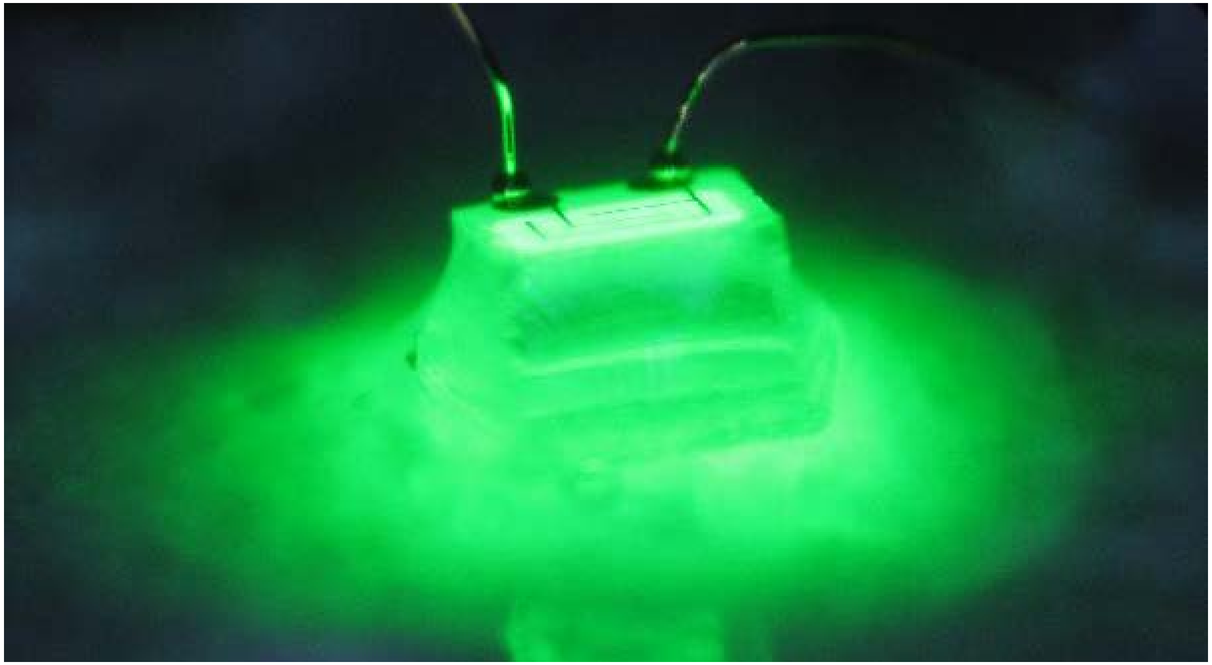
High Performance Green LEDs for Solid State Lighting



University of California, Santa Barbara

Professor Jim Speck

speck@ucsb.edu

Project Summary

Timeline:

Start date: September 30, 2017

Planned end date: September 30, 2019

Key Milestones

1. Green LEDs with ≥ 54% internal quantum efficiency (IQE) at 35 A/cm^2 , 9/30/2019
2. Green LEDs with ≥ 46% external quantum efficiency (EQE) at 35 A/cm^2 , 9/30/2019
3. Green LEDs with ≥ 35% power conversion efficiency at 35 A/cm^2, 9/30/2019

Budget:

Total Project $ to Date:

- DOE: $178,370.76
- Cost Share: $35,674.15

Total Project $:

- DOE: $999,996
- Cost Share: $250,130

Key Partners:

UCSB will share all progress and data with DOE SSL program and stakeholders in the DOE SSL program.

Project Outcome:

We have assembled a team of leading experts at UCSB in GaN-based materials growth, device processing and measurement, materials characterization and semiconductor physics to aggressively address the green gap and to meet or exceed the 2020 FOA goals for direct green LEDs.

