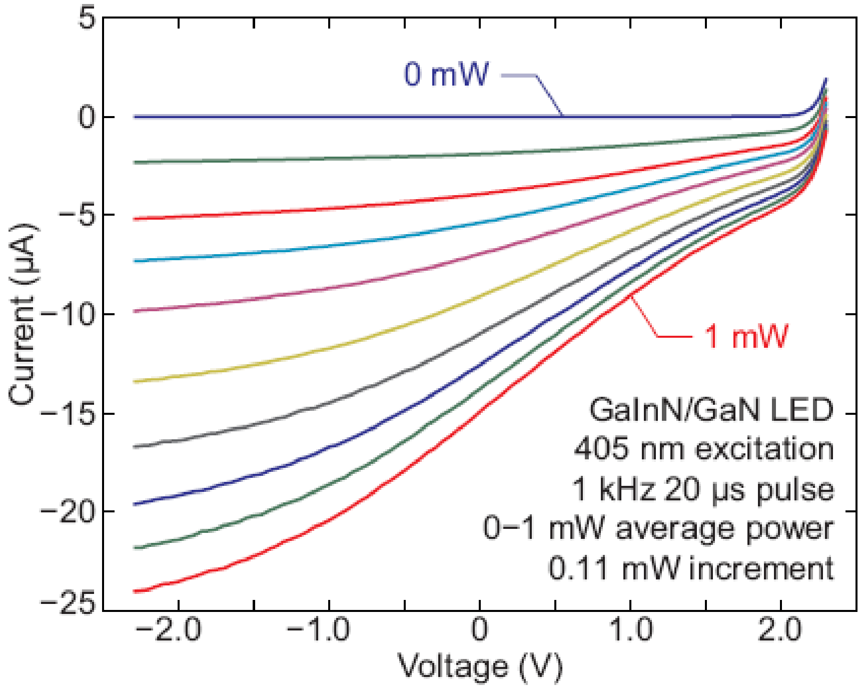
Since all photo-carriers are purposed to stay and recombine within the MQWs, the original idea is:

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

However, recent study suggests that the PL analysis method itself might be problematic.



PV effect is observed !



RPI APL 94, 081114, 2009

多谢

北京大学的各位老师和同学