U.S. DEPARTMENT OF **ENERGY**

# Identification and Mitigation of Droop Mechanism in Gallium Nitride (GaN)-Based Light Emitting Diodes (LEDs)

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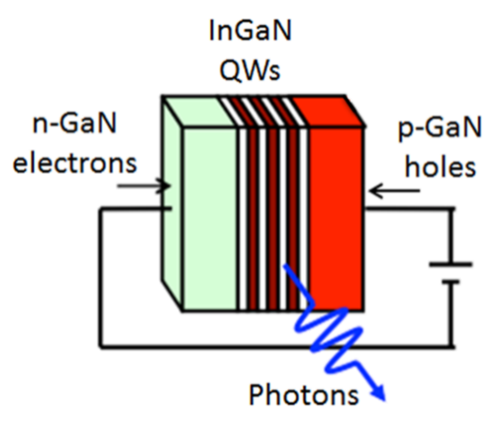
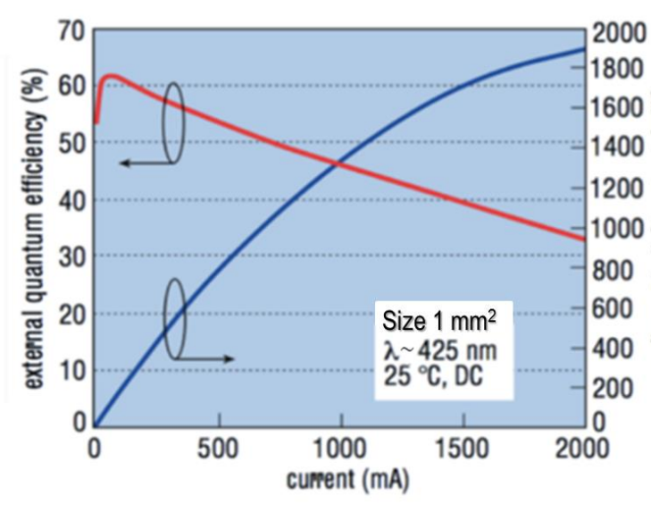
## BACKGROUND & MOTIVATION

### LED Droop Efficiency

Why do blue LEDs experience efficiency losses at high current density?





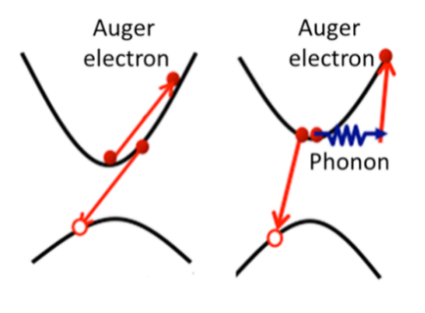
Sublinear increase in LED optical output power with increasing injected current density

*Drop* in external quantum efficiency

$$\eta_{EQE} = \left(\frac{\#\ of\ emitted\ photons}{\#\ of\ injected\ e-h\ pairs}\right)$$

### Proposed Droop Mechanisms

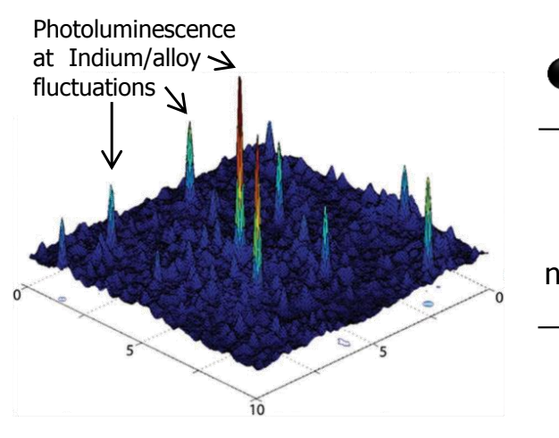
**AUGER RECOMBINATION**



- Direct or mediated by phonon/alloy scattering
- e-e-h or e-h-h processes

Shen et al. Lumileds, 2007
Van de Walle, UCSB, 2011

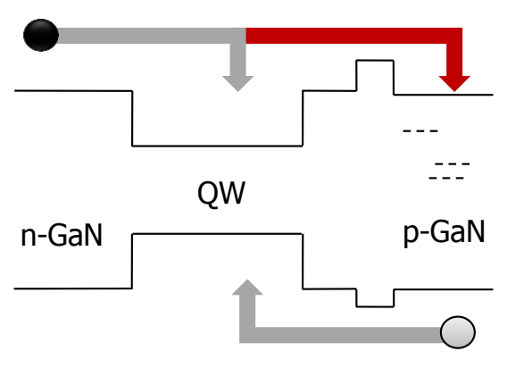
**LOCALIZATION OF CARRIERS**



Filling of localized states leads to activation of non-radiative defect recombination

Humphreys *et. al.*, Journal of Appl. Phys. 2012
De Chowdhury *et al.*, Adv. Funct. Mater. 2011

**CARRIER LEAKAGE, OVERSHOOT**



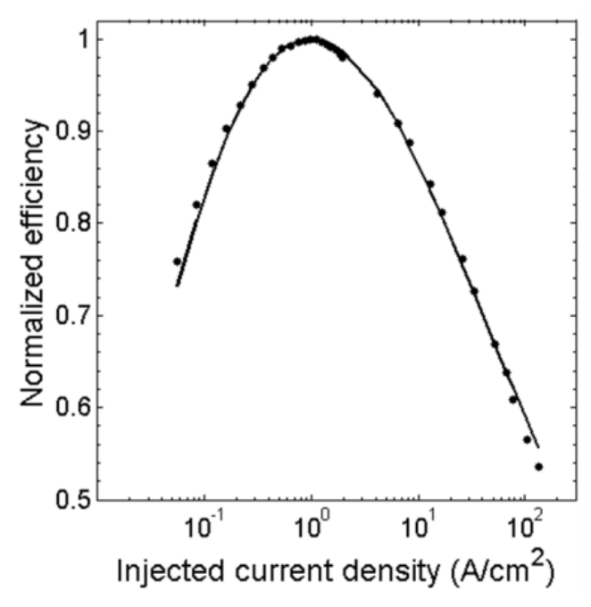
- Electrons miss QW(s)
- Recombine in defect rich p-GaN

Tansu *et al.*, Solid-State Electronics 2010
Wang, Hu, *et. al.* Optics Express 2011

### Limits of the ABC Analysis of Droop

Analysis of experimental EQE curve vs. injected current density

$$J = ed_{active}\,(An + Bn^2 + Cn^3) \qquad \eta_{IQE} = \frac{Bn^2}{An + Bn^2 + Cn^3}$$



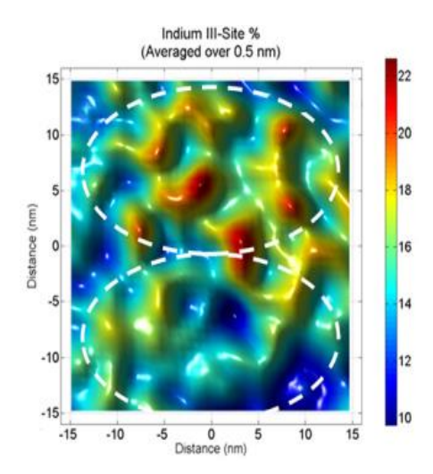
| Uncertainty in assumed parameters | | Large variations in fitted parameters | |
|---|---|---|---|
| $d_{active}$ (# QWs) | $B$ ($10^{-12}cm^3s^{-1}$) | $A$ ($10^6\ s^{-1}$) | $C$ ($10^{-30}cm^6s^{-1}$) |
| 1 | 7.9 | 1.8 | 0.9 |
| 8 | 7.9 | 0.6 | 2.5 |
| 1 | 20 | 2.8 | 3.6 |
| 8 | 20 | 1.0 | 10.2 |

Number of injected QWs of 3 nm thickness

Determination of A and C coefficients requires assumption of active region volume as well as B coefficient.
Small changes in active region volume result in very different A and C.

Inhomogeneity of the system not taken into account in the ABC model: There are several well known phenomena which make defining an active region volume difficult.

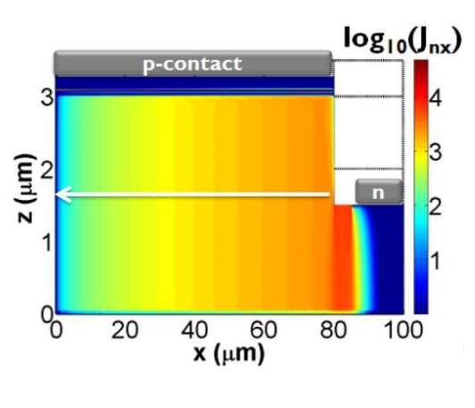
**COMPOSITIONAL FLUCTUATIONS**



Carriers are concentrated in potential minima

Wu et al., Appl. Phys. Lett. **101,** 2012

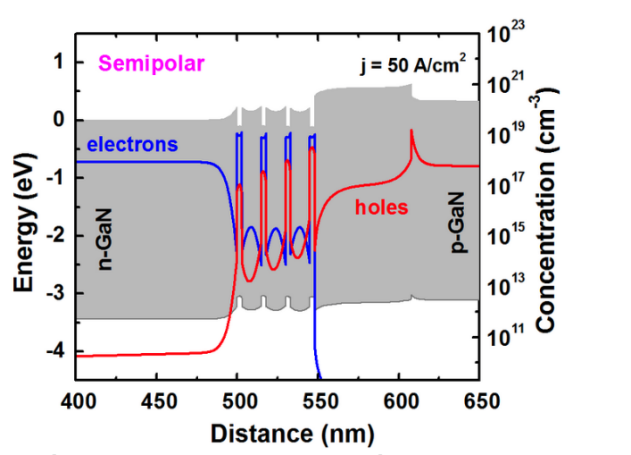
**CURRENT CROWDING**



Injection of carriers is stronger near the electrodes

Li et. al, IEEE Tr. El. Dev. **61**, 2 (2014)