Team

Prof. Shuji Nakamura
UCSB

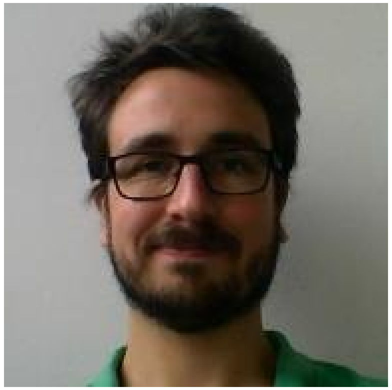
Prof. James Speck
UCSB

Prof. Steven DenBaars
UCSB

Prof. Claude Weisbuch
UCSB, École Polytechnique

Abdullah Alhassan
Postdoc, UCSB

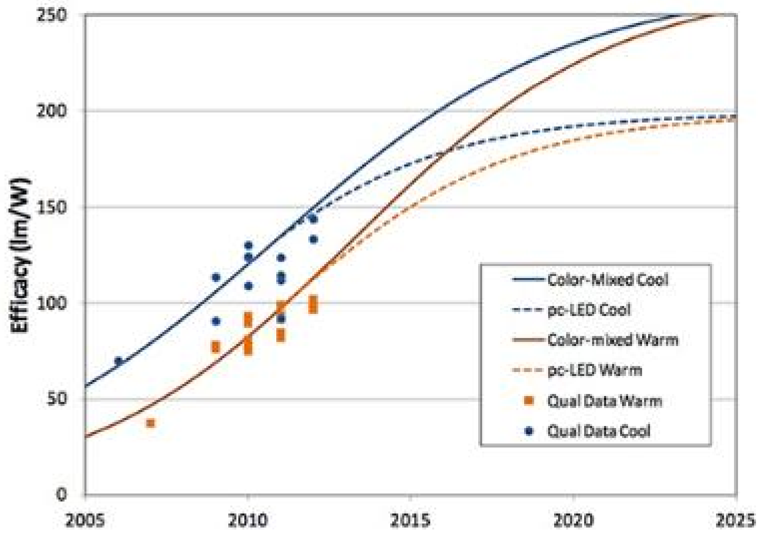
Cheyenne Lynsky
GSR, UCSB

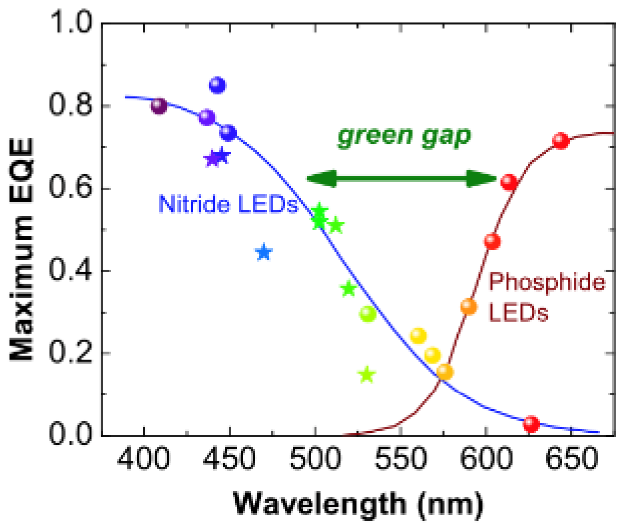


Guillaume Lheureux
Postdoc, UCSB

Bastien Bonef
Postdoc, UCSB

Challenge





White LED progress for solid state lighting has been driven by phosphor converted LEDs (pc-LEDs)

- Fundamental limitation of ~300 lm/W due to Stokes' losses between blue pump LED and phosphor

Color mixed LEDs (cm-LEDs) produce white light from red, green, blue, and amber (RGBA) LEDs

- Higher fundamental efficiency limit of ~400 lm/W

Poor efficiency of green and amber LEDs is the primary efficiency limitation for cm-LEDs

Poor performance of green LEDs due to:

1. Poor materials quality due to low temperature MOCVD growth
2. Large internal electric fields
3. An excess operating voltage ΔV_F much larger than in blue

Challenge

Problem Definition:

Fundamental limitations of pc-LEDs motivate the development of green LEDs for use in cm-LEDs. Green LEDs, however, suffer from poor materials quality, large internal electric fields, and excess operating voltage relative to SOA blue LEDs. The challenge therefore lies in identifying and understanding the fundamental limitations of green LEDs and then designing and implementing solutions to address these issues.

Target Audience and Market:

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

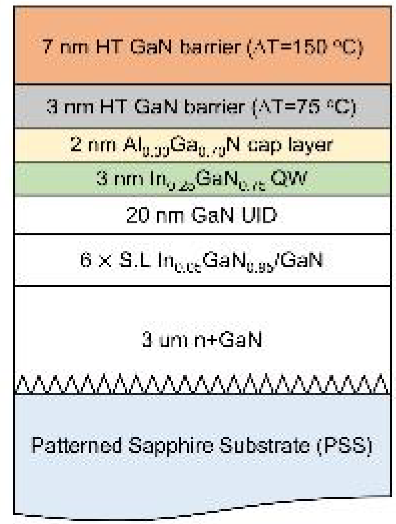
Approach

Reduction of SRH Recombination

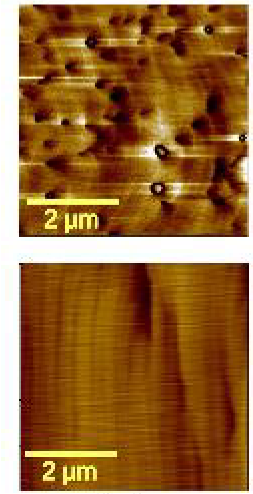
Active region optimization - high temperature MOCVD growth of InGaN QWs combined with AlGaN cap layers followed by higher temperature GaN quantum barriers

Systematic studies of growth temperature, metalorganic flows, carrier gas flows, and NH_3 flow

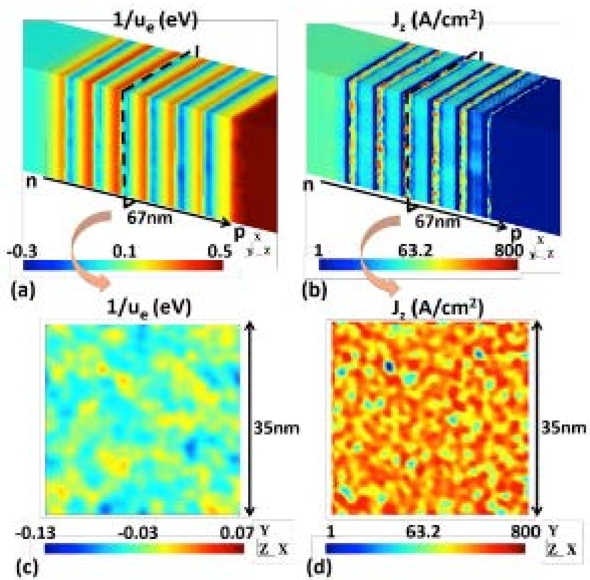
Use peak EQE and EQE at 35 A/cm^2 as metrics for improvement of material quality



2-step



3-step



Advanced Design

Use new device simulation tool based on landscape theory to account for the role of alloy fluctuations in carrier transport and recombination

Design reduced barriers for electron and hole injection into QWs, thus reducing operating voltage

Explore novel layer designs to reduce barriers for hole transport to deeper QWs so as to reduce overall carrier density and thus reduce droop

