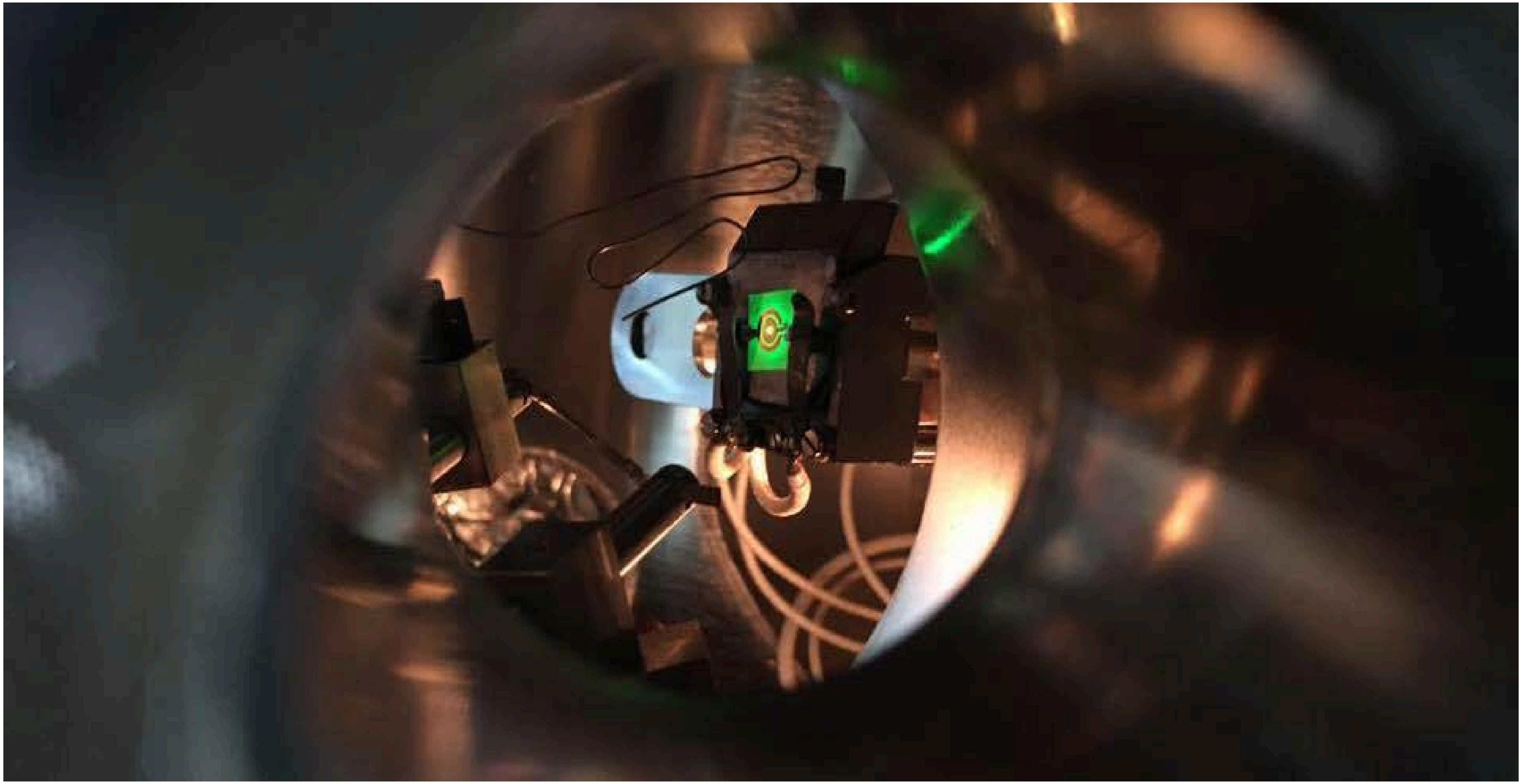
Identification and Mitigation of Droop Mechanism in GaN-Based Light Emitting Diodes (LEDs)

2017 Building Technologies Office Peer Review



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Project Summary

Timeline:

Start date: July 31, 2015

Planned end date: July 31, 2017

Key Milestones

1. Milestone 1.5: 10% quantum yield in photoemission spectroscopy
2. Milestone 3.1: Determination of dominant droop mechanism in blue LEDs
3. Milestone 2.1: Quantification of electron diffusion length in p-GaN

Budget:

Total Project $ to Date:

- DOE: $789,000
- Cost Share: $157,800

Total Project $:

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

Key Partners:

Cree (sample supplier)

Project Outcome:

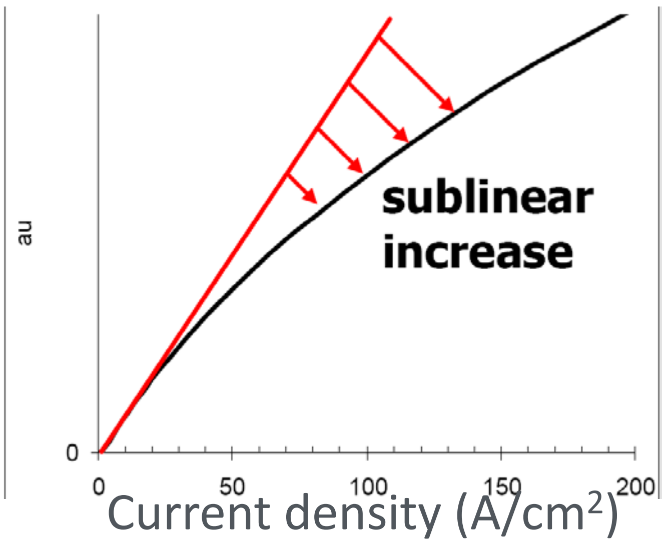
Development of a tool to directly identify the dominant non-radiative recombination mechanisms responsible for current droop, thermal droop, and the green gap in high performance LEDs used for solid state lighting.

