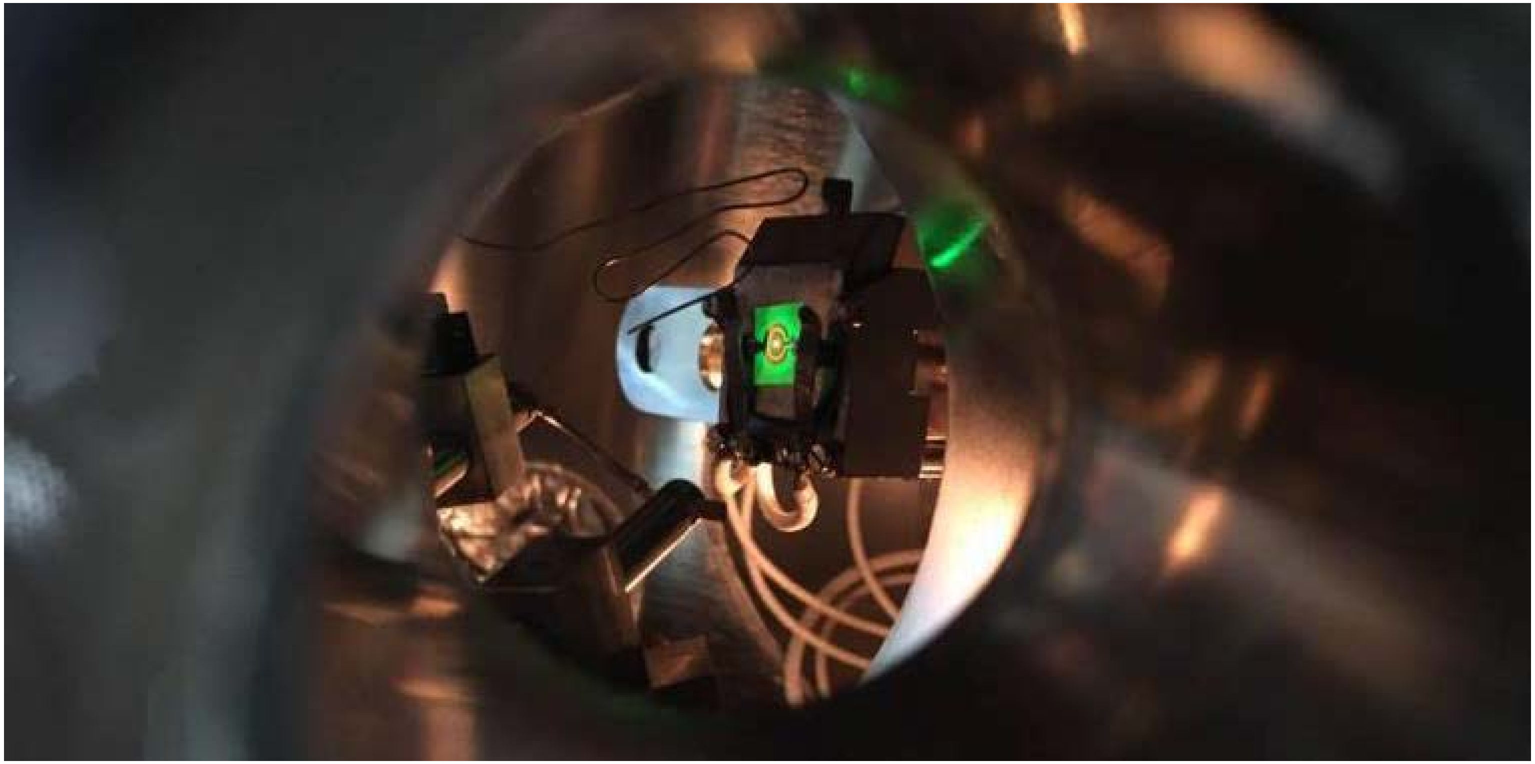
Identification and Mitigation of Droop Mechanism in GaN-Based Light Emitting Diodes (LEDs)



UC Santa Barbara

Professor James S. Speck

Speck@ucsb.edu

Project Summary

Timeline:

Start date: July 31, 2015

Planned end date: July 31, 2018

Key Milestones

1. Milestone 3.1: Determination of dominant droop mechanism in blue c-plane LEDs; date
2. Milestone 3.3: Determination of thermal droop mechanism in blue c-plane LEDs; date

Budget:

Total Project $ to Date:

- DOE: $935245.34
- Cost Share: $250,000

Total Project $:

- DOE: $1,000,000
- Cost Share: $250,000

Key Partners:

Cree, Inc.	

Project Outcome:

Development of a tool to directly identify the dominant non-radiative recombination mechanisms responsible for current droop, thermal droop, and the green gap.

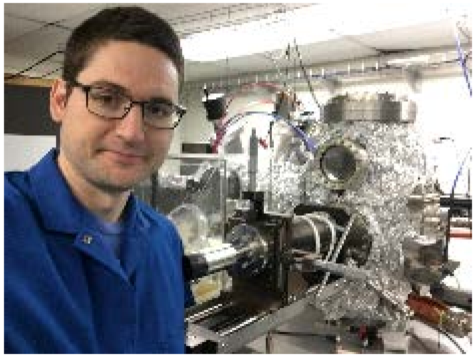
Team

Prof. James Speck
UCSB

Prof. Claude Weisbuch
UCSB/Ecole Polytechnique

CREE™

Cree, Inc.
U.S. Industry Partner



Daniel Myers
UCSB – Electroemission

Wan-Ying Ho
UCSB – Electroemission

Andrew Espenlaub
UCSB – Photocurrent

Challenge

Problem Definition:
To address the fundamental challenge of identifying the origins of current droop, thermal droop, and the green gap in state-of-the-art LEDs. Understanding the origins of LED *inefficiency* will lead to more efficient LEDs.

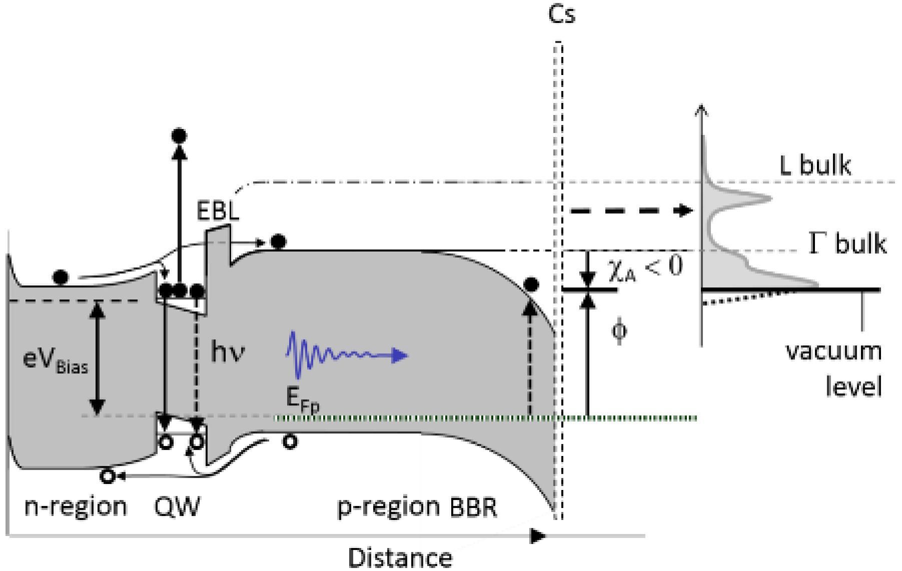
Target Market and Audience:
Audience: U.S.-based LED manufacturers and U.S. R&D community.
Target market: U.S. lighting market.