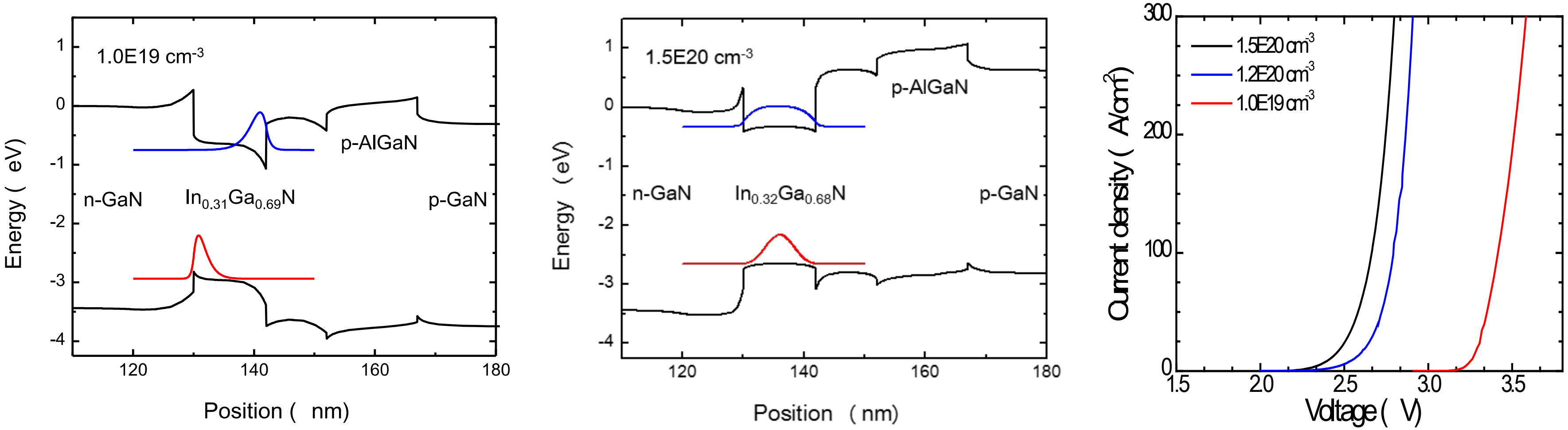
Approach

Polarization Engineering

Design, grow, and process structures with reduced polarization-related electric fields in the quantum to increase electron-hole overlap and thus radiative recombination rate

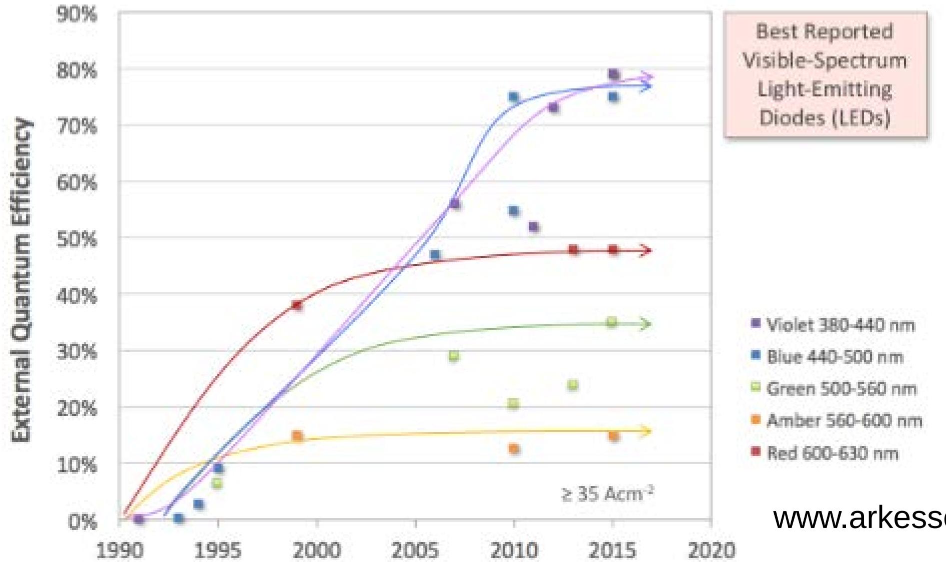
Heavily doped layers adjacent to the QWs have the potential to screen the piezoelectric induced field in the QW

Quaternary alloys will be explored for polarization matched quantum barriers



SiLENSe simulations of electron and hole wavefunctions and IV curves

Impact



www.arkesso.com

Because of their key role in cm-LEDs, realizing high performance green LEDs will advance LED technology

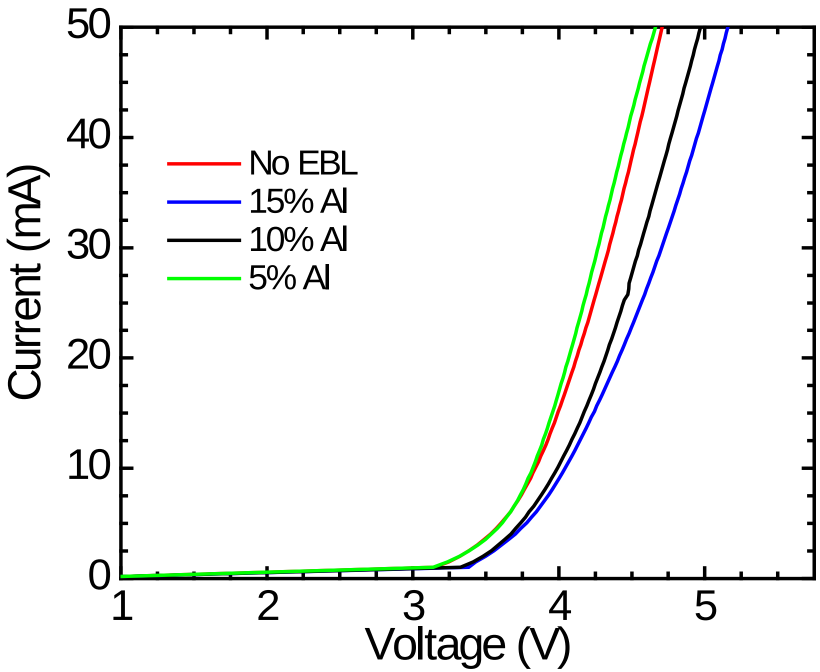
Compared to pc-LEDs, cm-LEDs have a higher fundamental efficiency limit