From the DOE 2016 Solid State Lighting R&D Plan: "**Emitter materials:** addressing current density and thermal droop, green and red efficiency, and red thermal stability. "

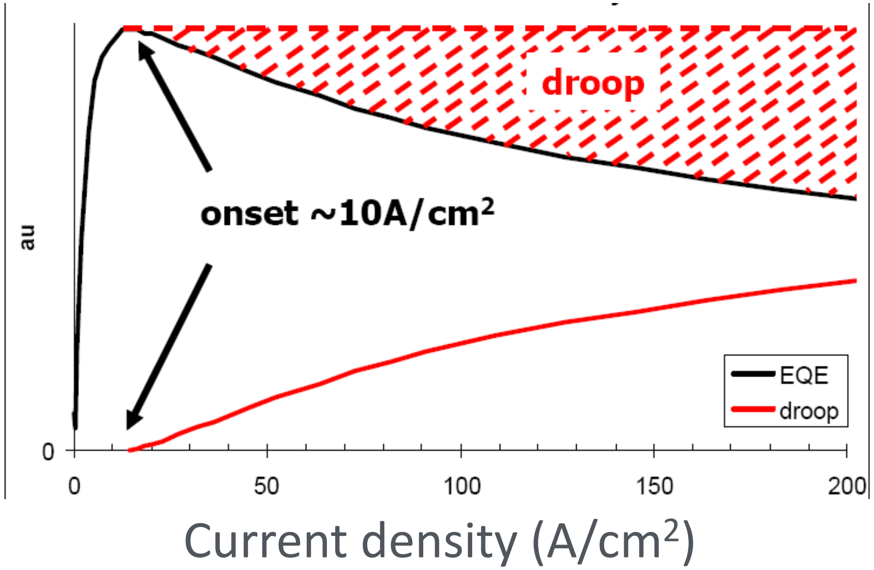
From the DOE BTO MYPP:
"**Core technology R&D** addresses efficiency, performance, and cost targets. Conducted primarily by academia, national laboratories, and research institutions, this work fills technology gaps and significantly advances the knowledge base related to LED and OLED technology"

Efficiency Droop

Optical flux



External quantum efficiency



InGaN-based LEDs

→ Peak EQE at 1 - 10 A/cm^2

→ At higher current, LED rapidly lose efficiency

→ Independent of color

Potential Cause: Auger recombination (internal efficiency) ~n^3

- Based on scaling of non-radiative loss - experimental measurement

[Shen et al. Appl. Phys. Lett. **91** 141101 (2007)

- First-principles rate indicate Auger recombination may be a significant factor

Purpose and Objectives

Problem Statement:
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.

Purpose and Objectives

Impact of Project:

Project's outputs?

Understanding fundamental high current density performance of LEDs

This understanding will yield new LED designs for more efficient lighting.

Projects contribution towards program performance and interim market goals?

1 year after project

New active region designs for LEDs for high current density operation

1-3 years after project

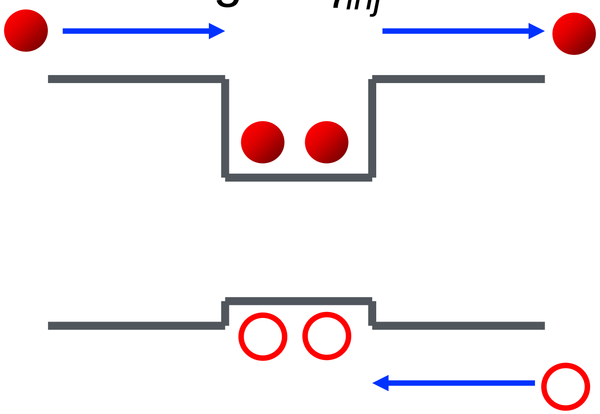
Advanced development of more efficient blue and green LEDs for high current density operation

3+ years after project

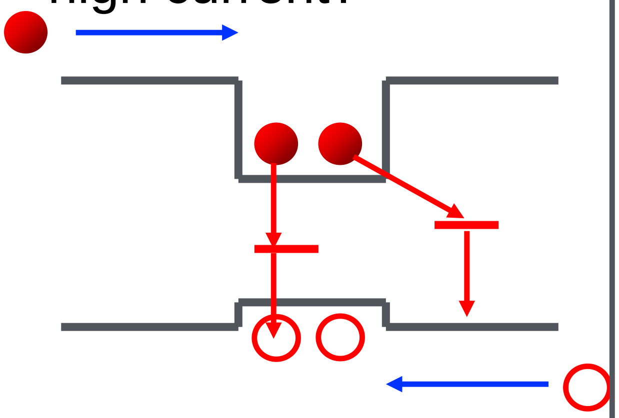
Mass production of high current density operation LEDs

Approach

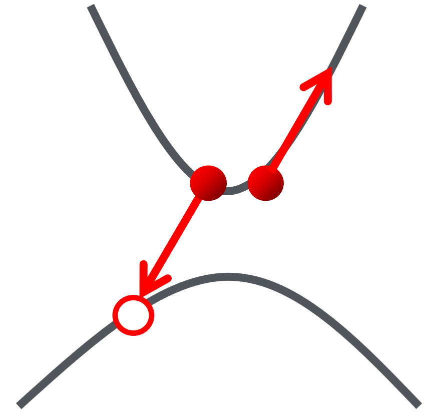
Carrier overshoot?
Changes η_{inj}



Defect activation at high current?



Auger recombination?



Engineer barrier heights, EBL, doping, etc.	Carriers are localized at low current, avoiding NR defects	Rate ~n^3 Diminish carrier density

- Based on scaling of nonradiative loss ~n^3 Auger effect been invoked [Shen 2007]
- But … other mechanisms can also be fitted. …
- Increasing active layer volume to decrease carrier density also decreases leakage