**HOLES DISTRIBUTION**



Holes are concentrated in MQWs near the p-contact layer

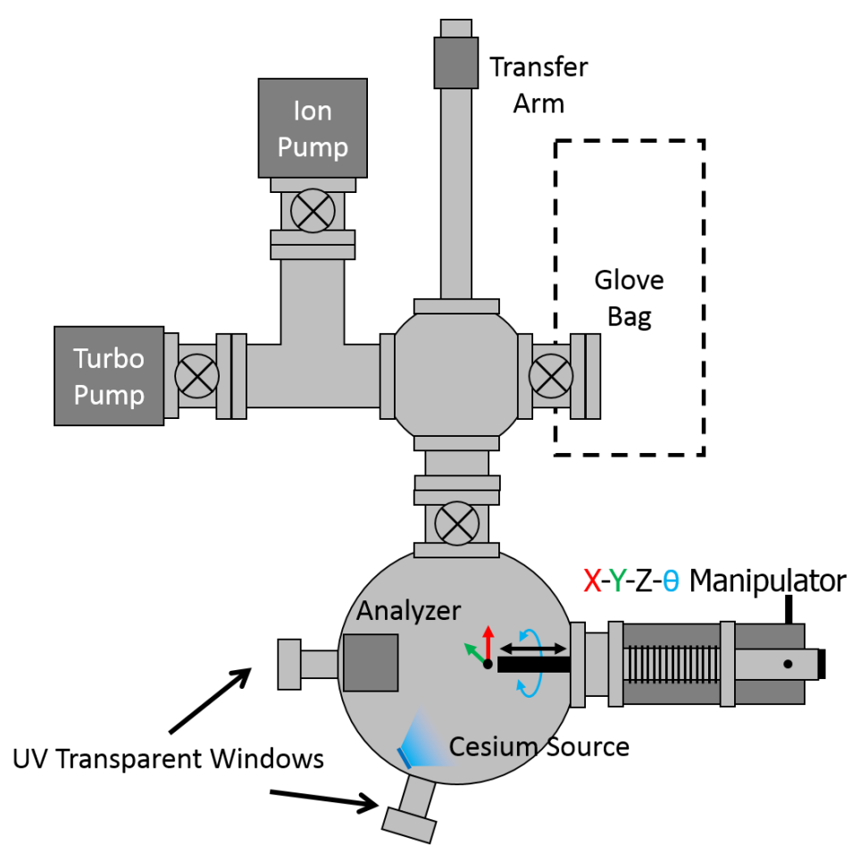
STR group, SiLENSe software for simulation of light-emitting heterostructures

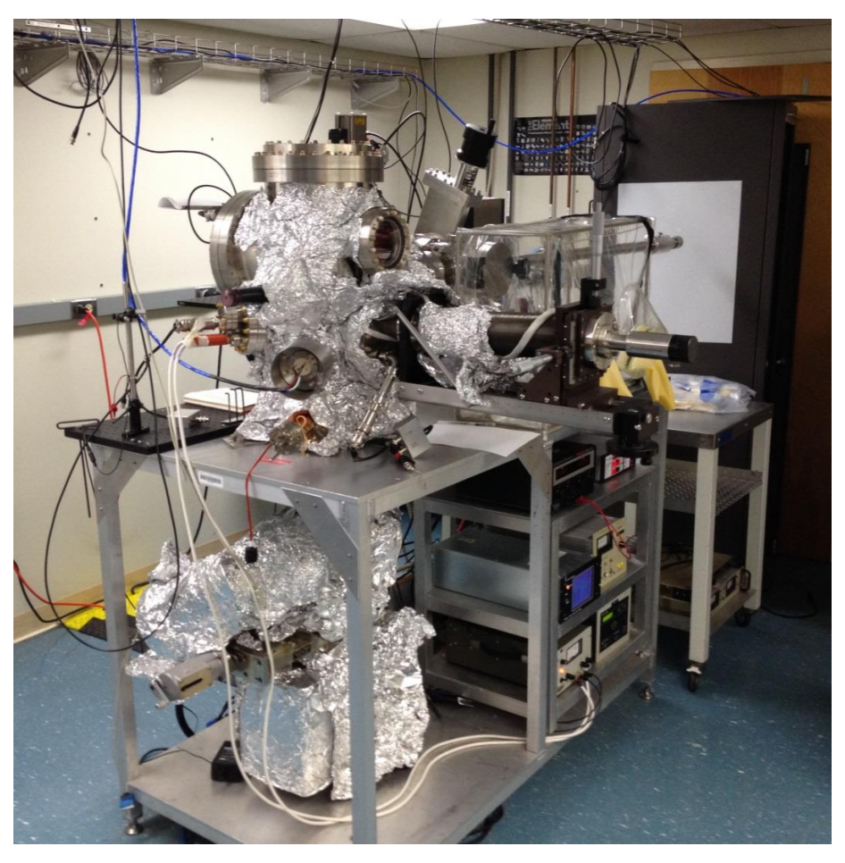
## DETECTING AUGER ELECTRONS

### Experimental Apparatus

How to accurately determine recombination mechanisms?
Direct measurement of the electrons energies.

UHV Electron Emission Spectroscopy chamber at UCSB.

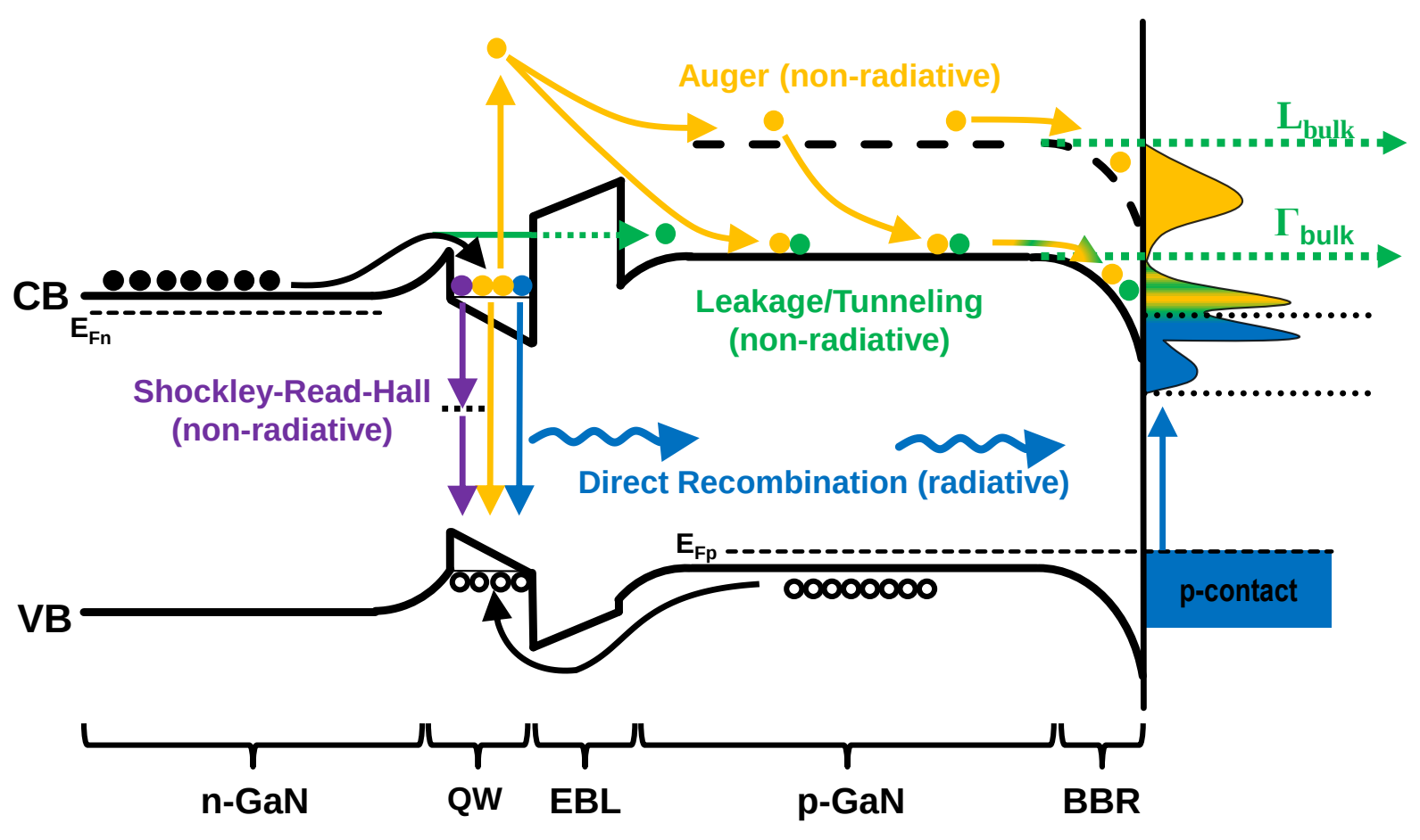




In-situ deposition of cesium monolayer to the surface of devices to allow electrons to be emitted from the p-GaN surface into vacuum.

### Principle of the Experiment

Band diagram of an LED showing the different recombination mechanisms as well as the associated electron energy distribution at the p-GaN surface.



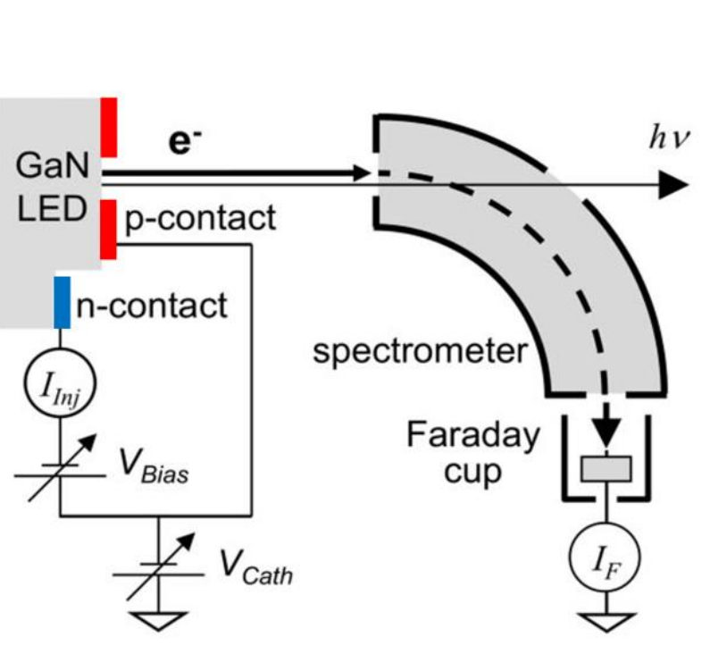
### Electron Emission Spectroscopy

How to measure the energy of the emitted electrons?