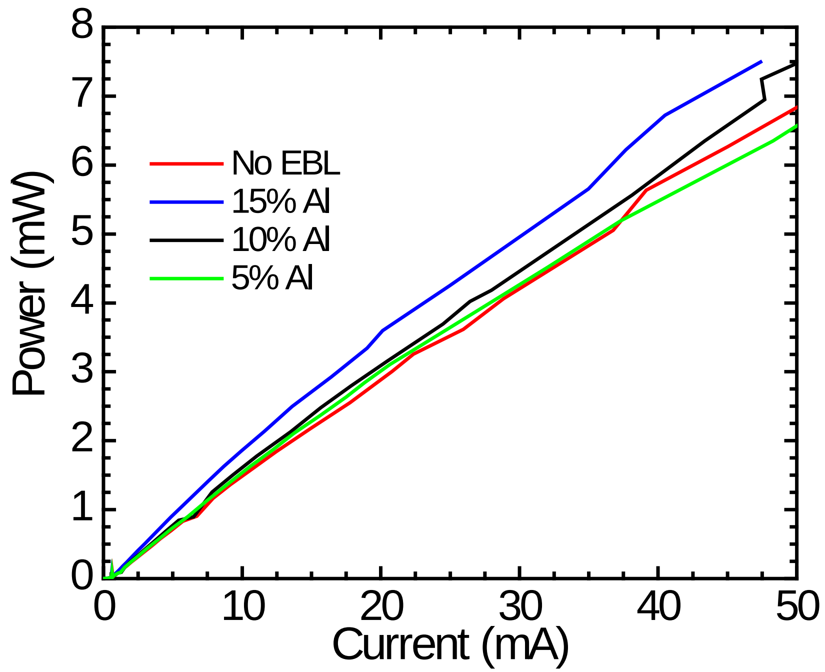
Color mixed white lighting has other inherent advantages over pc-LEDs in terms of color purity, stability, adaptive lighting, and small source size.

A thorough understanding of the green gap combined with novel approaches are essential to meeting all 2020 DOE targets for green LEDs

Progress

Subtask 4.1 Role of the electron blocking layer (EBL) in forward voltage

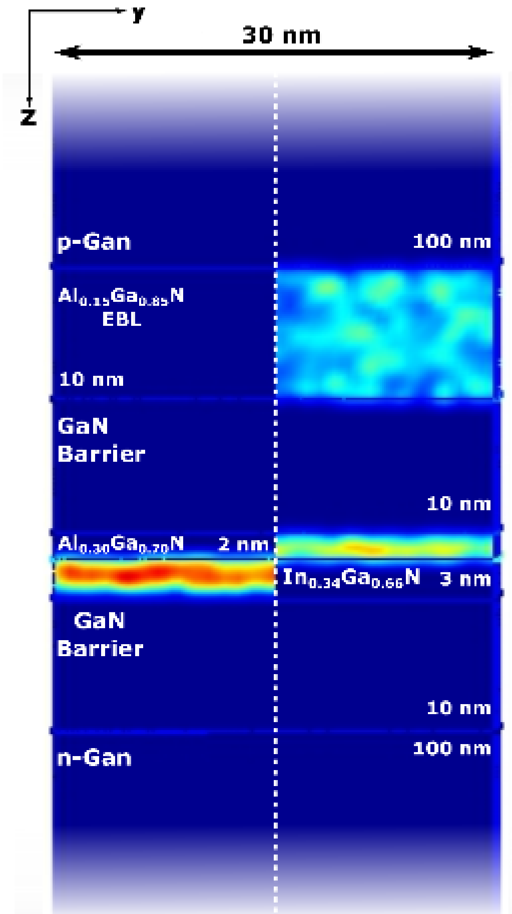


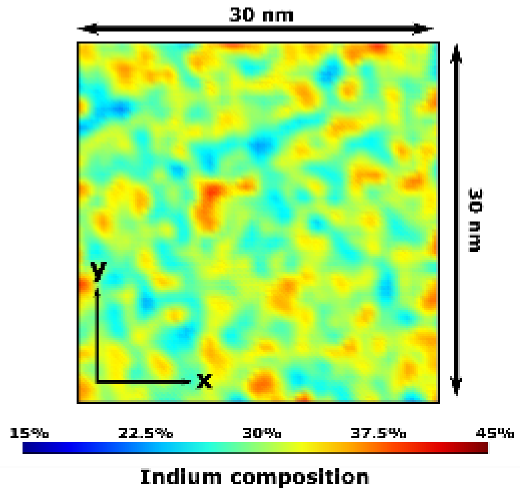


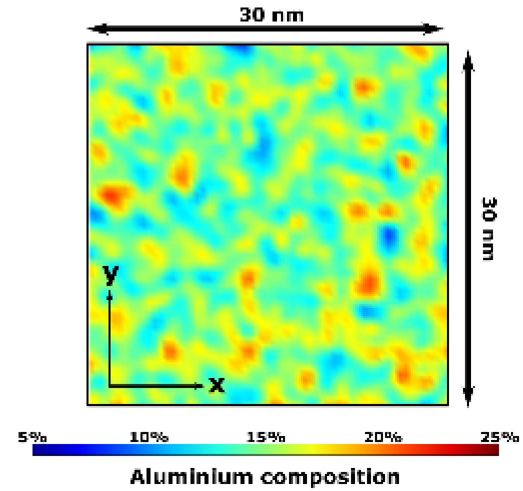
p-AlGaN EBL has a negative effect on V_F, however increasing the Al% in the EBL improves the output power