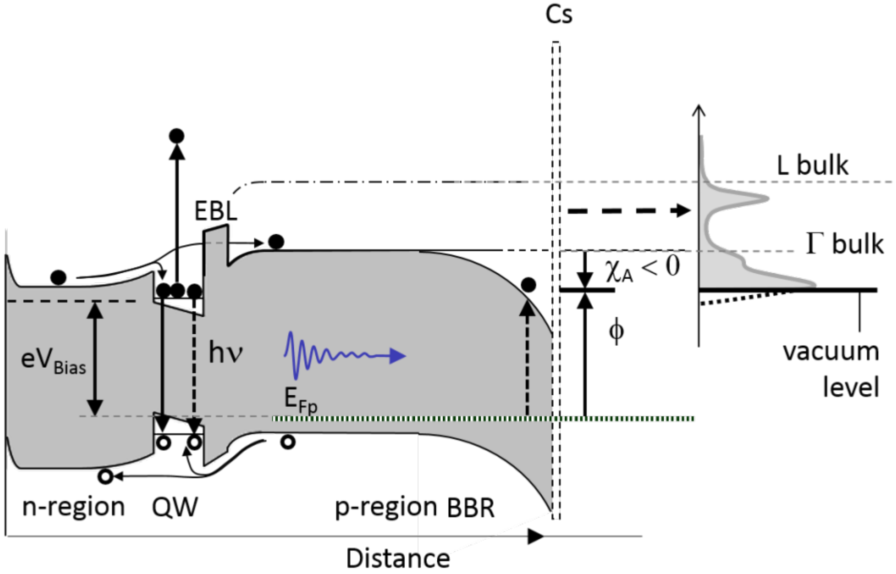
Until recently… *no* hard experimental "signature" for any mechanism

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

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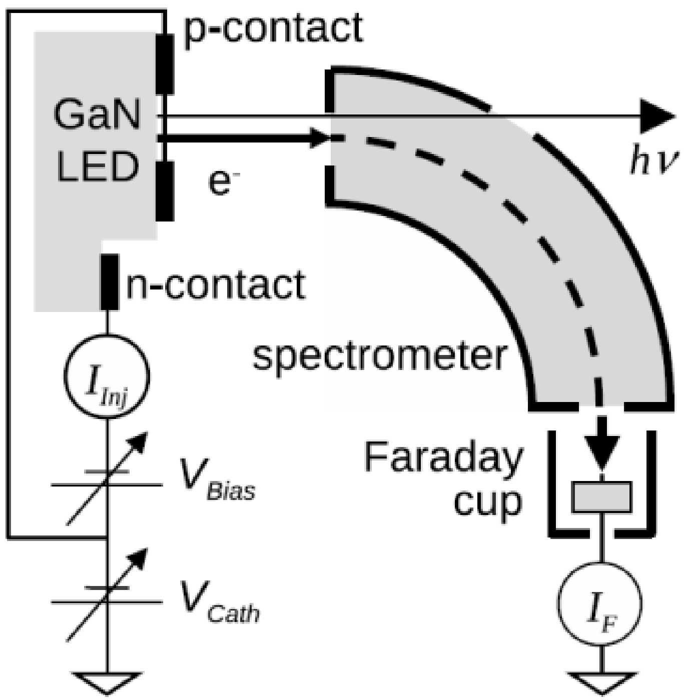
Approach

Low Energy Cylindrical Analyzer

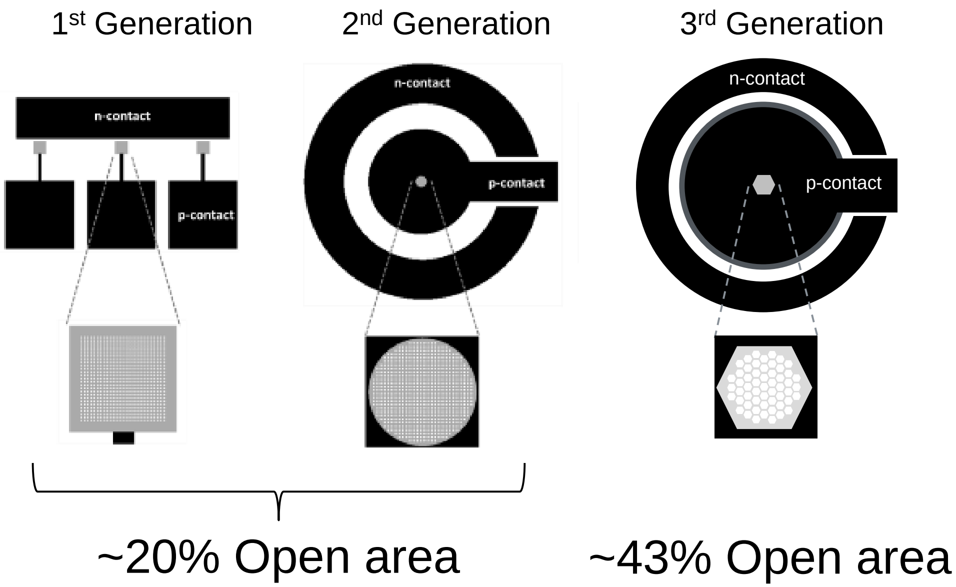


Vary V_{Cath} to sweep energy

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

- Constant energy -> analyzer potentials fixed
- 50 meV resolution
- $\Phi_{GaN/Cs}$ stable over several days