1. Openings in the p-contact provide an unobstructed path for electron emission.
2. UHV environment increases electron mean free path in vacuum.
3. Electrostatic energy analyzer.

Improvements to the analyzer geometry.

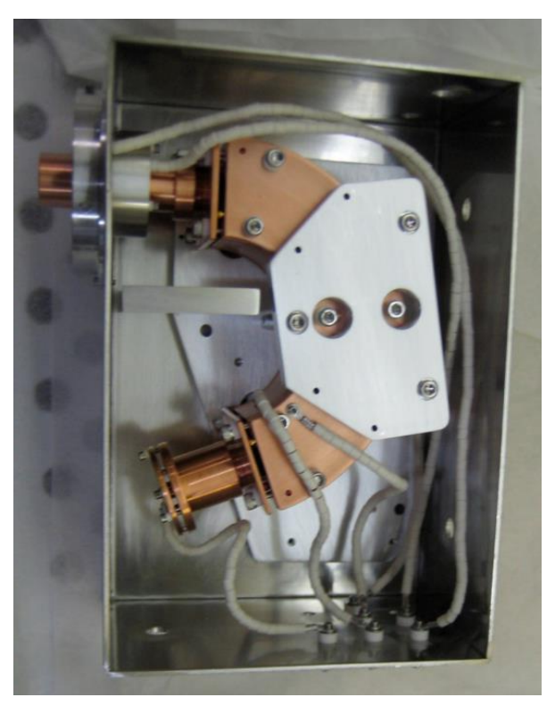
**Low Energy Electron Analyzer**



**Cylindrical**

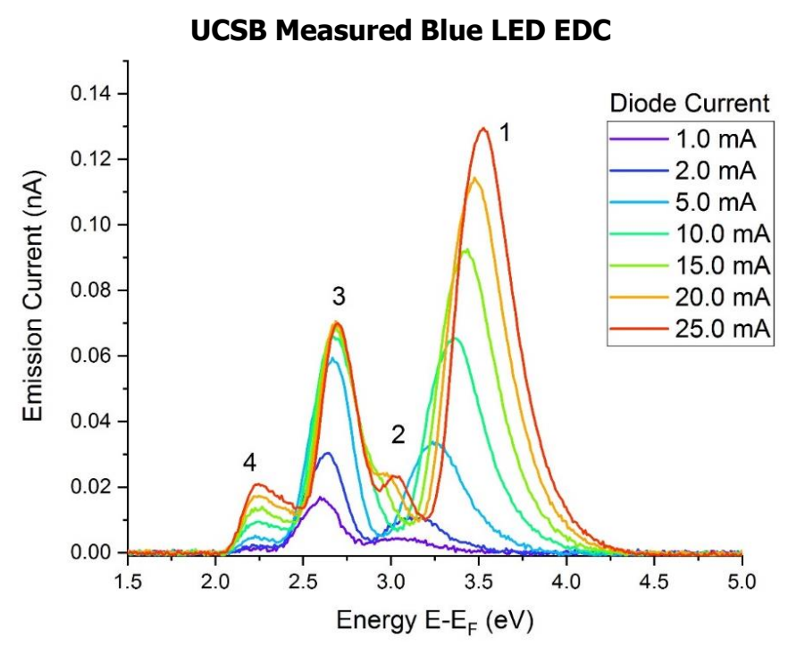
**PMC**

**Spherical Sector**



**UCSB**

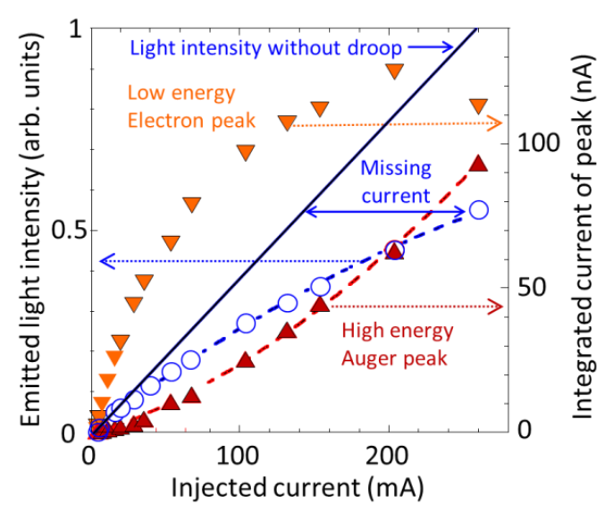
### Energy Distribution Curves



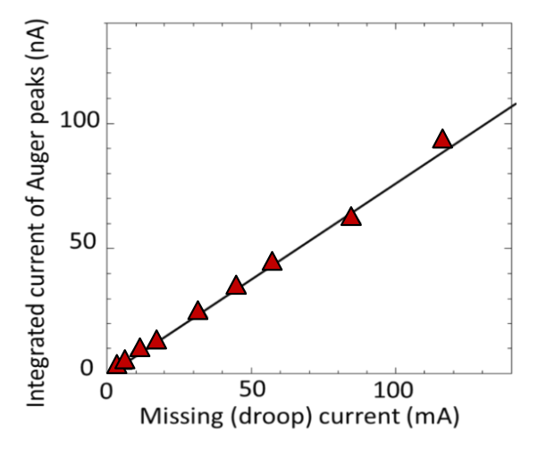
Peaks 1 and 2 (high energy)

Auger-generated electrons:

- 1 Hot carriers accumulated in the side L-valley.
- 2 L→Γ electrons transferred near the p-surface.
- 3 and 4 are low energy photo-generated electrons from metal p-contact by LED light.



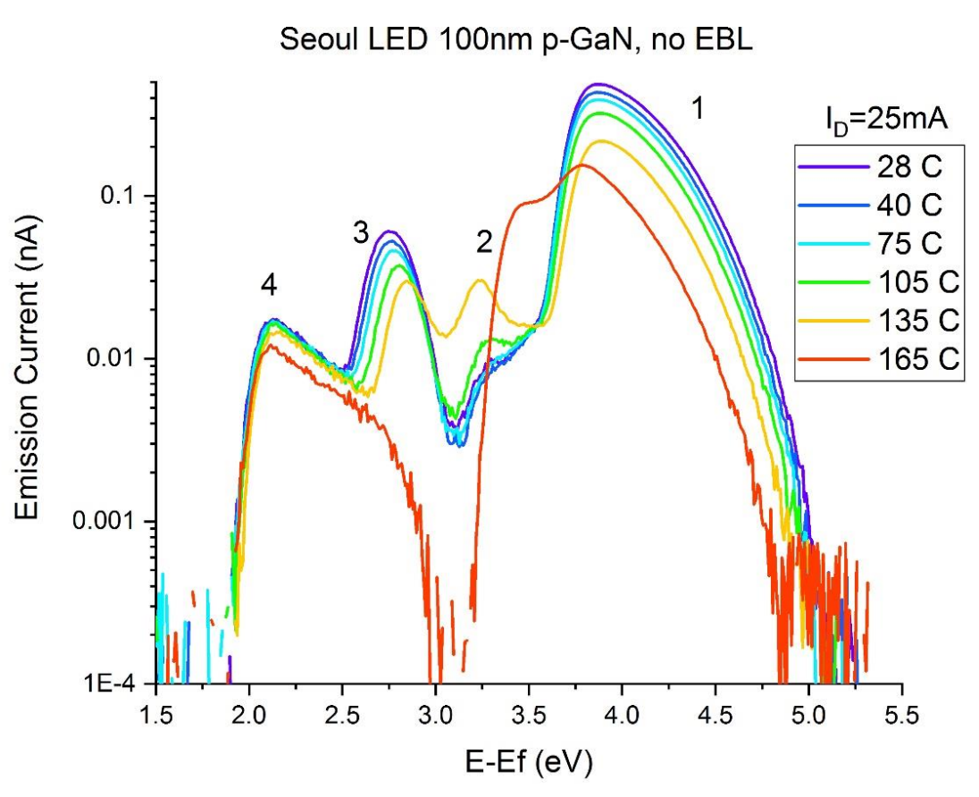
The Auger current and droop current scale linearly indicating that the two processes have the same dependence on carrier density. No other droop mechanism scales as Auger.