Approach

Measurements of droop mechanisms

- DC electrical or optical excitation (the 'ABC' model for EQE/IQE).
- Many uncertainties - some intrinsic and essential. Modeling fails to include disorder and the change of ABC parameters with injection.
- Measurements do not observe carrier dynamics inside LEDs (except time resolved emission measurements which yield dynamics, but no direct information on carriers energies).
- Carrier transfer in EL (Vampola, UCSB) could not differentiate between carrier leakage or Auger. Recent hot carrier transfer between quantum wells by Osram in PL.

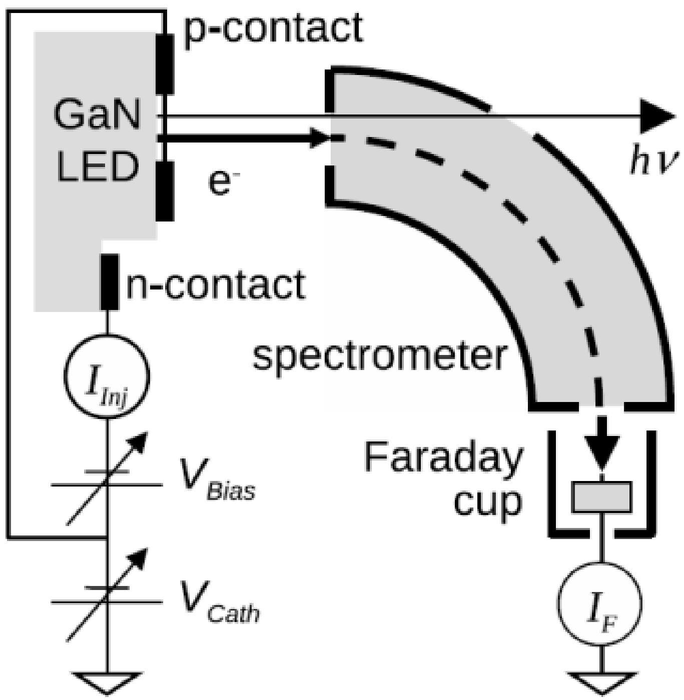
The electroemission technique



Measure electron energies and currents ***inside*** the LED under operation by measuring electron current and energies **outside** the LED

Approach

Low Energy Spherical Sector Analyzer



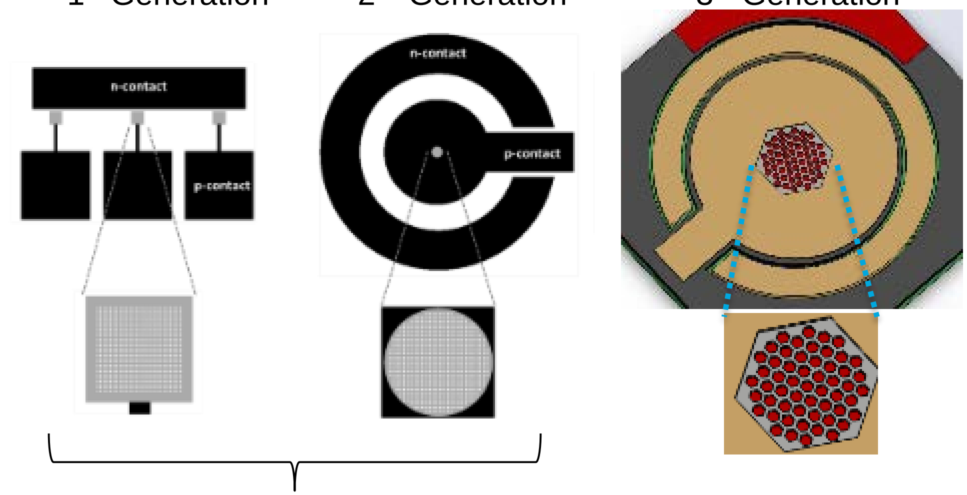
- Constant energy -> analyzer potentials fixed
- 50 meV resolution
- ~3 x 10^{-11} Torr ensures $\Phi_{GaN/Cs}$ stable over several days

Vary V_{Cath} to sweep energy

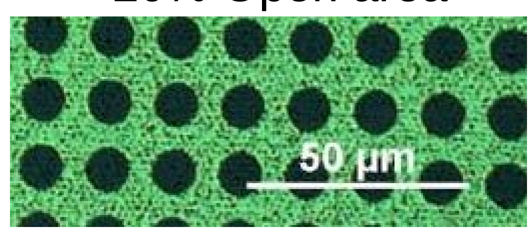
Note:
V_{Bias} relative to V_{cath}
V_{Bias} biased relative to ground

Device Design

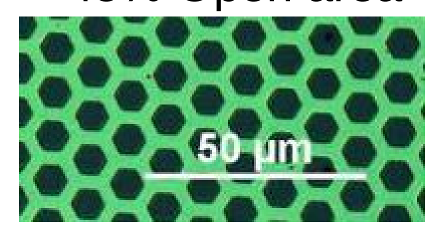
1st Generation | 2nd Generation | 3rd Generation