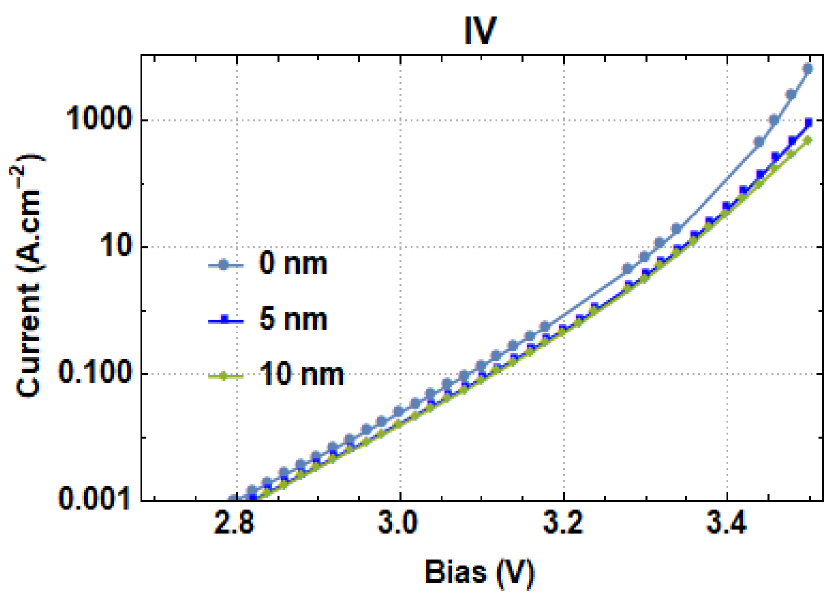
Progress

Subtask 2.4 Assess the necessity of the electron blocking layer in green LEDs



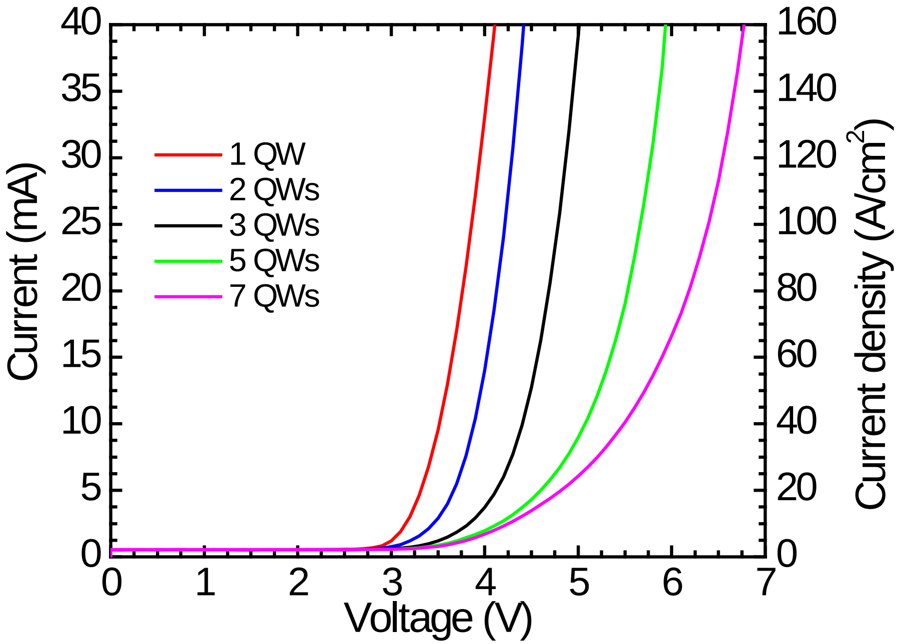


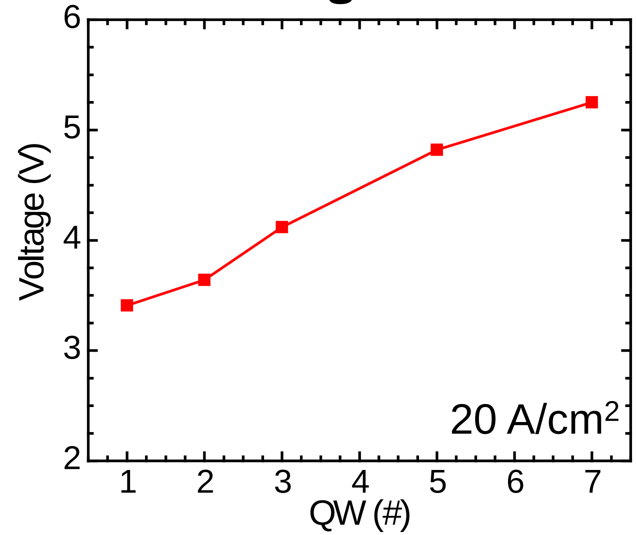


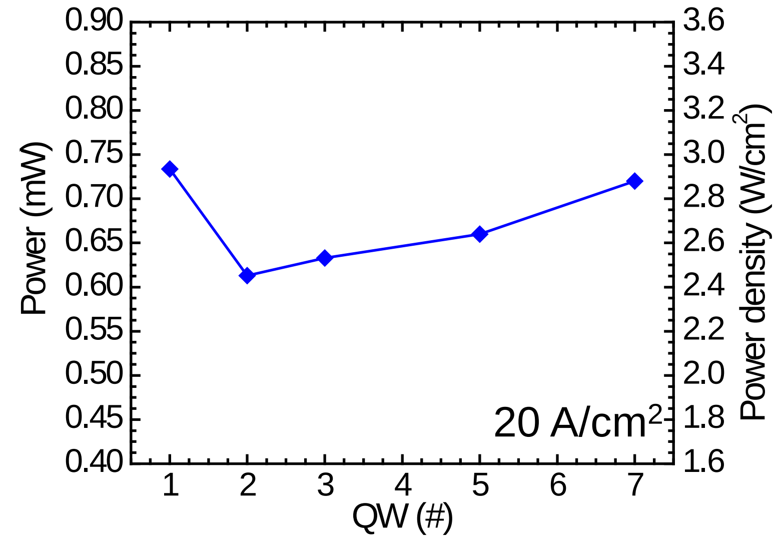


Progress

Subtask 4.2 Role of the number of quantum wells in forward voltage







Series resistance between 40 to 60 A/cm^2 :