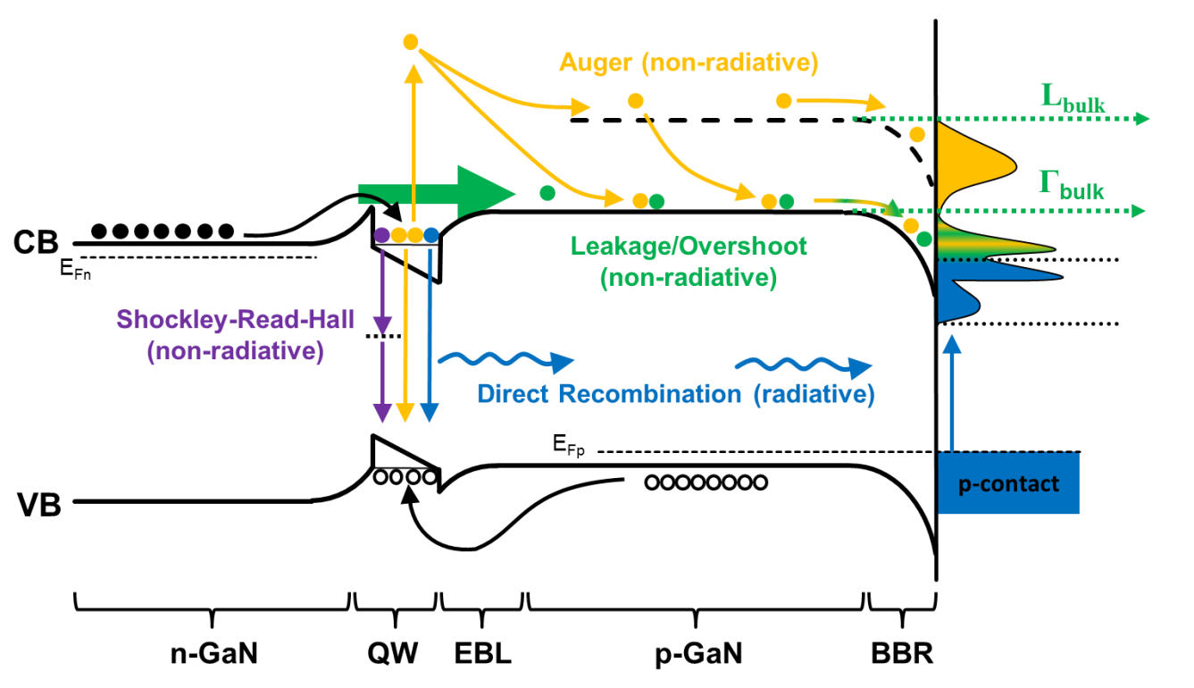
## MILESTONES & RESULTS

### Thermal Droop Mechanism (Blue)

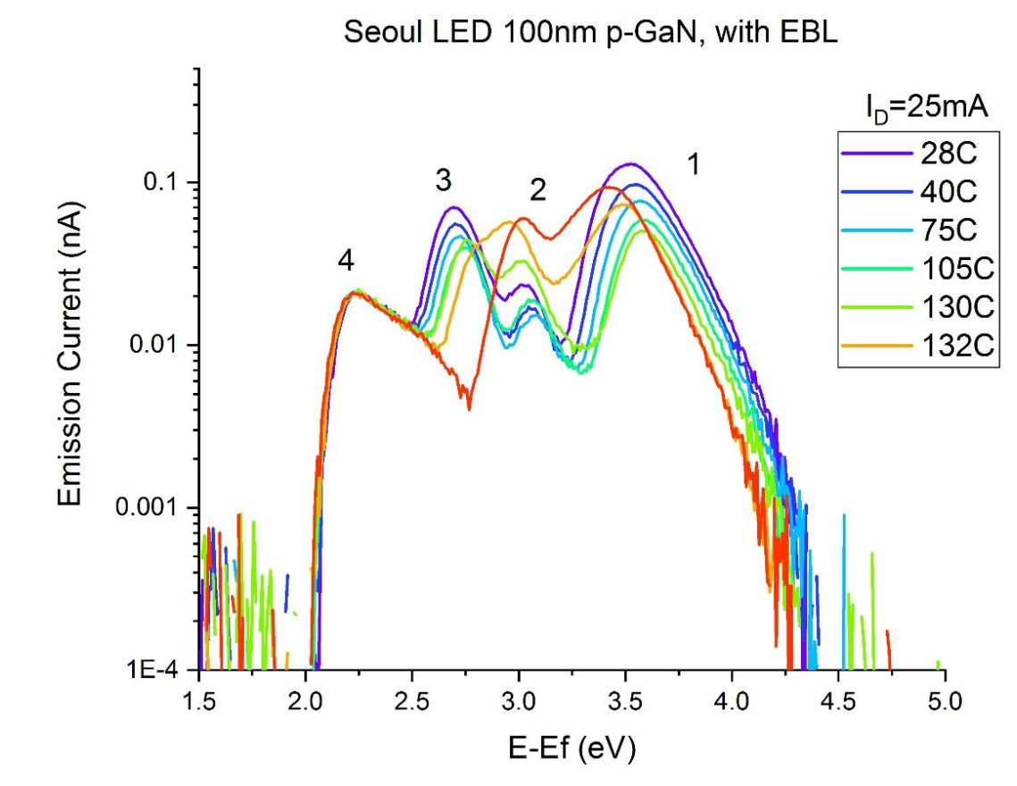
Temperature dependent electron energy distributions.



Large increase in peak 2 at temperatures above 75°C.

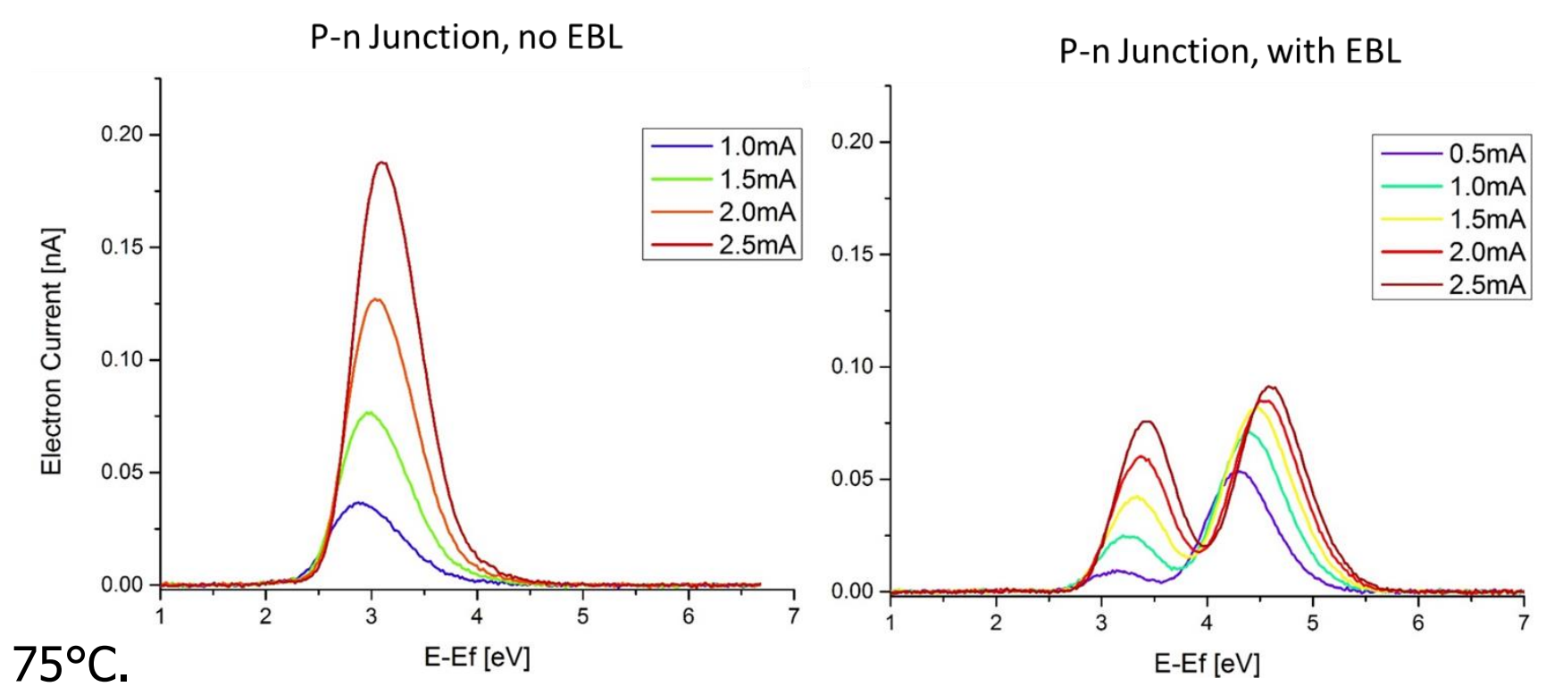


1. Peak 2 increases due to leakage and overshoot from thermal excitation.
2. Peak 1 decreases due to increased inter-valley scattering at elevated temperatures.

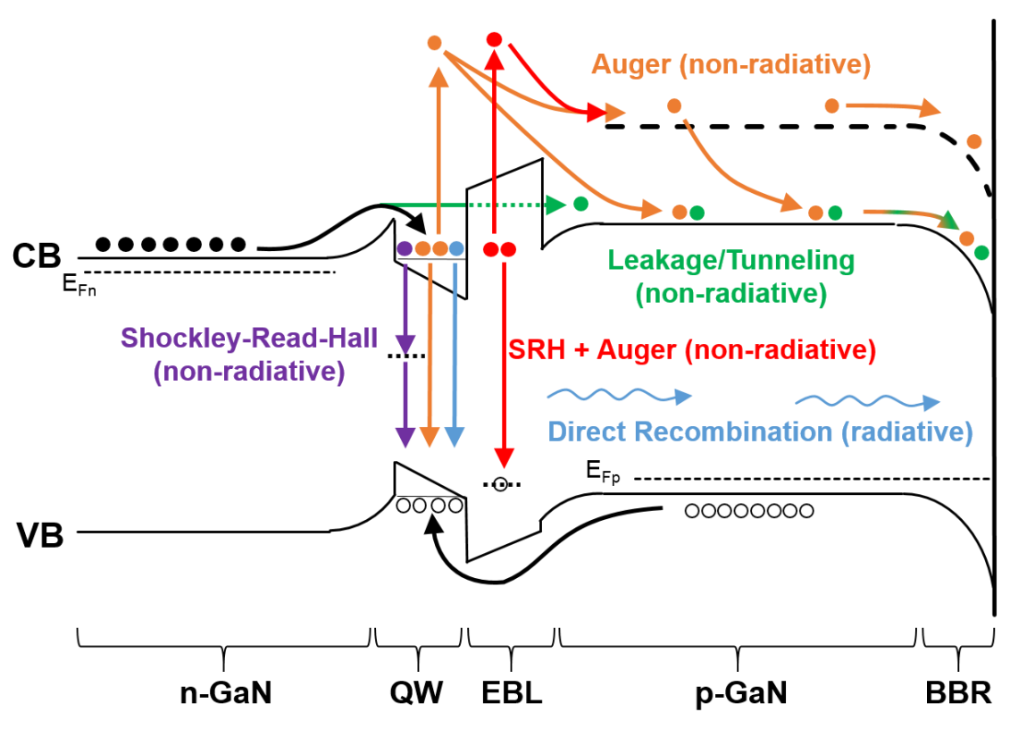


Peak 2 shows large increase at temperatures above 75°C.
Peak 1 shows increase in intensity at temperatures above 105°C.