~20% Open area

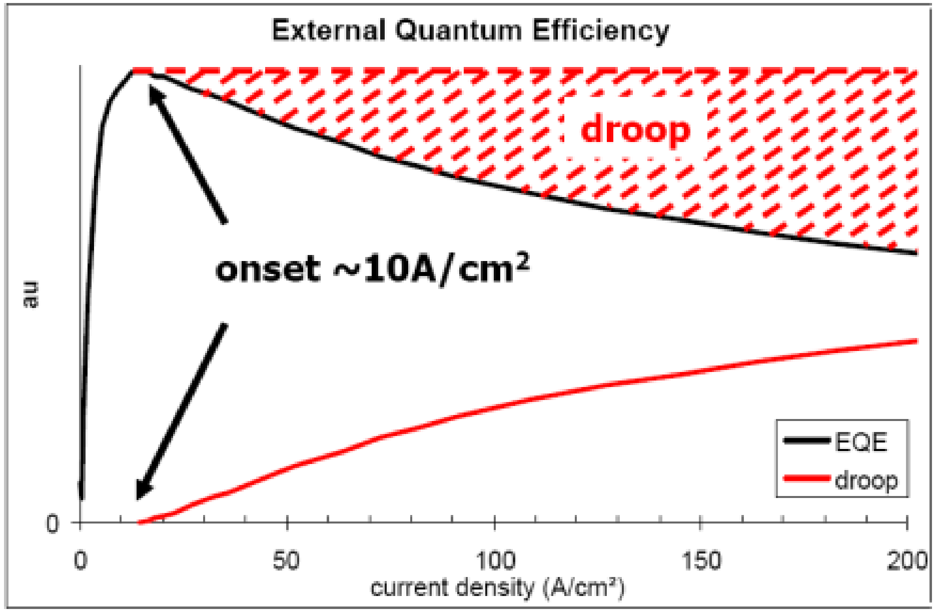


~45% Open area

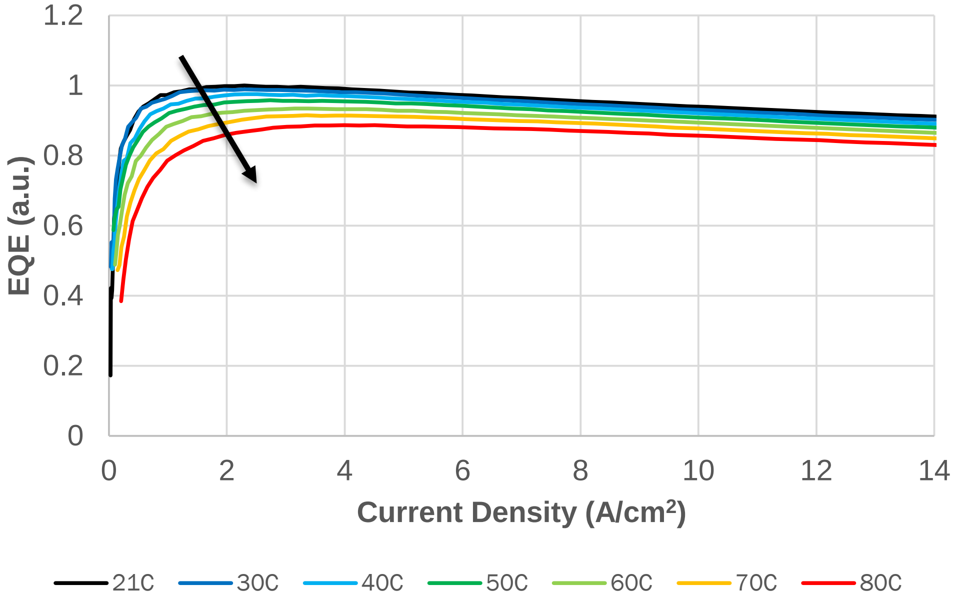


Impact

Current Droop



Thermal Droop



Advancement of LED technology by providing industry with physical mechanisms responsible for efficiency loss

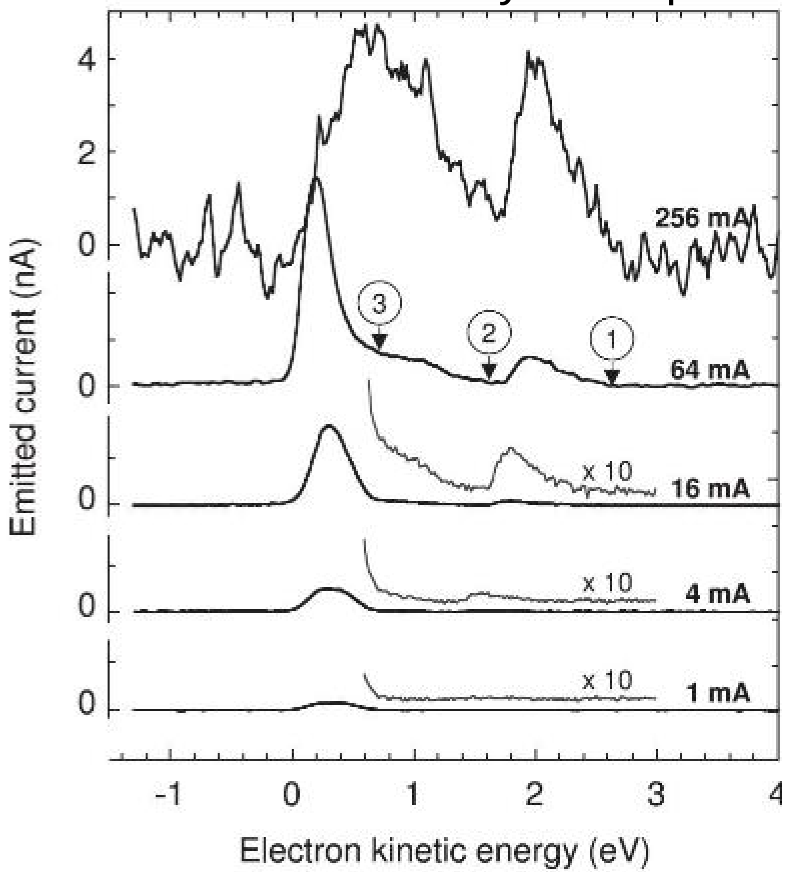
- Understanding electron transport phenomena to optimize semiconductor design.
- Provide pathways for engineering solutions to efficiency problems in LEDs past current state-of-the-art.

Progress

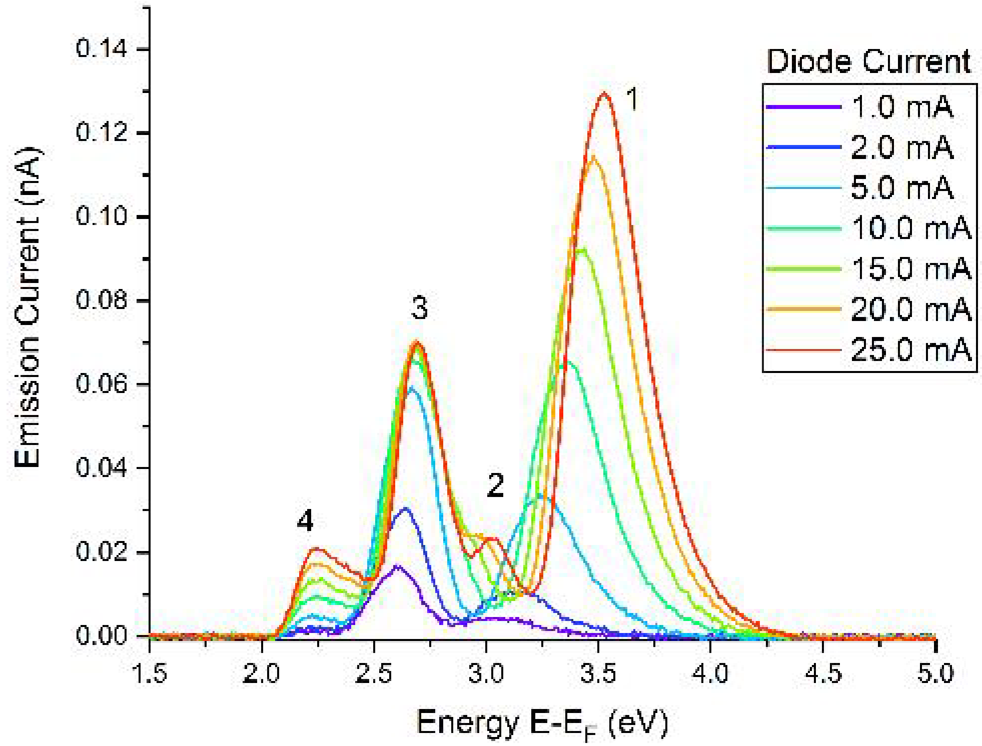
Subtask 3.1: EES on Commercial Grade Blue: Dominant Droop Mechanisms