Device Design



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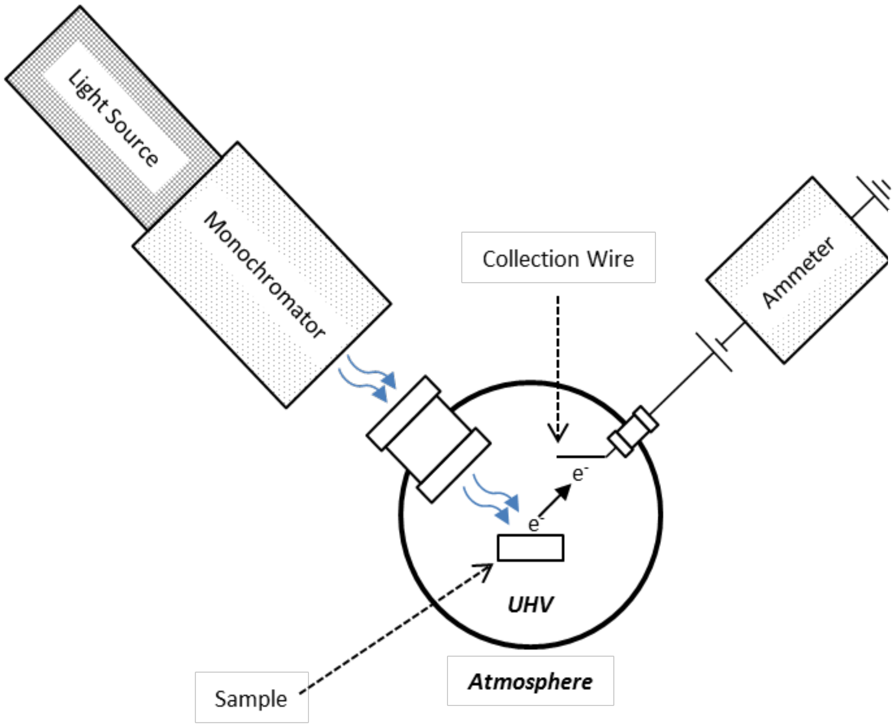
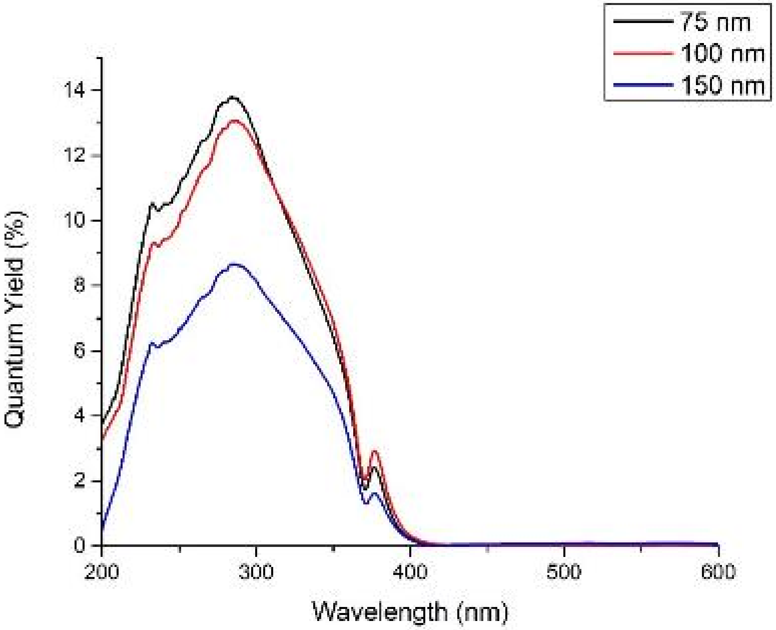
Progress and Accomplishments

Milestone 1.5: >10% quantum yield in photoemission spectroscopy from



QY >13% at ~280 nm excitation on p-GaN



Quantum yield measurement
The total electron current emitted as a function of excitation wavelength with a calibrated source.

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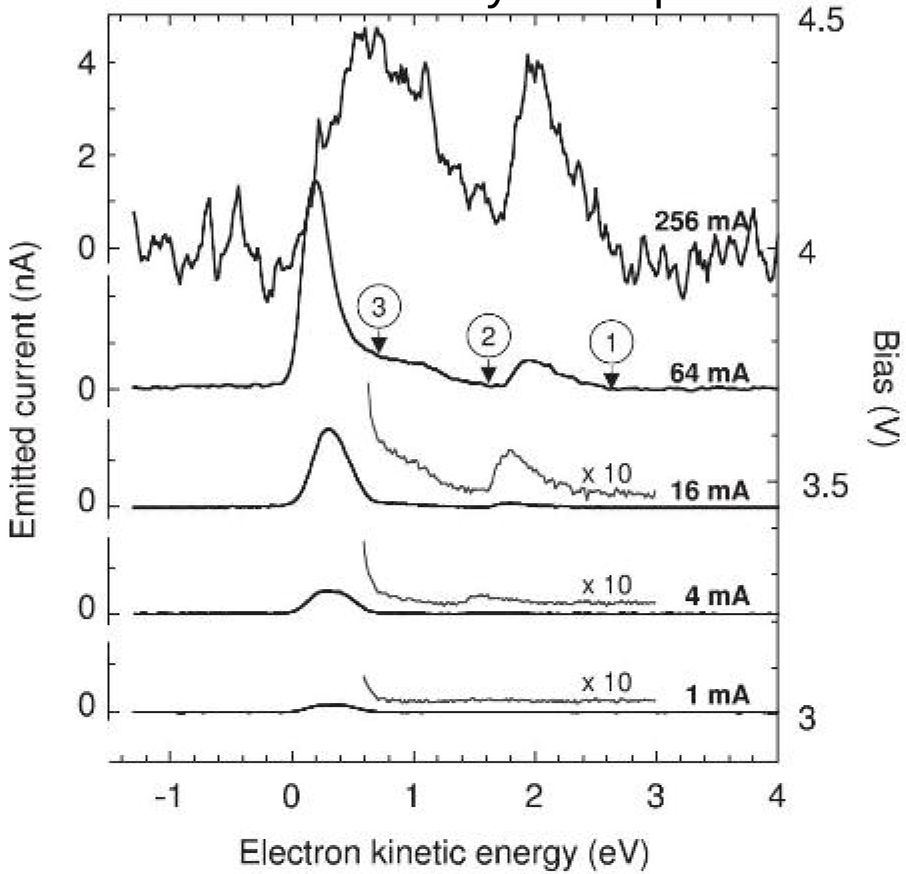
Progress and Accomplishments

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

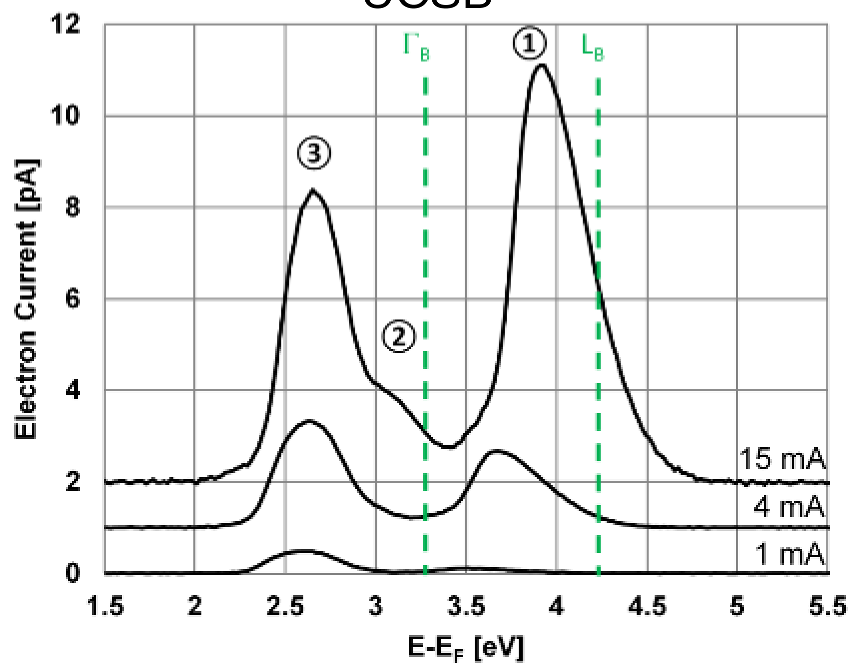
UCSB repeats measurements of hot carriers emitted from LEDs.