1QW = 3 Ω

2QW = 2.95 Ω

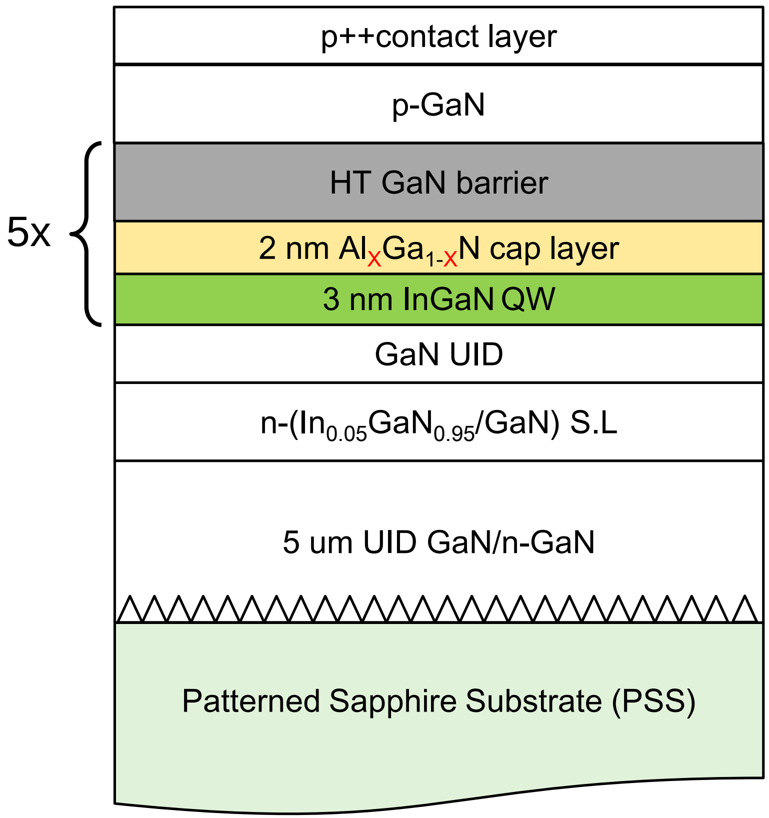
3QW = 3.3 Ω

5QW = 5.3 Ω

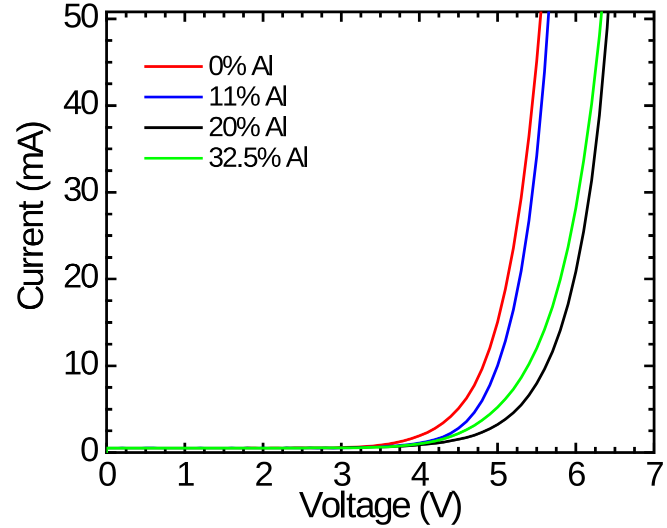
7QW = 8.1 Ω

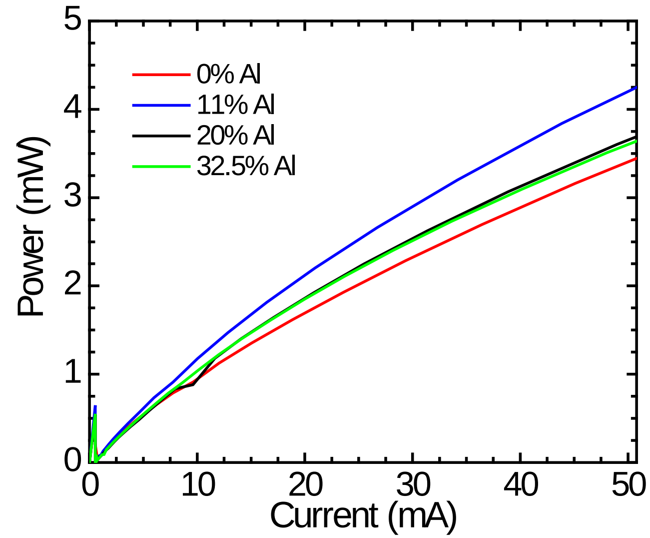
Progress

Reduction in internal barriers by reducing the Al % in the AlGaN cap layer



X = 0, 0.11, 0.20 and 0.33

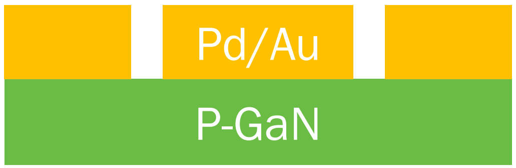




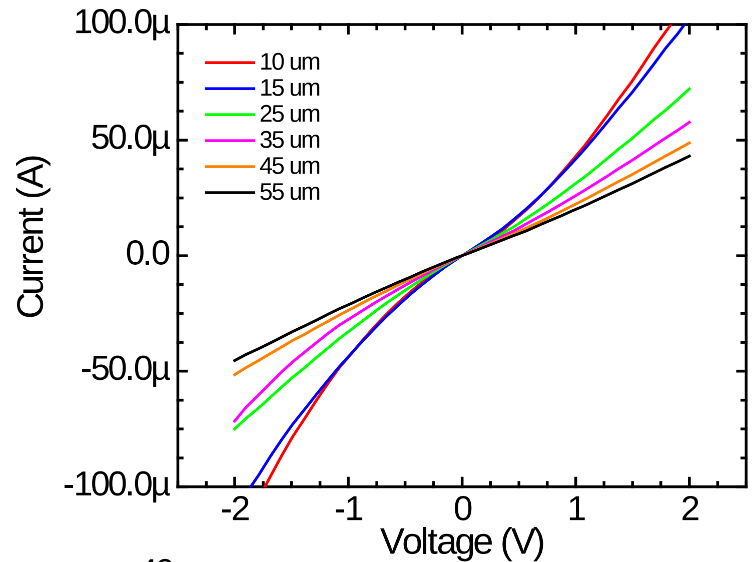