UCSB confirms measurements of hot carriers emitted from LEDs.

CNRS-École Polytechnique

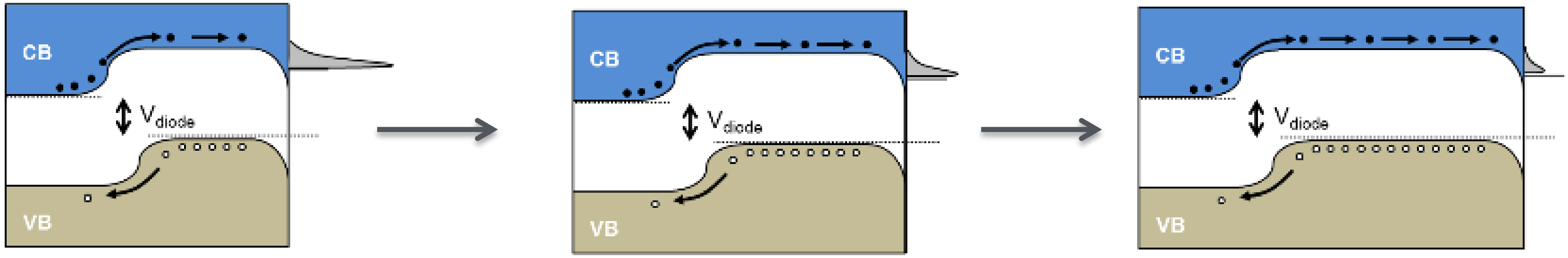


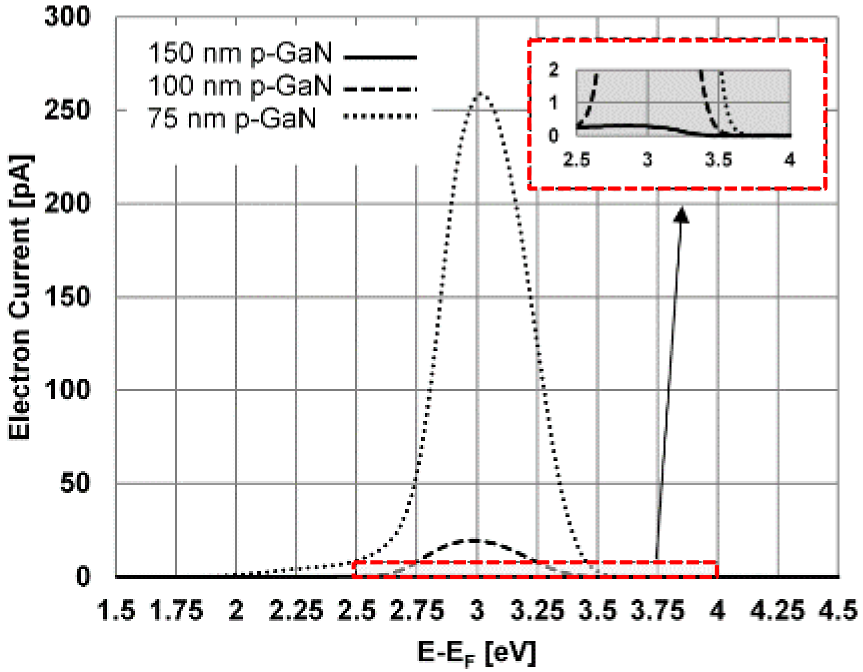
UCSB

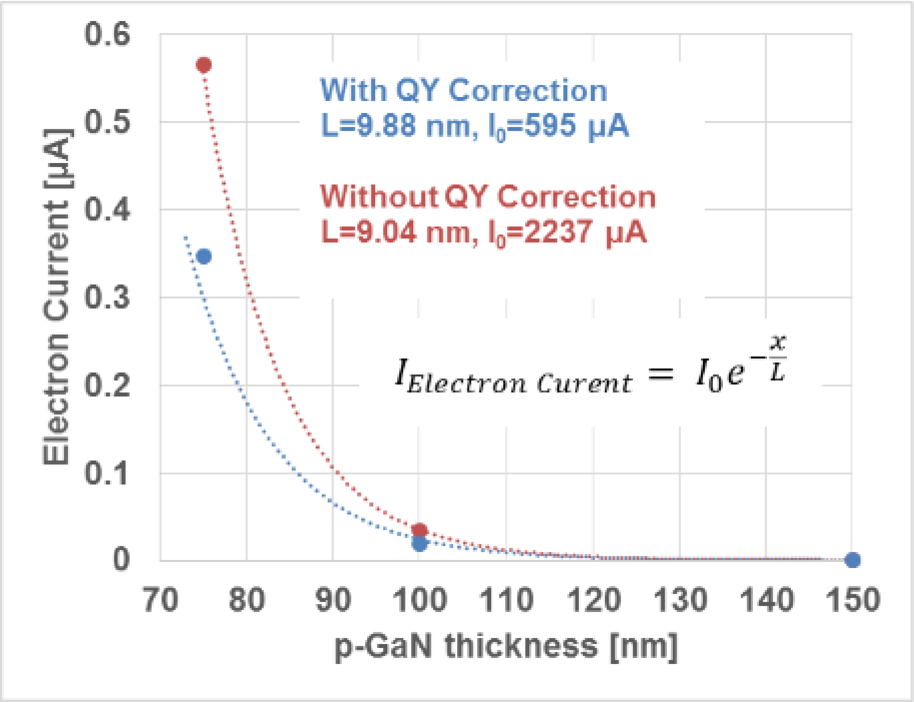


Progress

Milestone 2.1: Quantification of electron diffusion length in p-GaN

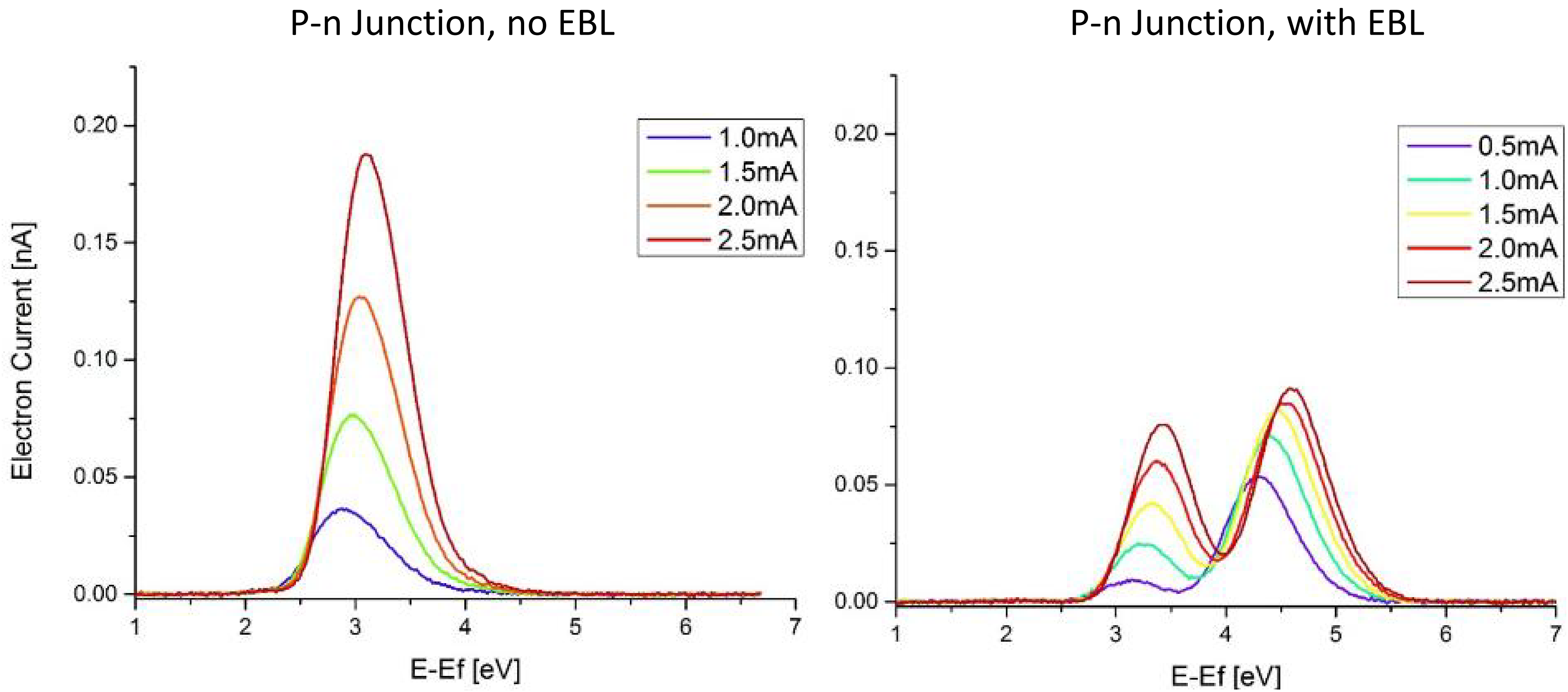