CNRS-École Polytechnique



Corrected for analyzer efficiency

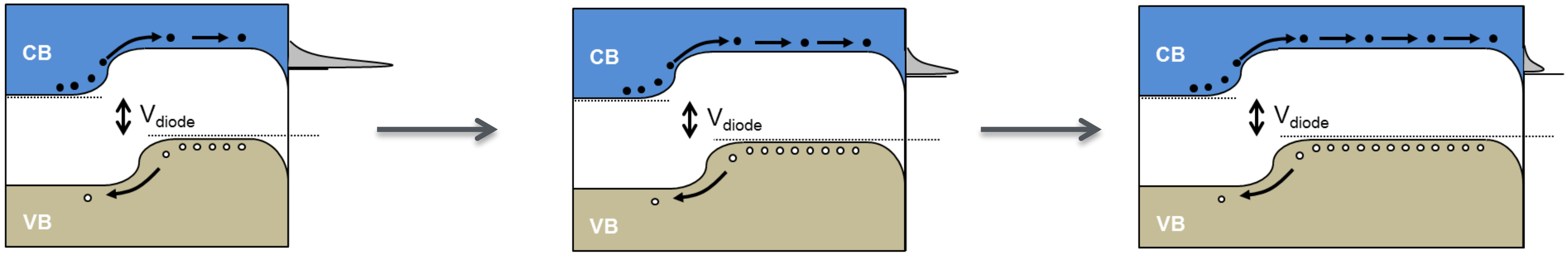
UCSB

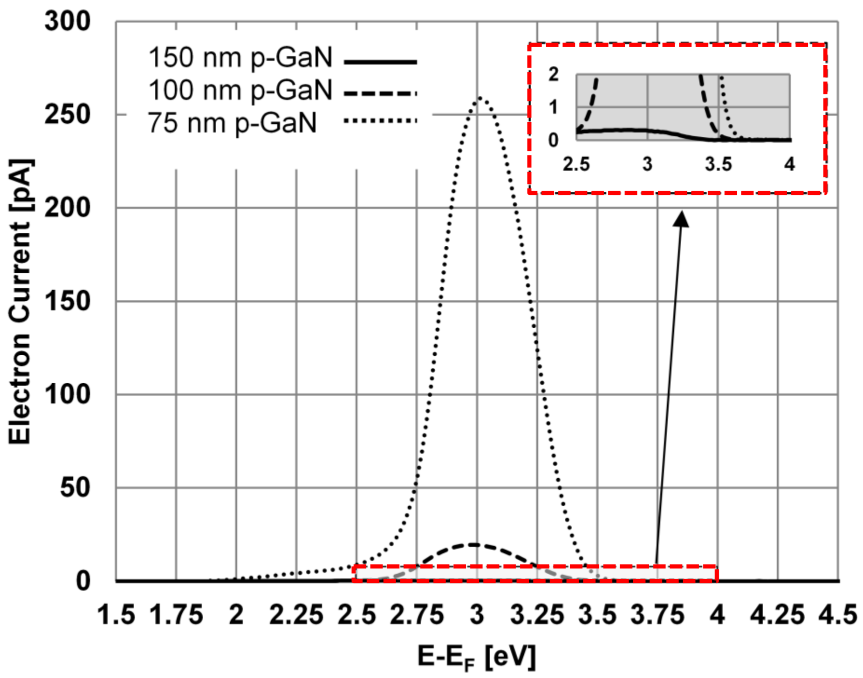


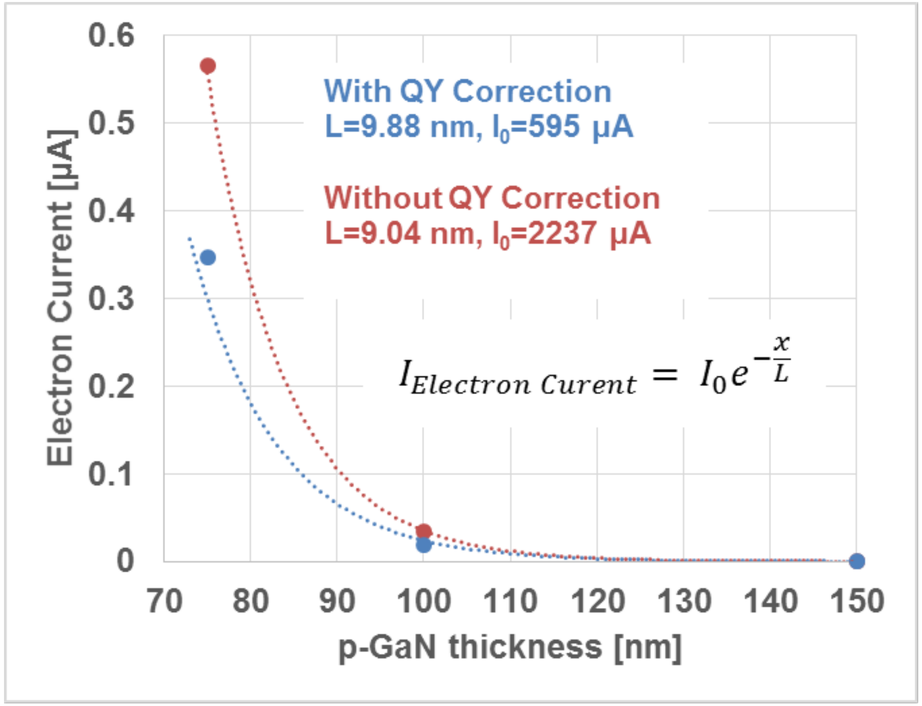
Not corrected for analyzer efficiency

Progress and Accomplishments

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



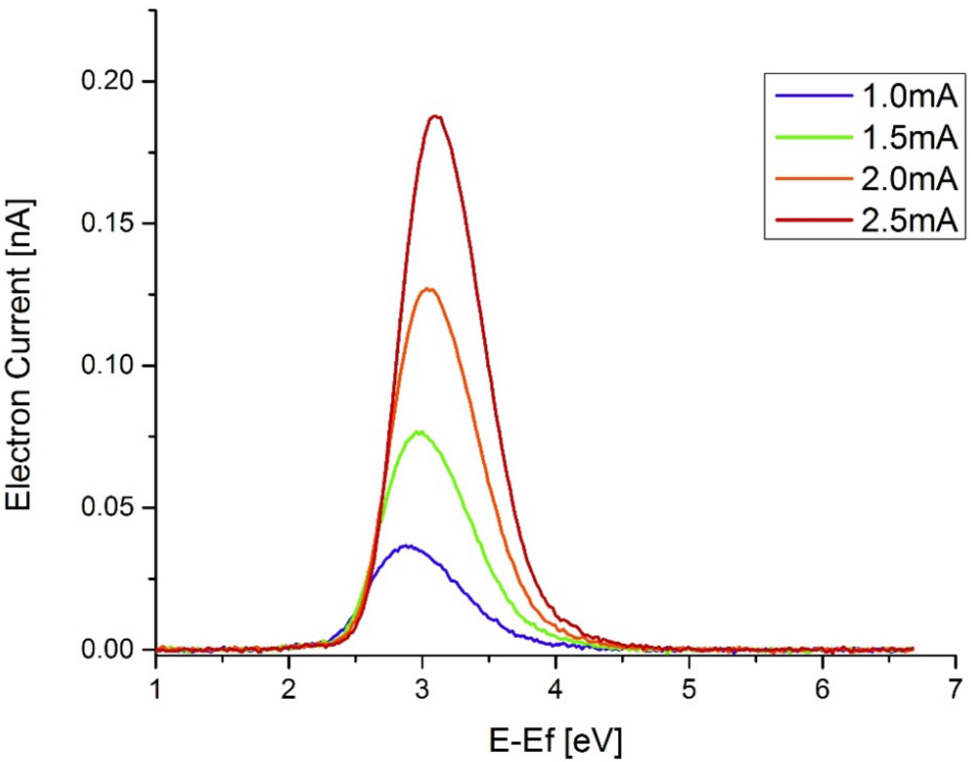




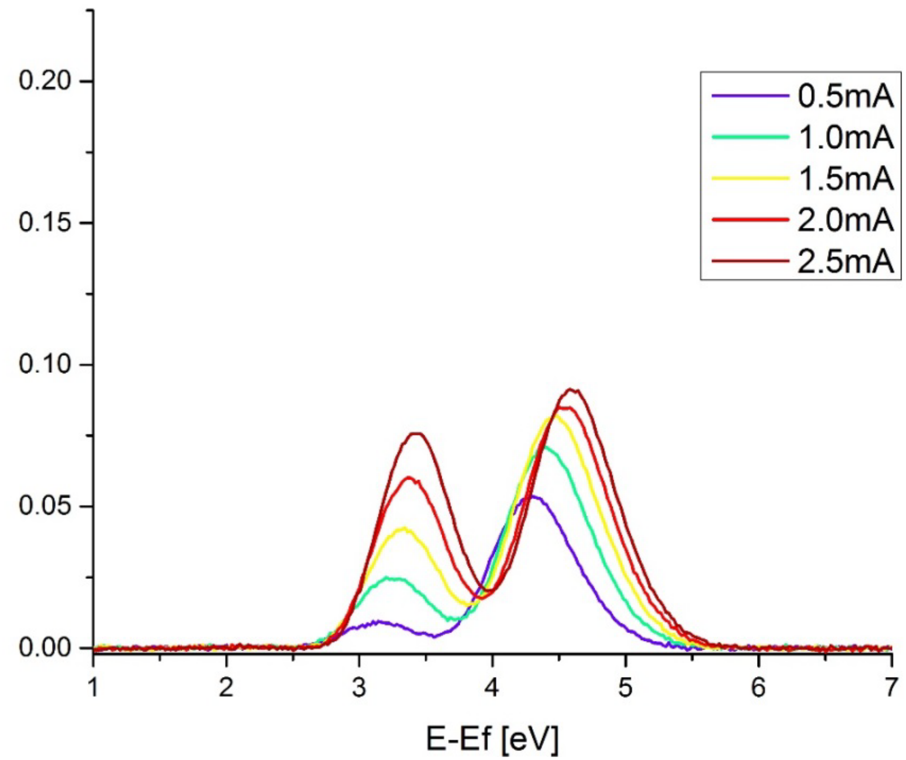
Progress and Accomplishments

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

P-n Junction, no EBL



P-n Junction, with EBL



Progress and Accomplishments

Market Impact:
Fundamental understanding of efficiency loss mechanisms enables the engineering solutions which mitigate these physical processes.

Including:

1. Field screening of quantum wells.
2. Semipolar GaN LED substrates.

These solutions allow for increase in quantum well thickness allowing for lower carrier concentration in LED active regions.