Progress

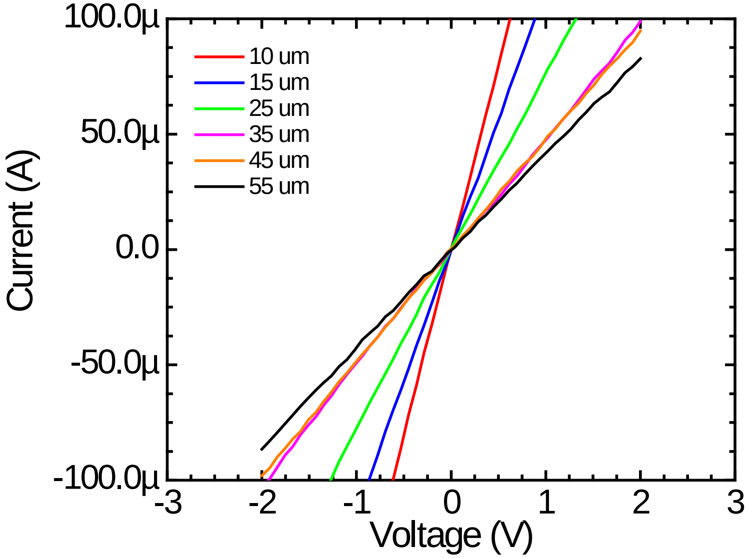
Subtask 4.4 Detailed I-V measurement and analysis

Optimizing p++GaN contact layer

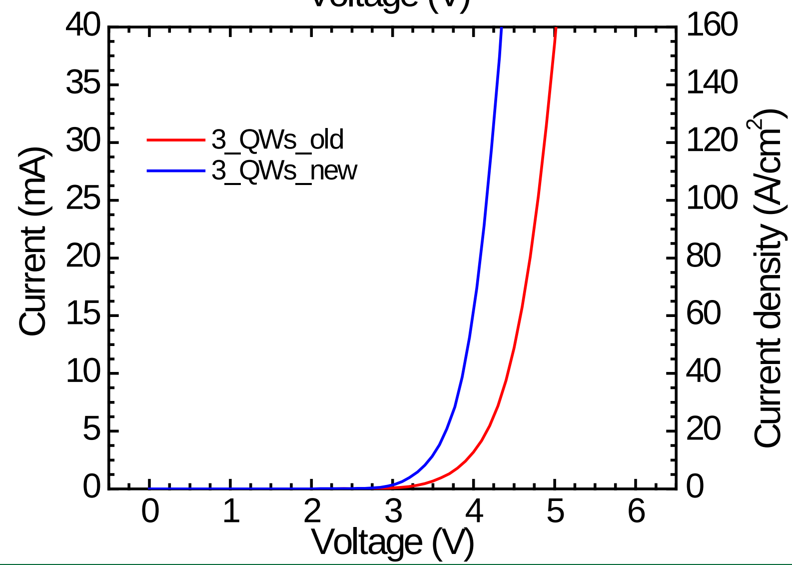


Unoptimized contact





Optimized contact



Stakeholder Engagement

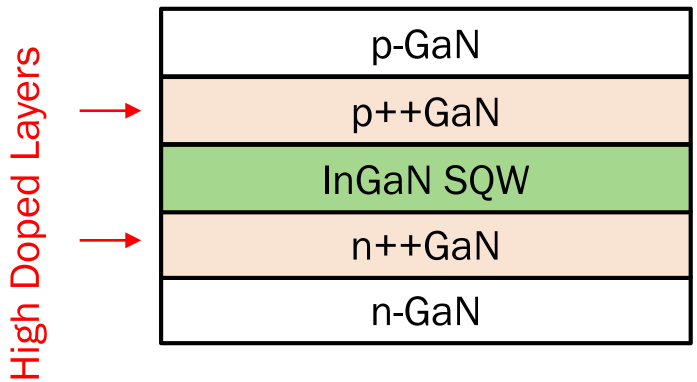
Stakeholders:
U.S. Department of Energy
U.S. Academic R&D community