Progress

Milestone 2.2: Quantification of the efficacy of the AlGaN EBL via EE spectroscopy

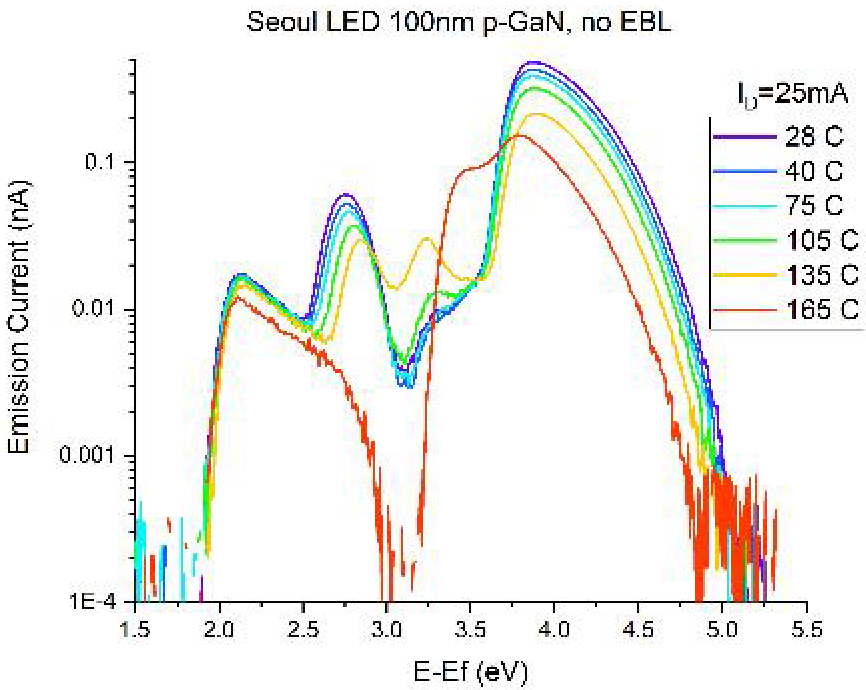


Electron blocking layer is capable of producing hot carriers.

- Only Γ-valley emission is seen from pn-junctions
- Hot carriers present in pn-junctions with EBLs may be generated by trap-assisted Auger recombination.