The addition of an electron blocking layer in a simple p-n junction provides pathway for hot electron generation.



Comparison of spectra between a p-n junction and a p-n junction with a 10 nm AlGaN EBL.
Hot electrons are measured in the sample with EBL.

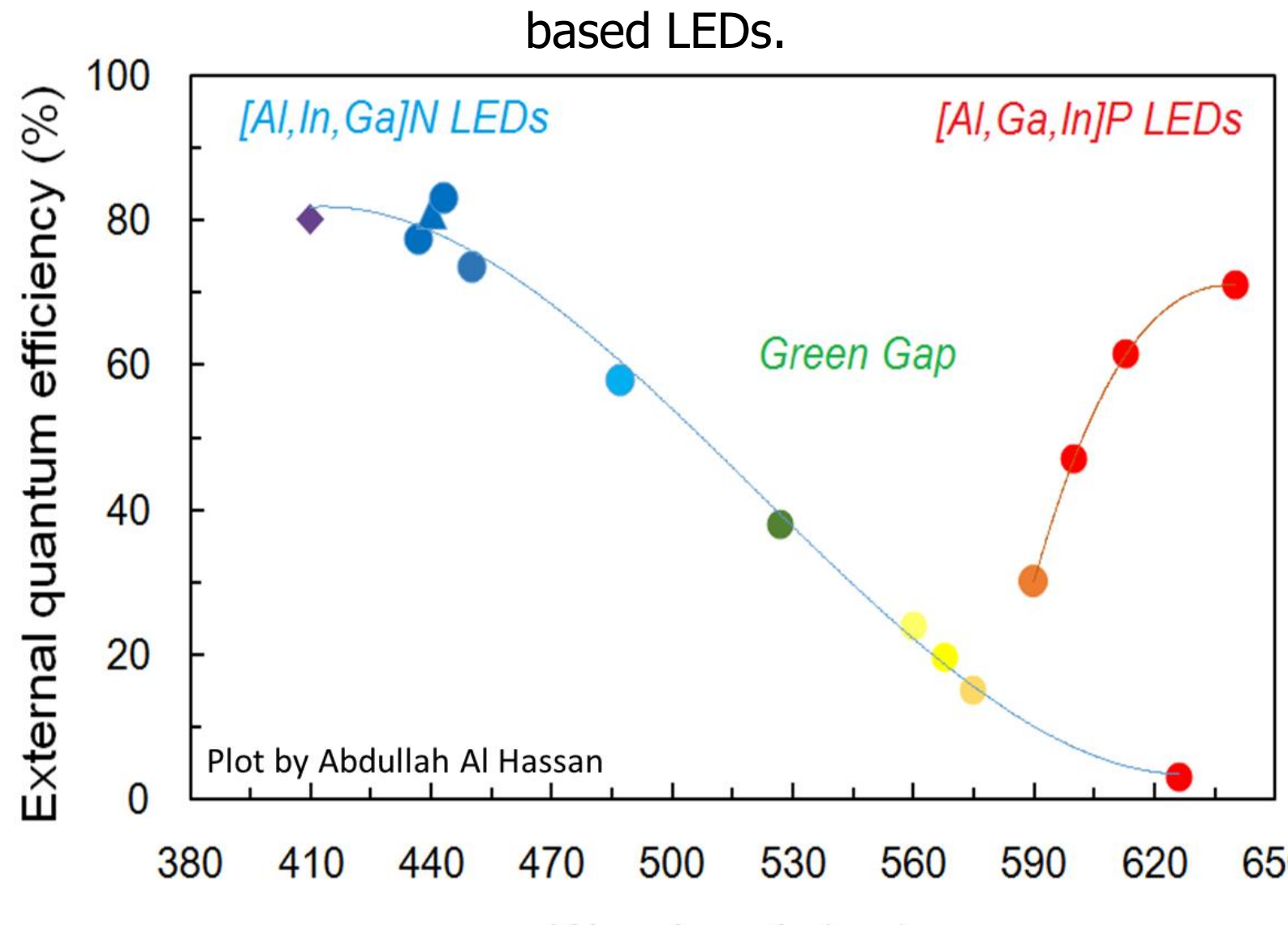


1. Peak 2 increases due to carriers tunneling through the barrier.
2. Peak 1 initially decreases, but increases at temperatures above 130°C from SRH + Auger process in the EBL. At high temperatures significant number of electrons are interacting with the EBL.