Project Integration and Collaboration

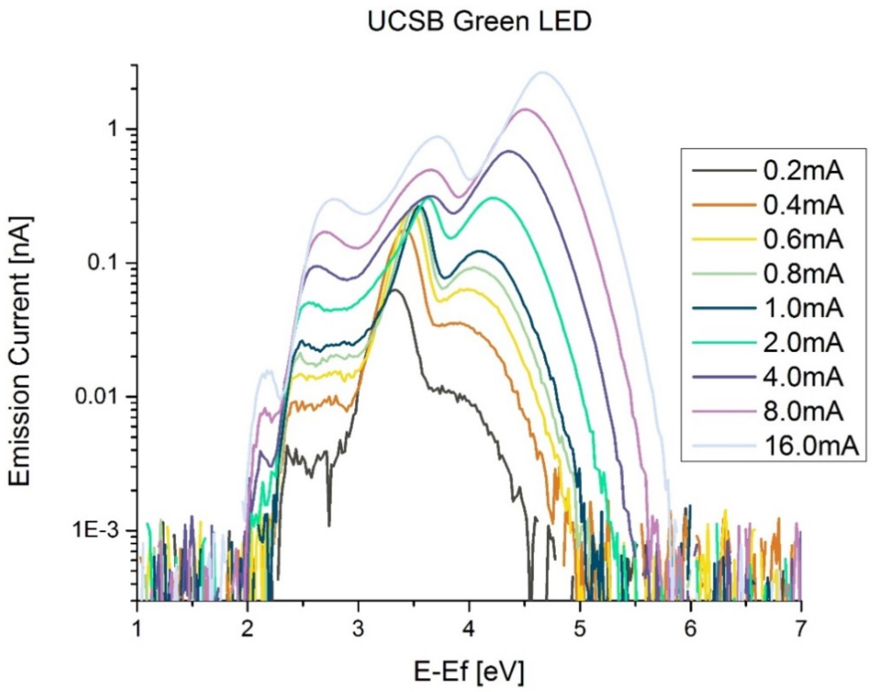
Project Integration:
Industry partnerships have supplied sample material for the study of state-of-the-art devices. This provides a pathway to understanding efficiency problems which persist in commercially available solid state lighting.

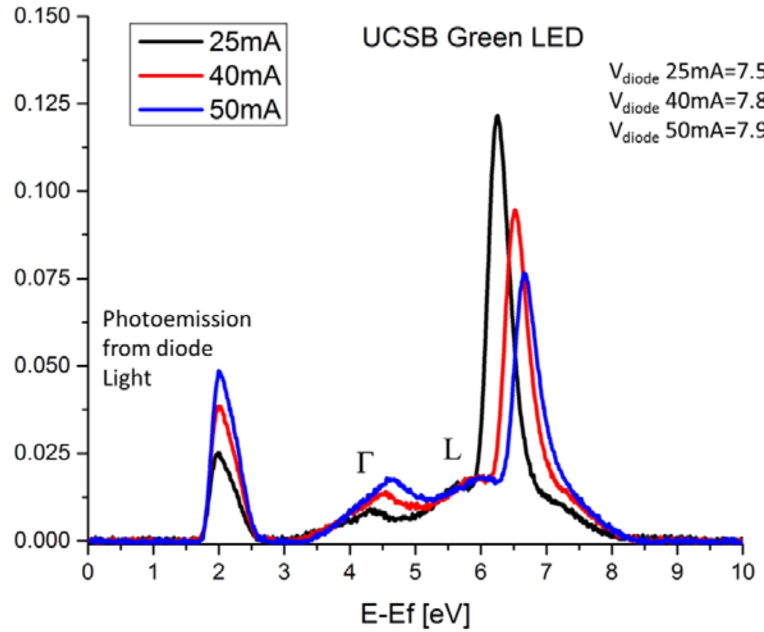
Partners, Subcontractors, and Collaborators:
Cree

Communications:
DoE SSL workshops

Next Steps and Future Plans

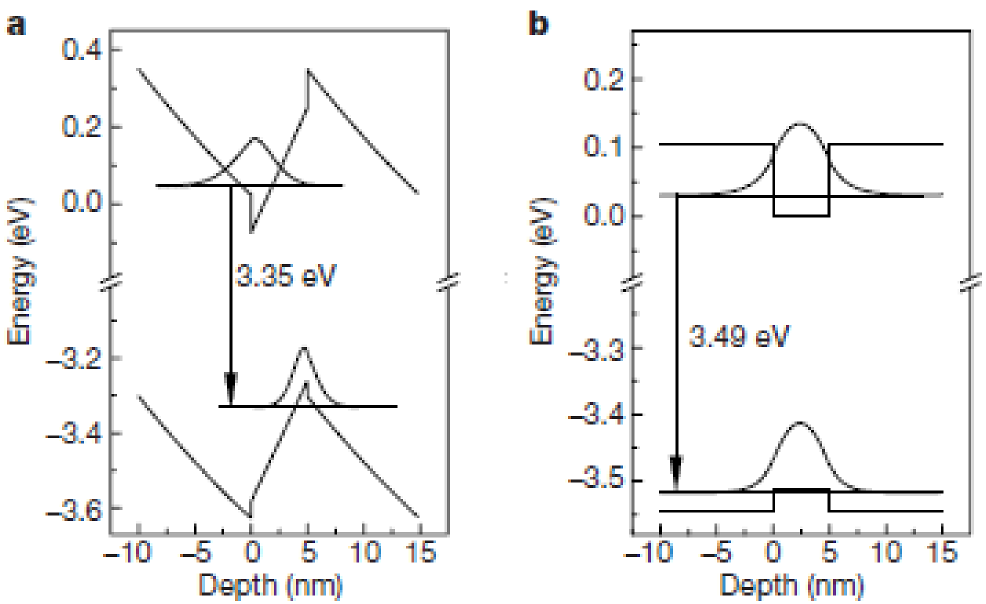
Milestone 3.2: Determination of dominant droop mechanism in green LEDs