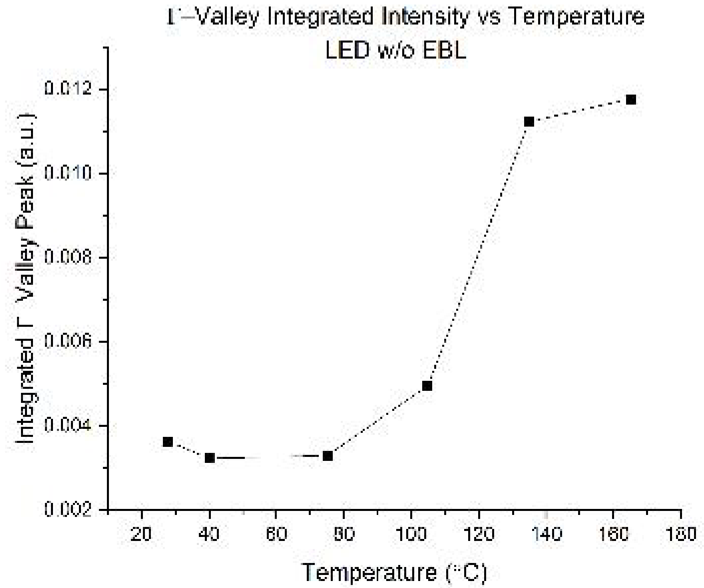
Progress

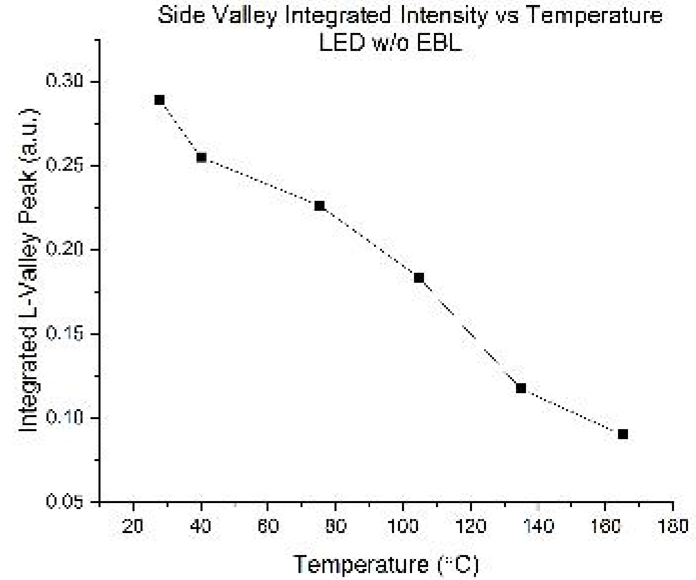
Milestone 3.3 & 5.4: EES to determine thermal droop mechanisms



Temperature dependent EES

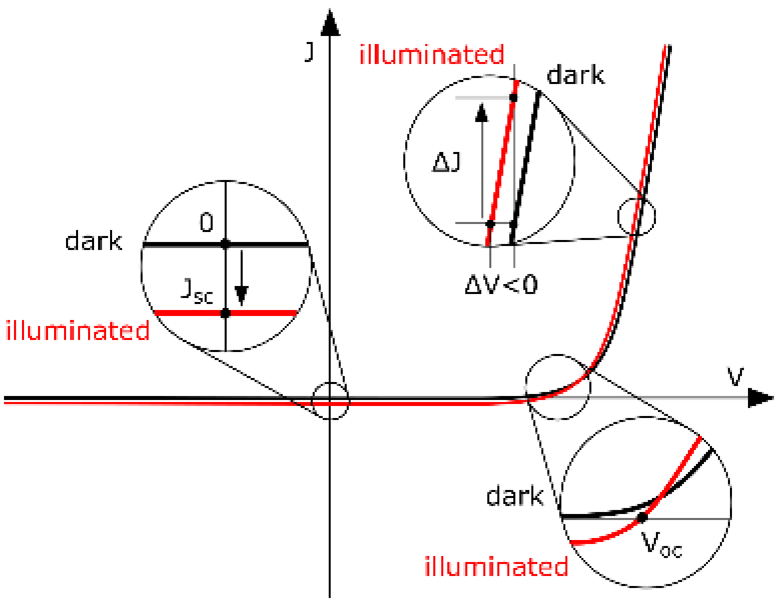
- Increases in Γ-valley electrons at temperatures above 75 °C suggests increases in QW overshoot and/or leakage.





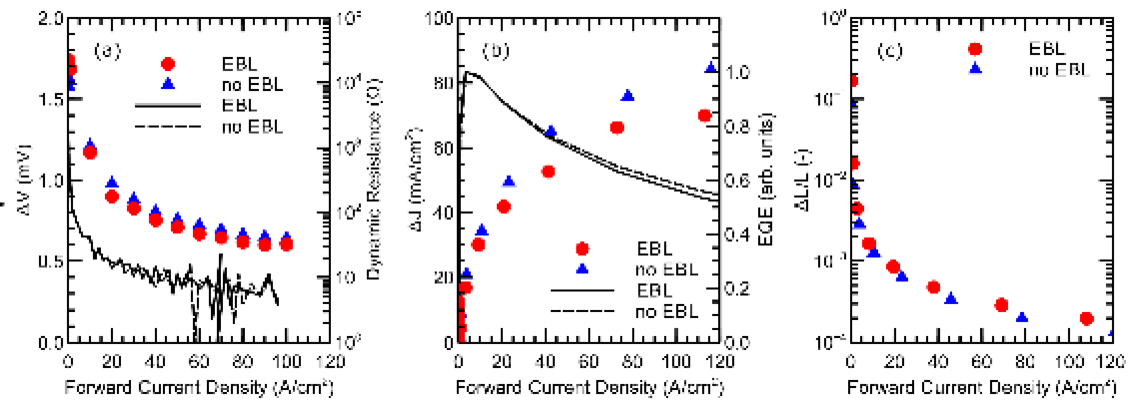
Progress

Additional Work on Auger-Detection by Benchtop Photocurrent Measurements



Photocurrent in Forward-Biased LEDs

Increase in forward current (and EL intensity) in forward biased LEDs -> can only be explained by Auger-generated hot carrier current



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

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

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*Figures from **Espenlaub, et al., Appl. Phys. Lett., 112, 141106 (2018)** – recently published (Editor's Pick)*

Stakeholder Engagement

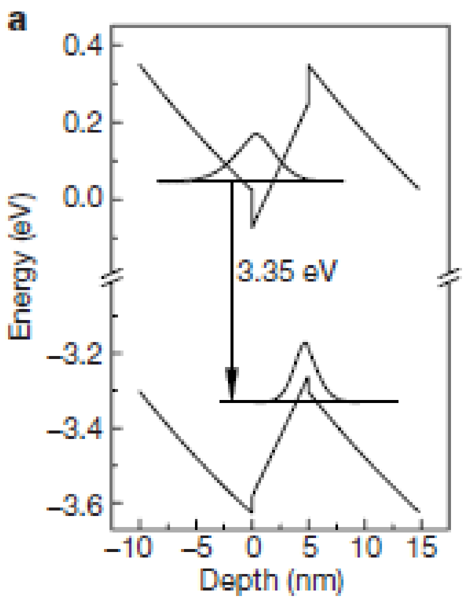
Stakeholders:
U.S. Department of Energy
Cree, Inc. (U.S. industrial partner)
U.S. Academic R&D community

Engagement with Industry:
Industry partnerships have supplied sample material for the study of state-of-the-art devices. This provides us a pathway to understanding efficiency problems which persist in commercially available solid-state lighting.