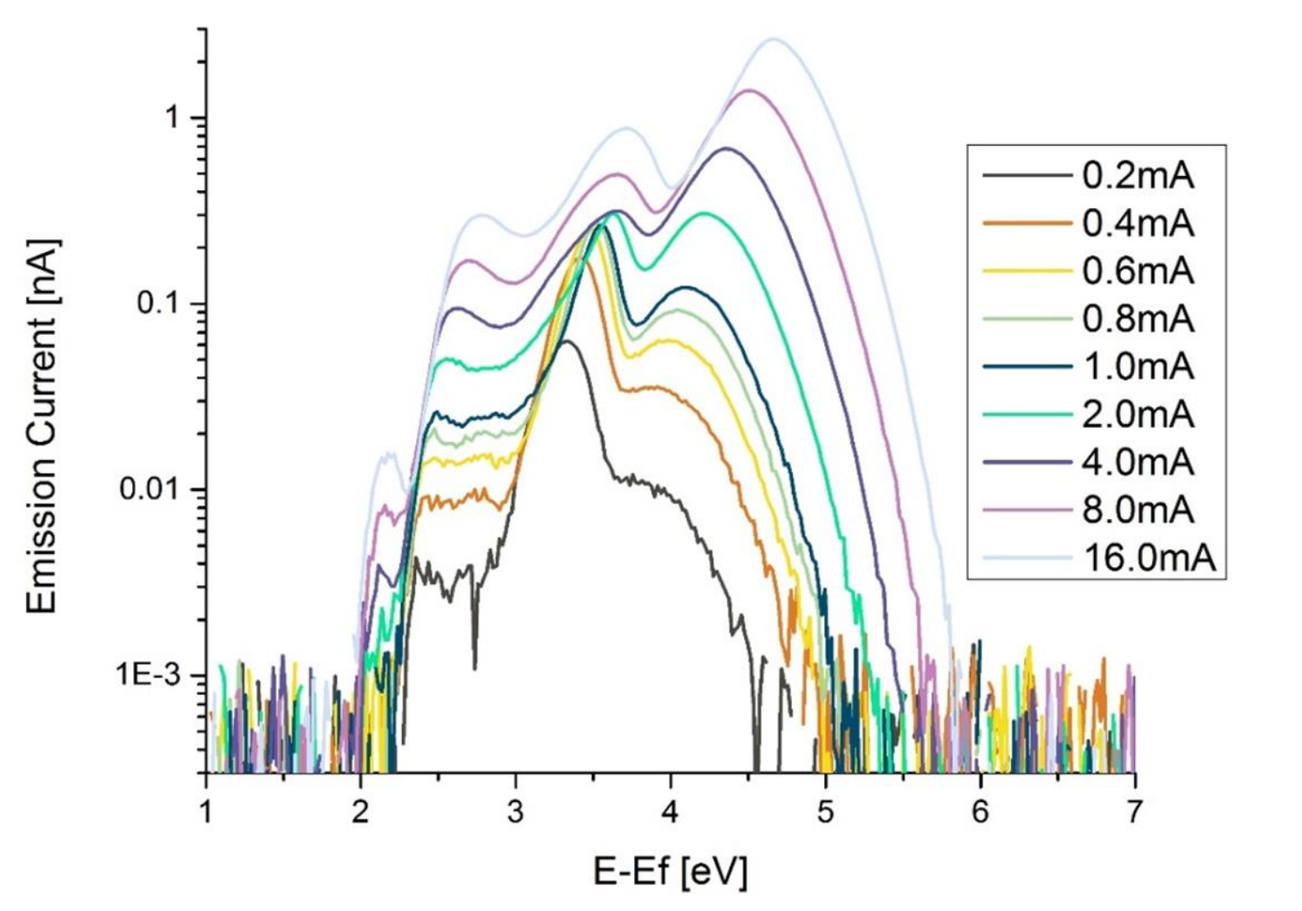
## RECENT & FUTURE WORK

### Droop Mechanism in Green

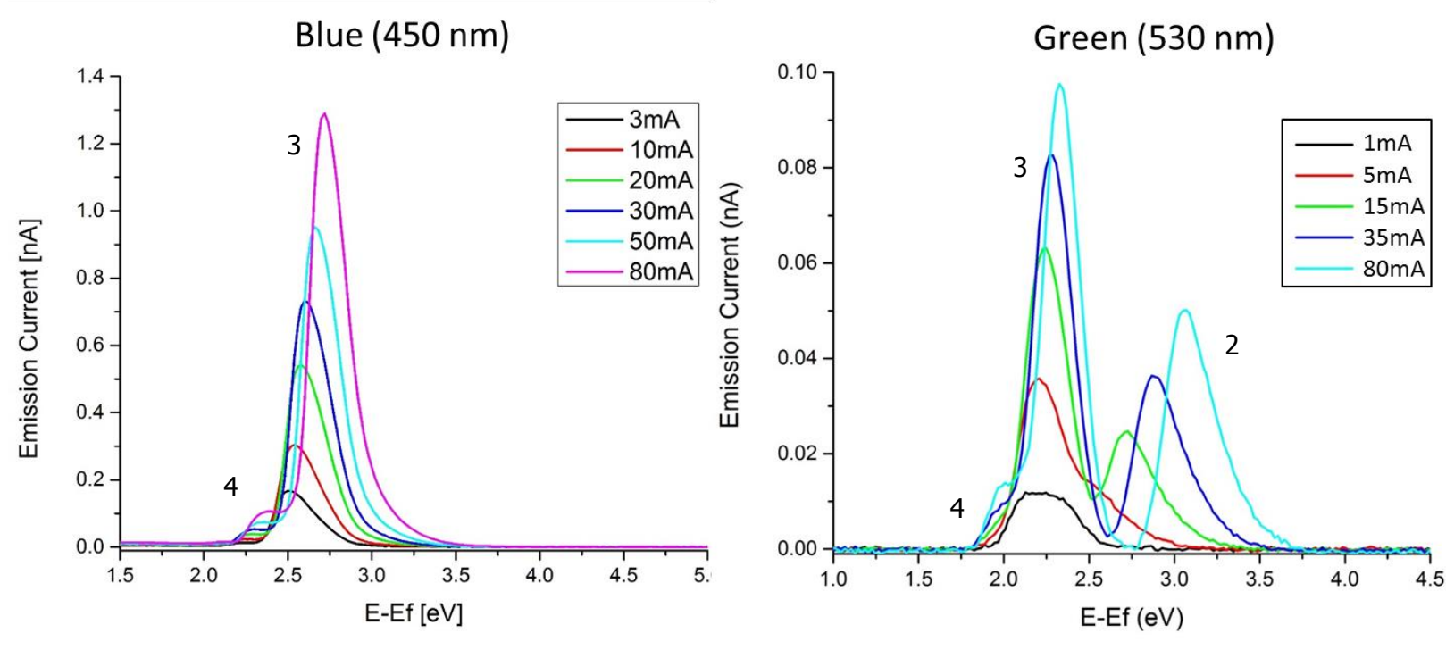
Ongoing efficiency problems in long wavelength nitride based LEDs.



Applying electron emission spectroscopy technique to try to understand loss mechanisms in green LEDs.

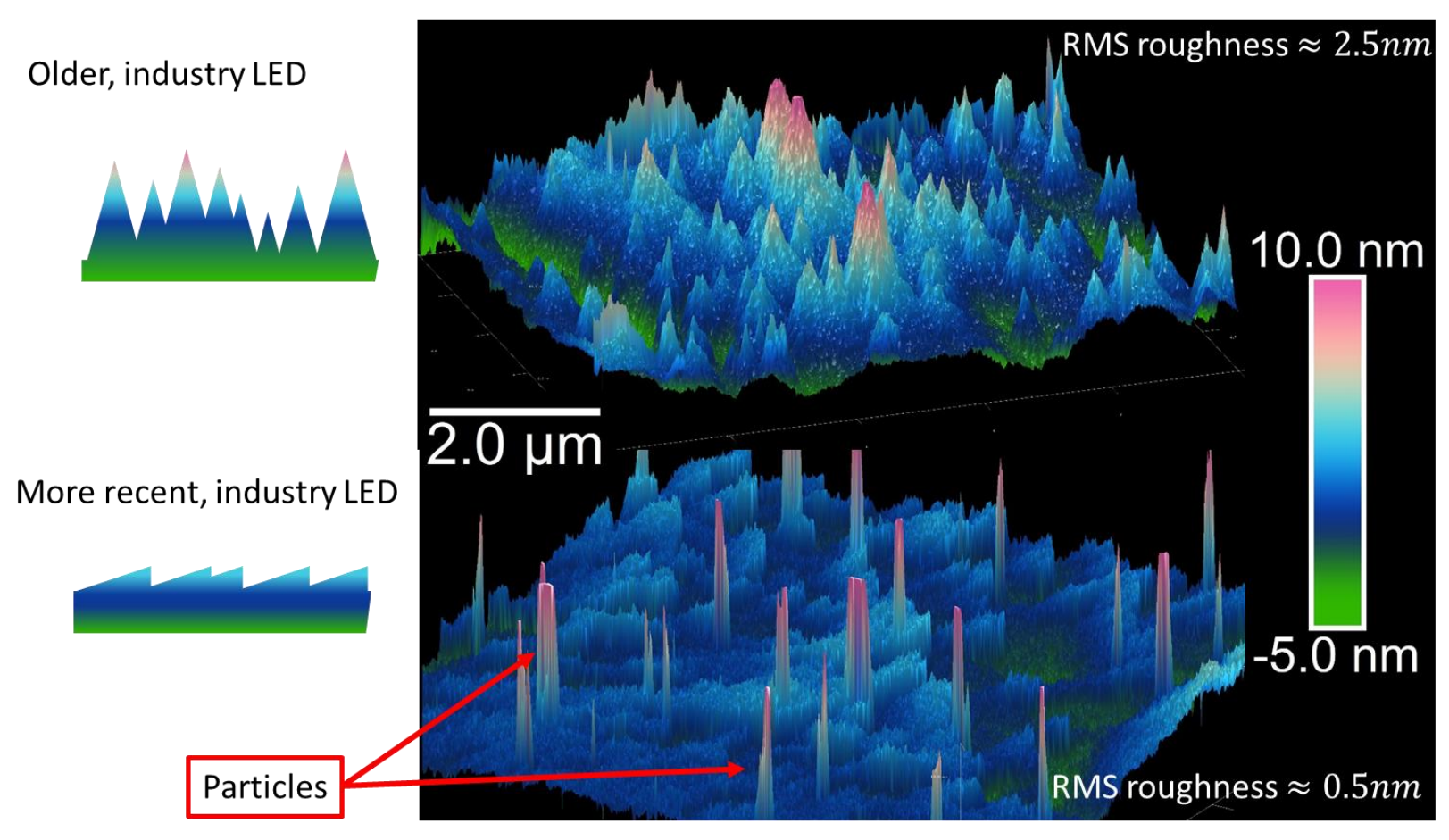


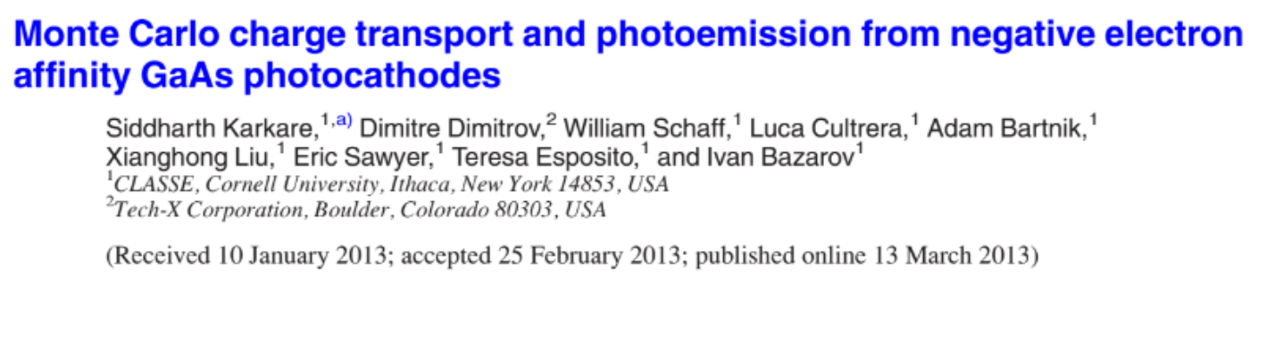
Presence of large peak 2 at very low injection currents is very different to spectra from blue LEDs.



Electron spectroscopy from new industry partner.
Shows similar large peak 2 emission from green LED.
However, this material does not show any peak 1 (Auger).

### Hot Electron Escape & K-Conservation





**Monte Carlo charge transport and photoemission from negative electron affinity GaAs photocathodes**

Siddharth Karkare,[1,a)] Dimitre Dimitrov,[2] William Schaff,[1] Luca Cultrera,[1] Adam Bartnik,[1] Xianghong Liu,[1] Eric Sawyer,[1] Teresa Esposito,[1] and Ivan Bazarov[1]
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[2]*Tech-X Corporation, Boulder, Colorado 80303, USA*

(Received 10 January 2013; accepted 25 February 2013; published online 13 March 2013)

**In order to be emitted the electron must be able to satisfy both conservation laws.**

$$E + E_V - E_A = E', \qquad \vec{\boldsymbol{k}}_\perp + \vec{\Lambda}_\perp = \vec{\boldsymbol{k}'}_\perp$$

**In other words, emission in vacuum requires that the emitted electron must have a non negative wavevector in the longitudinal direction in vacuum.**

**The longitudinal component of the vacuum wave vector can be written as**

$$\vec{\boldsymbol{k}'}_\parallel = \sqrt{\frac{2m_e(E - E_A + E_V)}{\hbar^2} - (\vec{\boldsymbol{k}}_\perp + \vec{\Lambda}_\perp)^2}$$

**If $\vec{\boldsymbol{k}'}_\parallel \geq 0$, the electron can be emitted.**

**If the valley from which the electron is being emitted, is in the direction of the surface normal, then $\vec{\Lambda}_\perp = 0$. Otherwise, typically**

$$\vec{\Lambda}_\perp^2 \gg \frac{2m_e(E - E_A + E_V)}{\hbar^2}$$

**making $\vec{\boldsymbol{k}'}_\parallel$ imaginary and thus restricting emission from such valleys.**

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**For GaN, an electron in the L-valley $[\frac{1}{2}\frac{1}{2}\frac{1}{2}]$ at a (100) surface. In this case,**

$$\vec{\Lambda}_\perp^2 = 0.5\left(\frac{2\pi^2}{3a^2} + \frac{\pi^2}{c^2}\right) = 0.508\ \text{Å}^{-2}$$