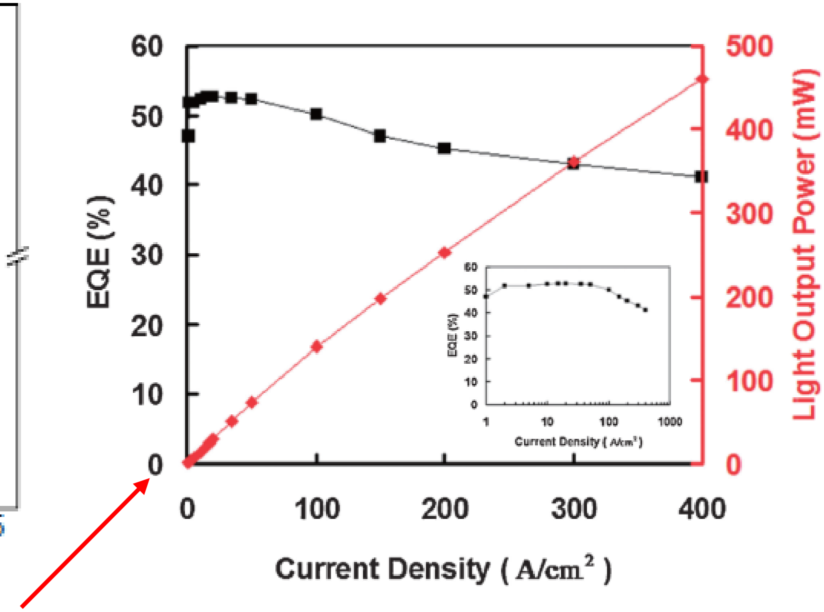
Next Steps and Future Plans

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



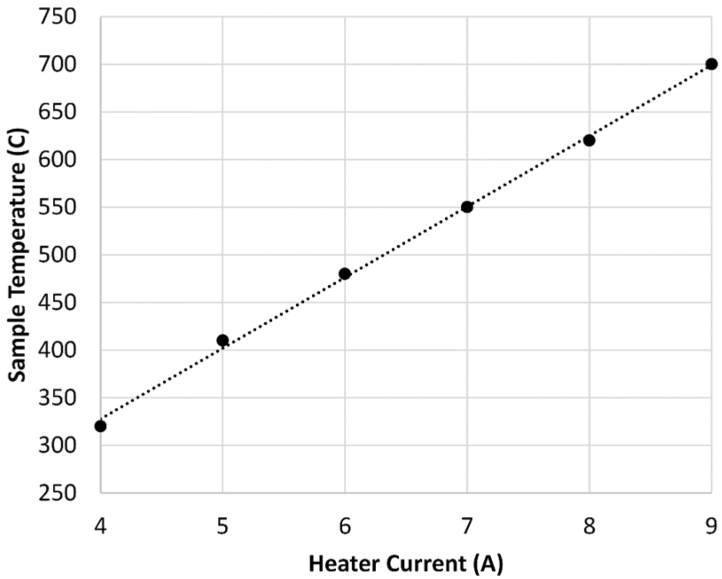
c-plane LED

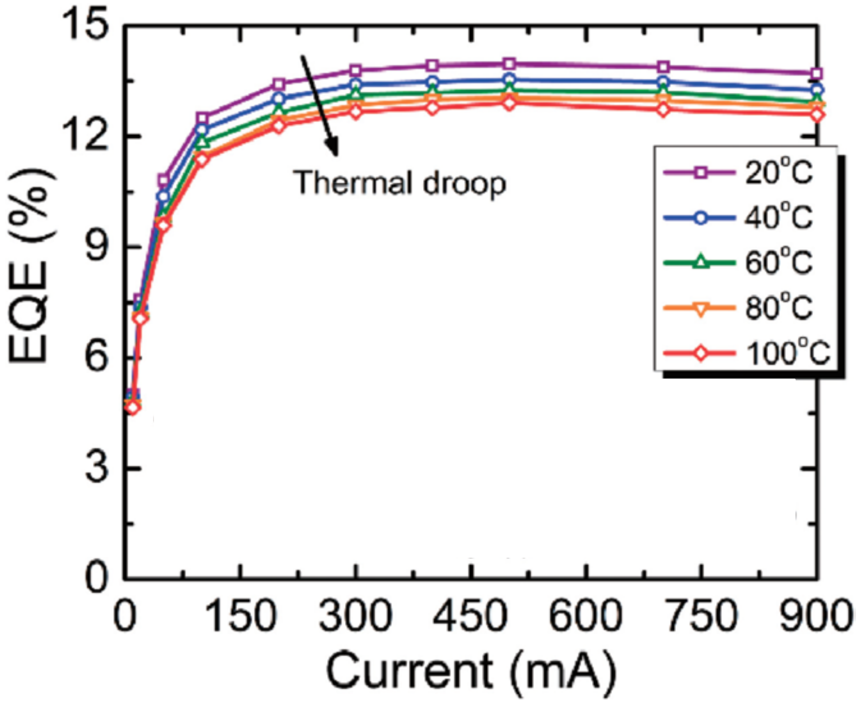
Semipolar LED



Next Steps and Future Plans

Milestone 3.3 & 5.4: EES to determine thermal droop mechanisms





REFERENCE SLIDES

Project Budget

Spending to Date: 79%

Budget History					
July 31, 2016 – FY 2016 (past)		FY 2017 (current)		FY 2018 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$500,000	$125,000	$500,000	$125,000		

Project Plan and Schedule

Project Schedule									
Project Start: July 31, 2015		Completed Work							
Projected End: July 31, 2017		Active Task (in progress work)							
		Milestone/Deliverable (Planned)							
		Milestone/Deliverable (Actual)							
	FY2016				FY2017				
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	
Past Work									
Q1 Milestone 1.1: Annealable ohmic contacts to p-GaN									
Q2 Milestone 1.2: Reduction in metal photoemission via dielectric coating of p-contact									
Q3 Milestone 1.3: 1% quantum yield in photoemission spectroscopy									
Q4 Milestone 1.4: Determination of quantum yields of Γ and L valley hot electrons									
Q4 Milestone 2.1: Quantification of electron diffusion length in p-GaN									
Q4 Milestone 2.2: Quantification of the efficacy of the AlGaN EBL via EE spectroscopy									
Q4 Milestone 3.1: Determination of dominant droop mechanism in blue LEDs									
Q1 Milestone 1.5: 10% quantum yield in photoemission spectroscopy									
Q2 Milestone 1.6: Determination of inter-valley transfer efficiencies									
Current/Future Work									
Q2 Milestone 3.2: Determination of dominant droop mechanism in green LEDs									
Q3 Milestone 1.7: 25% quantum yield in photoemission spectroscopy									
Q3 Milestone 5.2: Identify droop mechanisms in semipolar (20-2- 1) blue LEDs									
Q4 Milestone 5.4: Identify thermal droop mechanisms in semipolar (20-2- 1) blue LEDs									
Q4 Milestone 3.3: Determination of dominant thermal droop mechanism in blue LEDs									