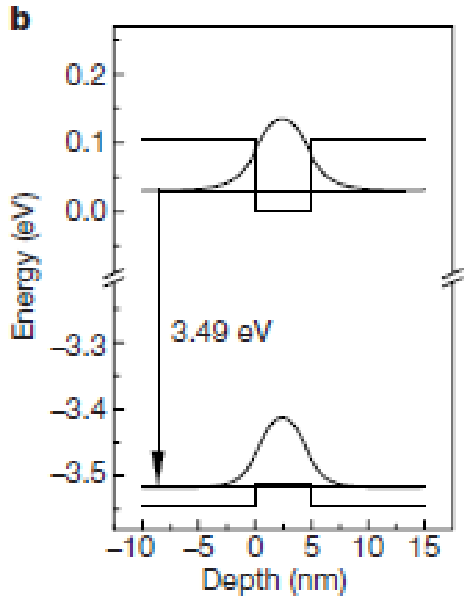
Communication with Stakeholders:
DoE SSL workshops
Scientific publications (recent article published in *Appl. Phys. Lett.*)

Remaining Project Work

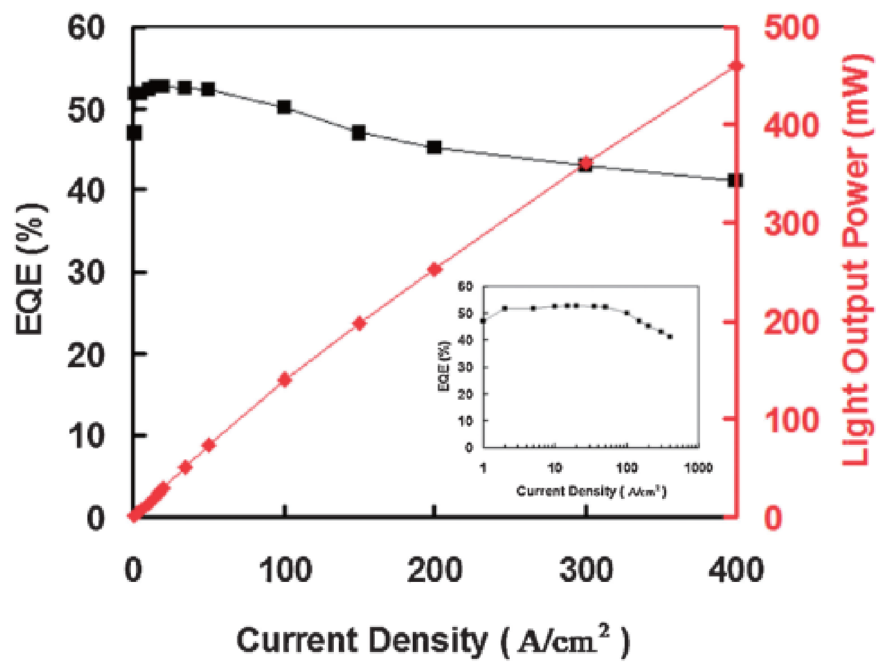
Milestone 5.2: Identification of residual current droop mechanism in semipolar $(20\bar{2}\bar{1})$ blue LEDs



c-plane LED



Semipolar LED



EES measurements will provide explanation of low-droop characteristics of semipolar $(20\bar{2}\bar{1})$ LEDs

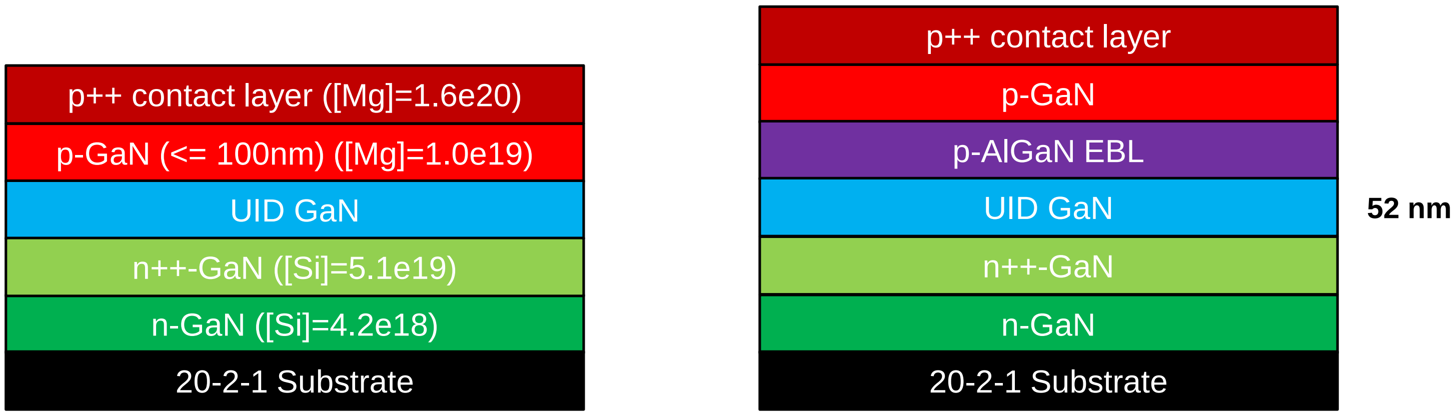
- Improvements to wavefunction overlap by reduction of electric fields in active region.
- Reduction of QCSE → Reduced Auger recombination related efficiency losses.

Remaining Project Work

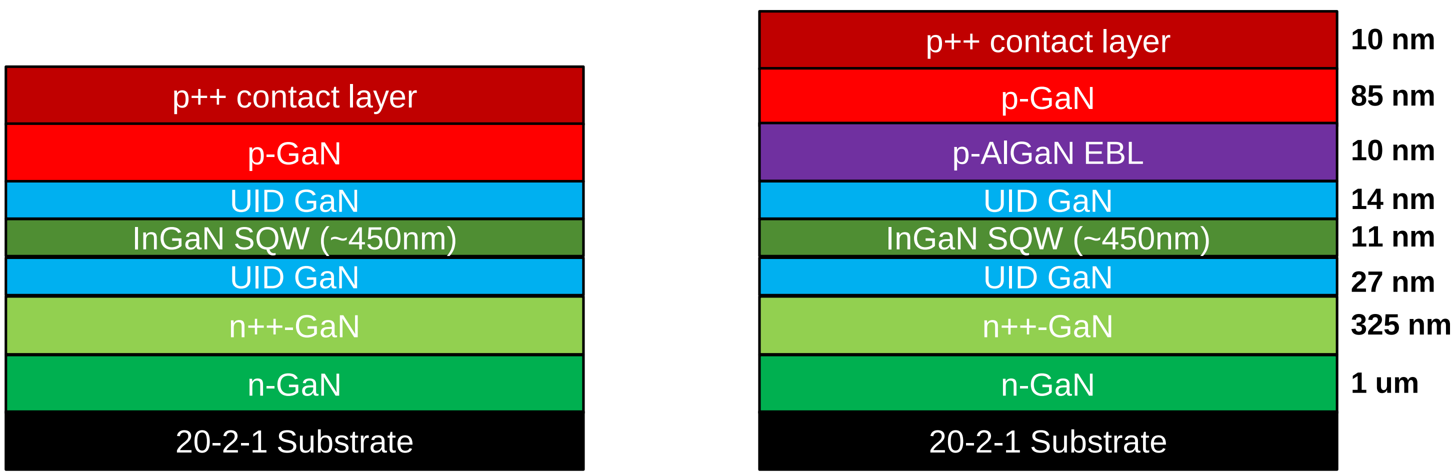
Milestone 5.2: Identification of residual current droop mechanism in semipolar $(20\bar{2}\bar{1})$ blue LEDs