**Where 'a' and 'c' are the lattice constants of GaN. ($a = 3.189$ Å, $c = 5.178$ Å)**

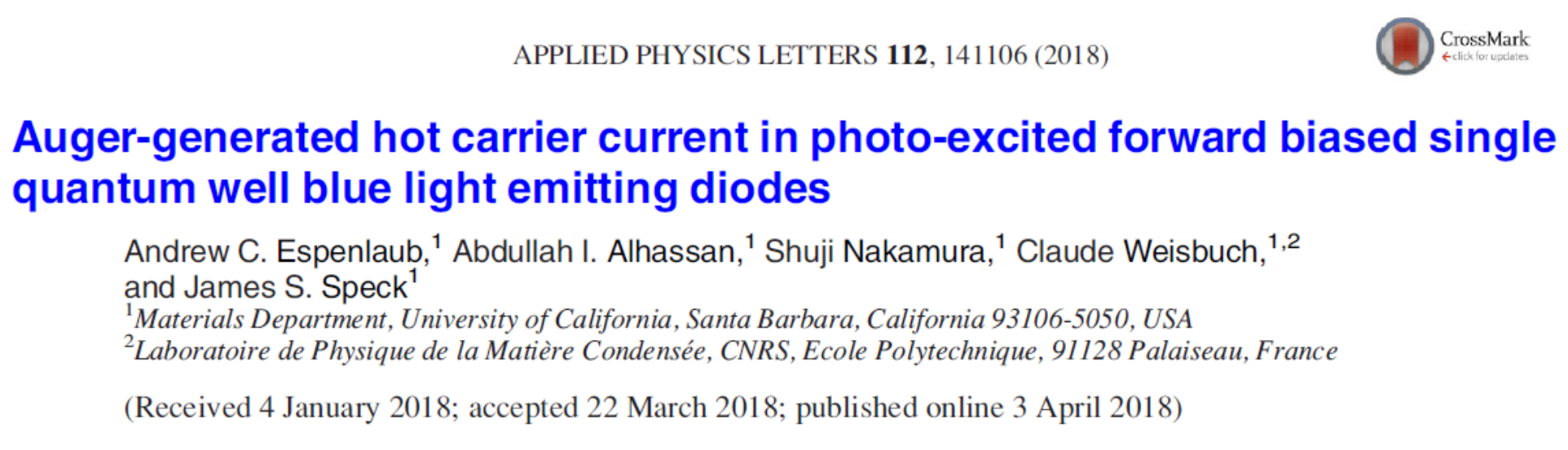
**For $E_V = 0.9eV$ and a typical value of $E_A = -1.1\ eV$ we can calculate**

$$\frac{2m_e(E - E_A + E_V)}{\hbar^2} = 0.074\ \text{Å}^{-2} \ll \vec{\Lambda}_\perp^2$$

$$\vec{\boldsymbol{k}'}_\parallel = \sqrt{0.074\ \text{Å}^{-2} - (\vec{\boldsymbol{k}}_\perp + 0.508\ \text{Å}^{-2}{}_\perp)^2}$$

**$\vec{\boldsymbol{k}'}_\parallel$ is imaginary and forbidding emission from this valley.**

### Photocurrent Measurements



APPLIED PHYSICS LETTERS **112**, 141106 (2018)

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**Auger-generated hot carrier current in photo-excited forward biased single quantum well blue light emitting diodes**

Andrew C. Espenlaub,[1] Abdullah I. Alhassan,[1] Shuji Nakamura,[1] Claude Weisbuch,[1,2] and James S. Speck[1]
[1]*Materials Department, University of California, Santa Barbara, California 93106-5050, USA*
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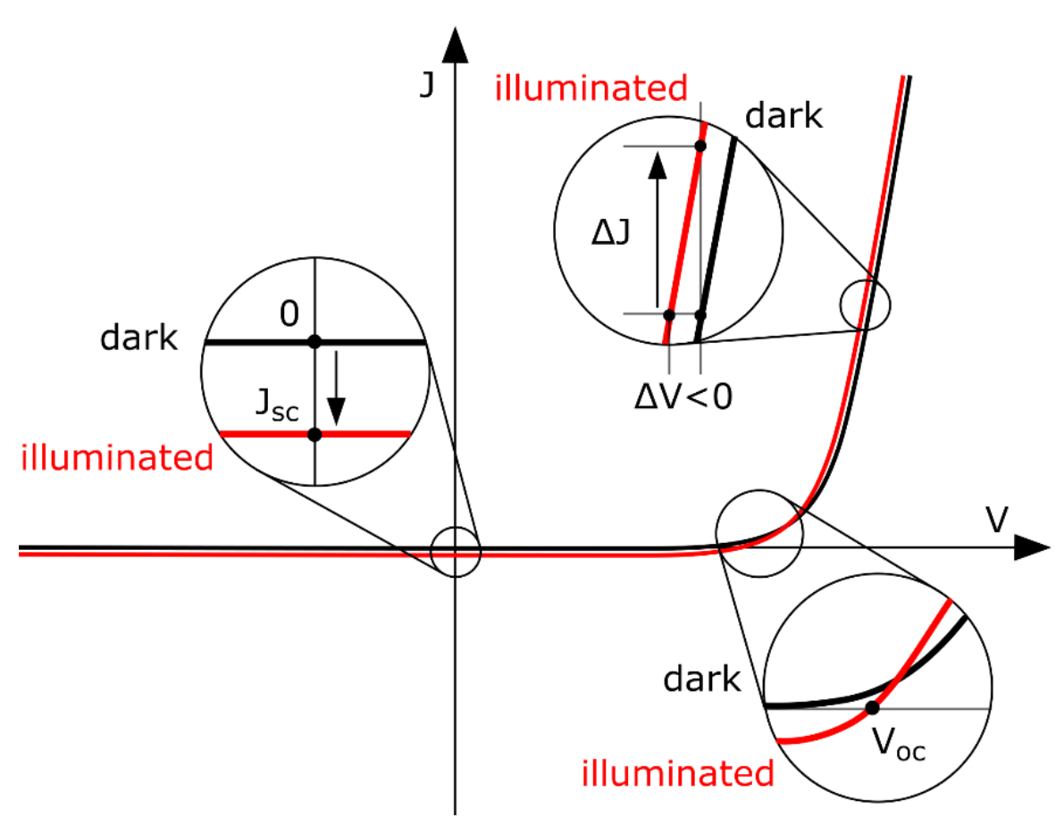
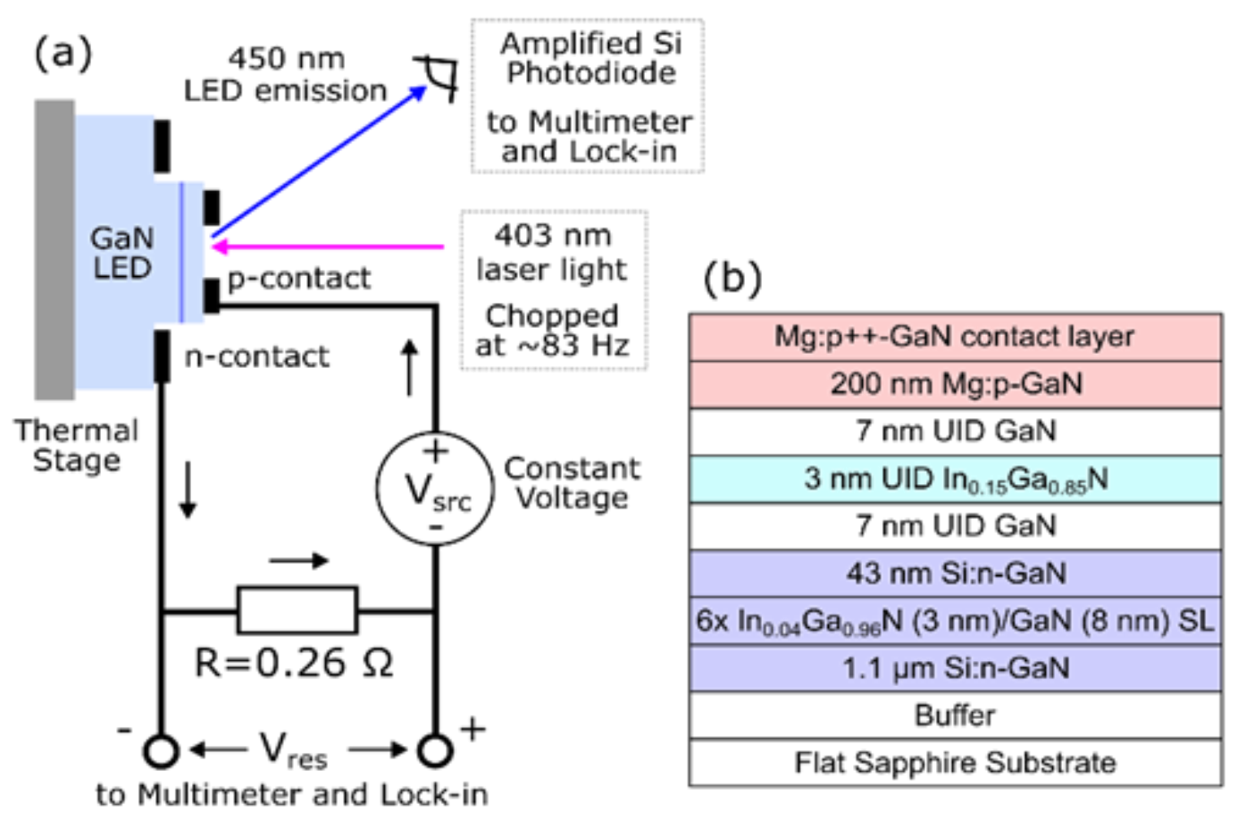
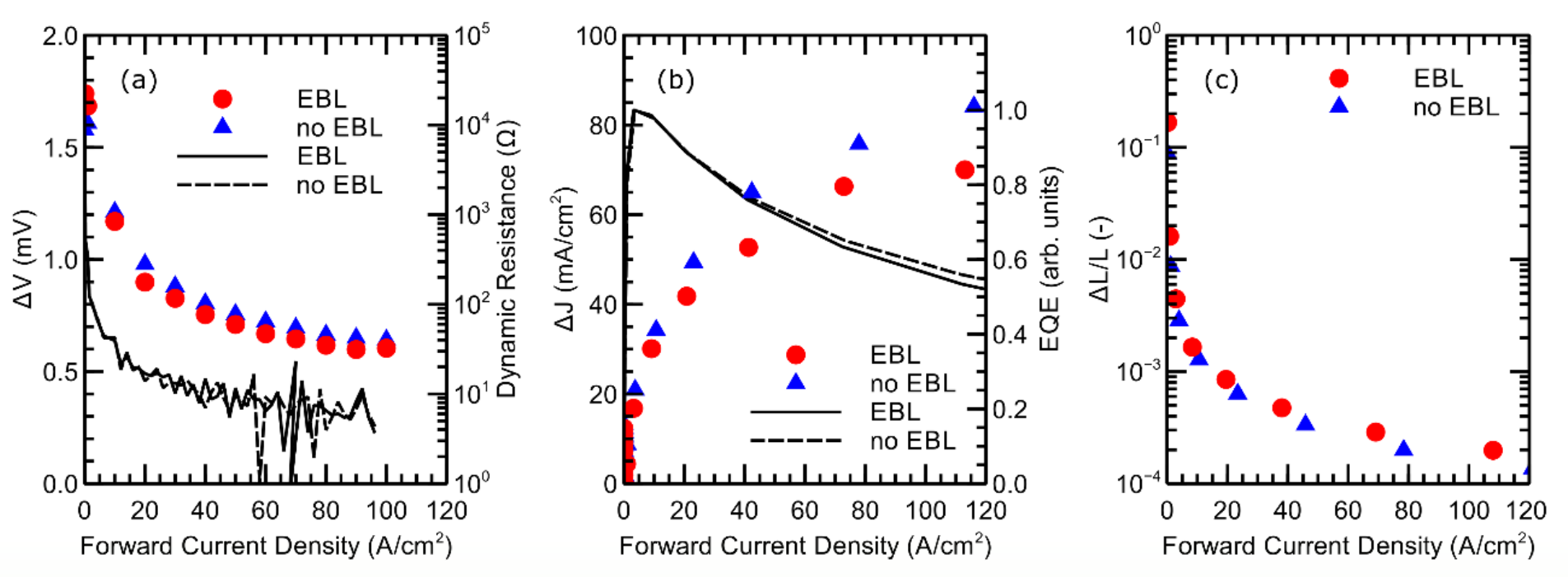
Recently work at UCSB, published in *Applied Physics Letters*