Growth details of reference pn-junctions and LEDs for EES experiments

pn-junctions



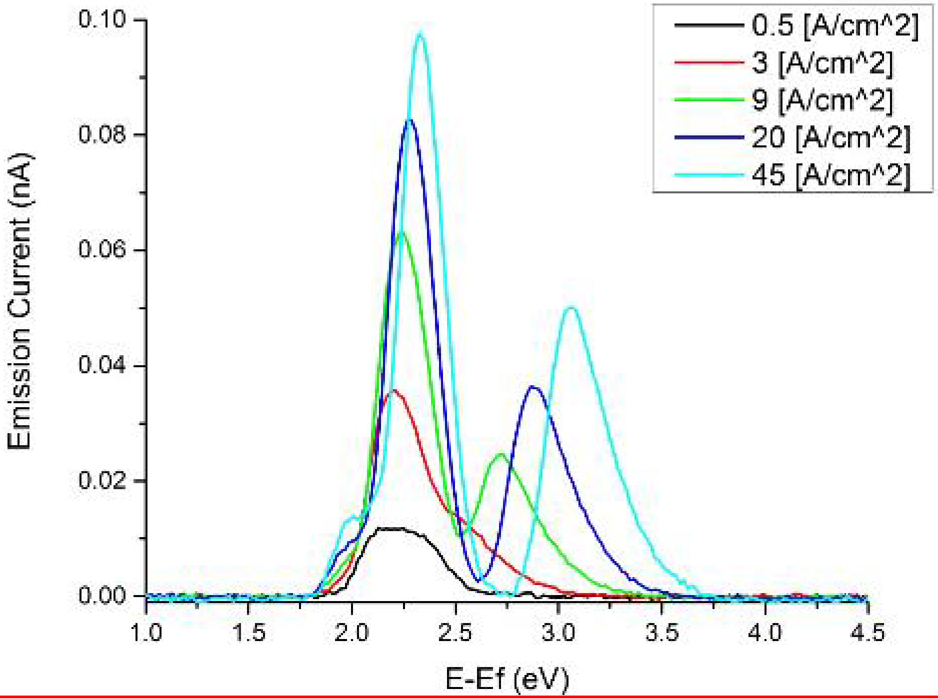
LEDs



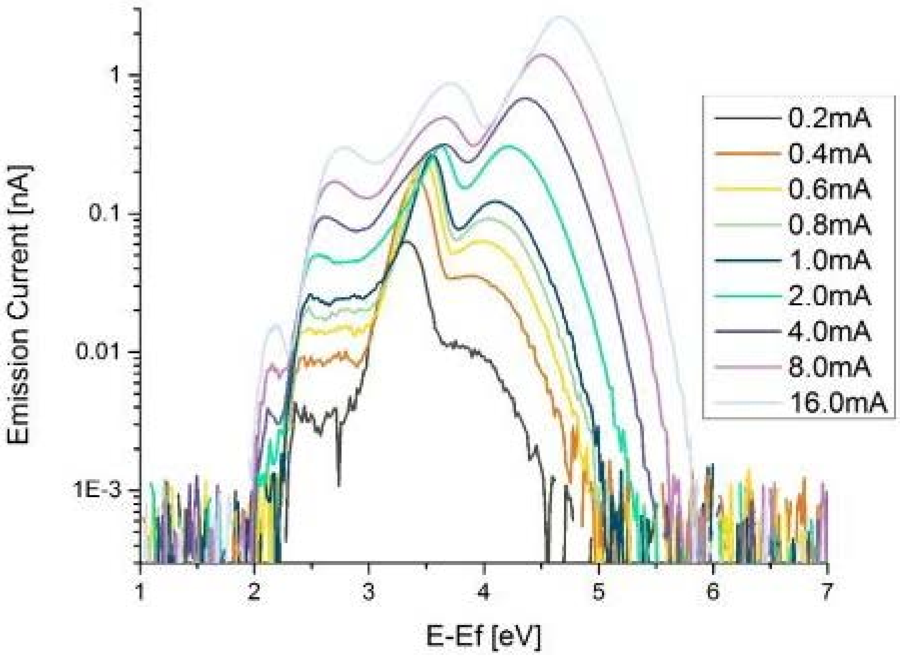
Remaining Project Work

Milestone 3.2: Determination of dominant droop mechanism in green LEDs

Industry Grown Green (520nm)



UCSB Green LED



Ongoing work towards understating droop mechanisms in green LEDs

- Large Γ-valley emission at low current density operation
- Auger generated electrons have lower energy in green → possibly different intervalley transfer efficiency.

Thank You

UC Santa Barbara
Professor James S. Speck
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REFERENCE SLIDES

Project Budget

Project Budget: FY 2018: No cost extension
Variances: One year no cost extension to complete tasks.
Cost to Date: $935,245.34 to DOE … estimated balance = $0 on 6/30/2018
Additional Funding: None

Budget History					
FY 2016 (past)		FY 2017 (past)		FY 2018 (current)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
550,000	137,495	450,001	112,505	NCE	NCE

Project Plan and Schedule

Project Schedule	
Project Start: July 31, 2015	Completed Work
Projected End: July 31, 2018	Active Task (in progress work)
	Milestone/Deliverable (Planned)
	Milestone/Deliverable (Actual)

	FY2016				FY2017				FY2018			
Task	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Q1 Milestone 1.1: Annealable ohmic contacts to p-GaN												
Q2 Milestone 1.2: Reduction in metal photoemission												
Q3 Milestone 1.3: 1% quantum yield												
Q4 Milestone 1.4: Quantum yields of Γ and L												
Q4 Milestone 2.1: Electron diffusion length in p-GaN												
Q4 Milestone 2.2: Efficacy of the AlGaN EBL												
Q4 Milestone 3.1: Dominant droop mechanism in blue LEDs												
Q1 Milestone 1.5: 10% quantum yield												
Q2 Milestone 1.6: Inter-valley transfer efficiencies												
Q4 Milestone 3.3: Thermal droop c-plane in blue LEDs												
Current/Future Work												
Q3 Milestone 1.7: 25% quantum yield												
Q2 Milestone 3.2: Dominant droop mechanism in green LEDs												
Q3 Milestone 5.2: Droop mechanisms in semipolar blue LEDs												
Q4 Milestone 5.4: Thermal droop in semipolar blue LEDs												