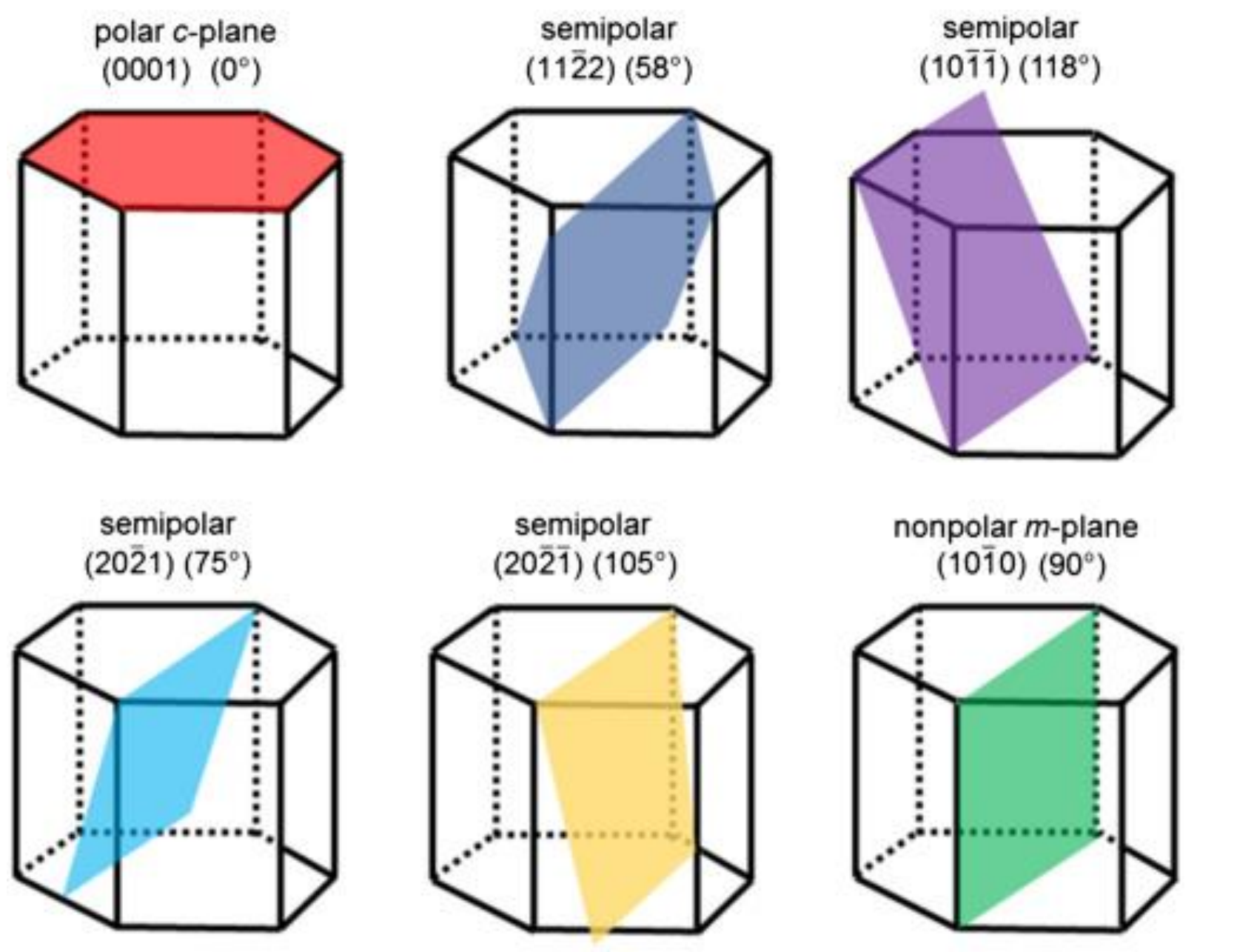
An **increase** in forward current (and EL intensity) in forward biased LEDs is observed.

The only photo-excitable carrier escape mechanism out of the QW active region which can explain this is **Auger-generated hot carrier escape.**

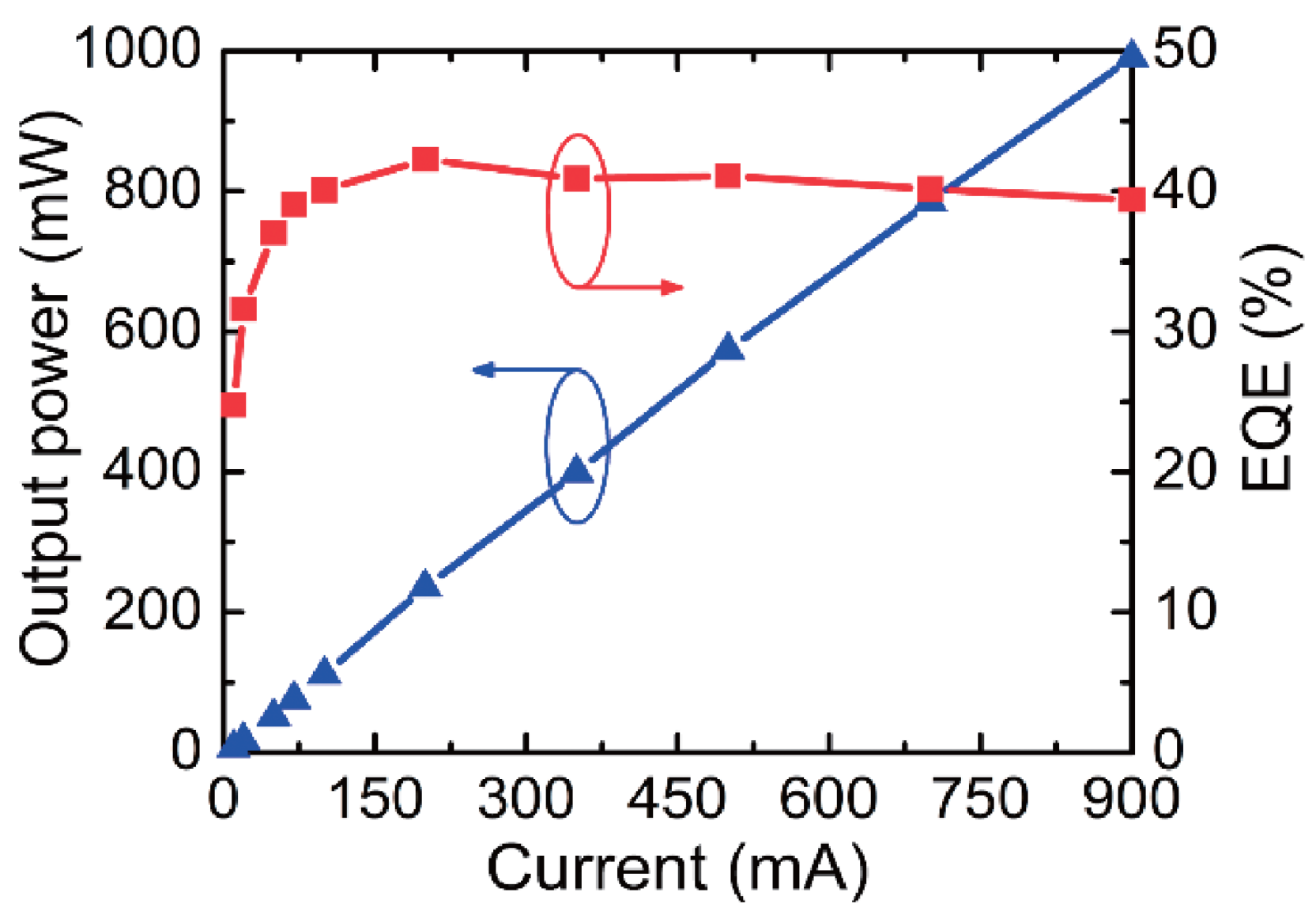




### Semi-polar $(20\bar{2}\bar{1})$



**Exploration of electronic energy populations in "droop free" devices**



Measurement of vacuum emitted electrons from semi-polar LEDs could confirm if improvements in droop are related to reduced Auger recombination.

## ACKNOWLEDGEMENTS

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