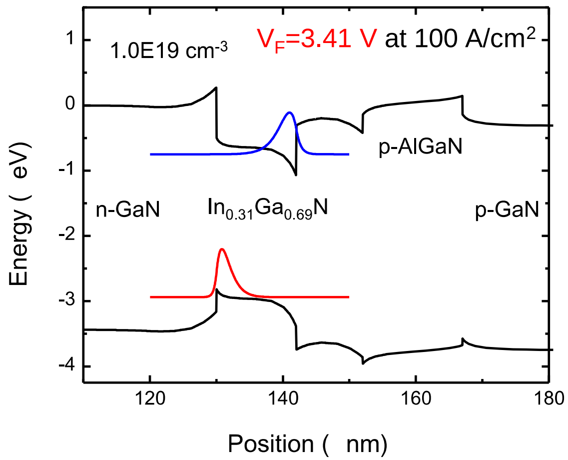
Engagement with Industry:
Share all progress with U.S. industry via DOE SSL Roundtable and Workshops

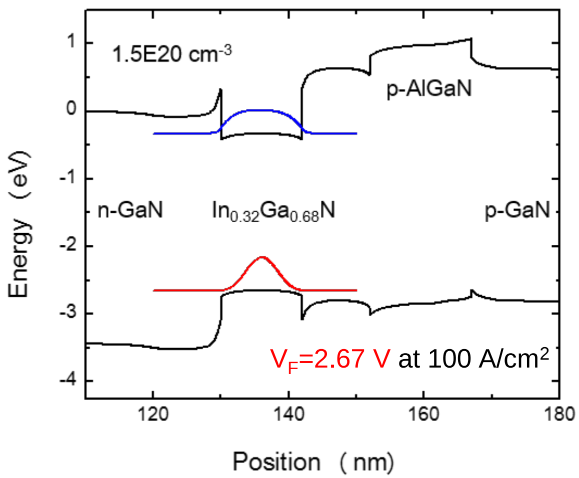
Communication with Stakeholders:
DoE SSL workshops

Remaining Project Work

Subtask 3.1 Polarization-field screened QWs







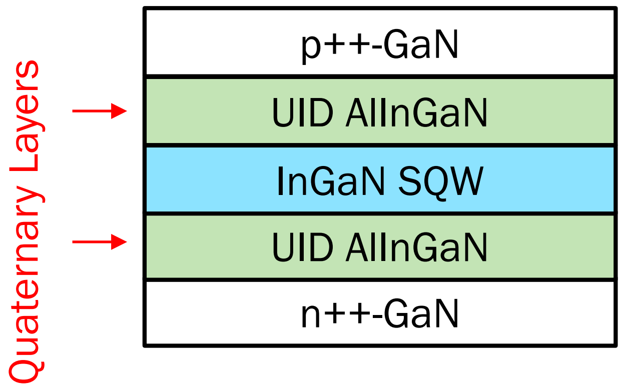
Doping layers adjacent to QWs to reduce electric field

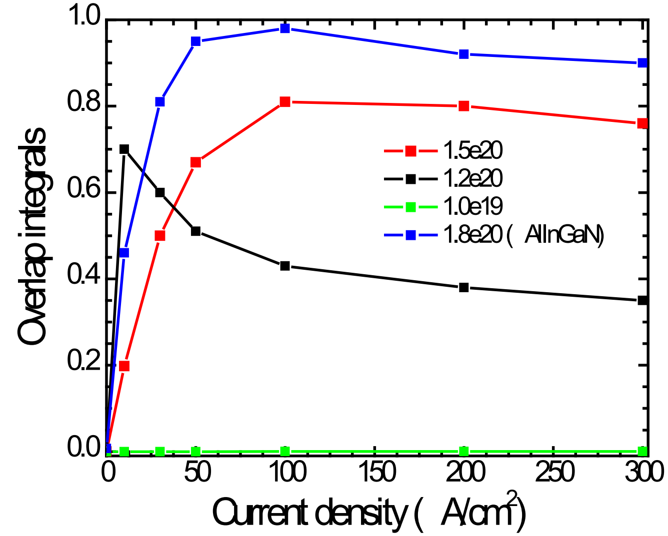
Grow thicker (screened) QWs to achieve reduced carrier densities

Bias-dependent photocurrent and PL to quantify screening

Remaining Project Work

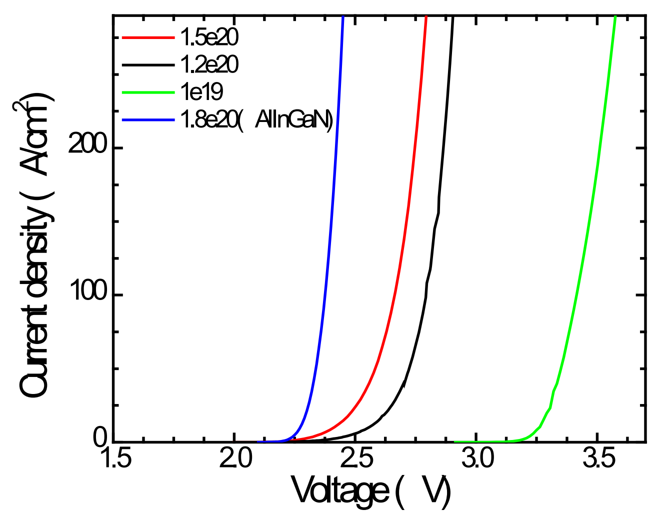
Subtask 3.3 Polarization-field screened QWs with polarization-matched QBs





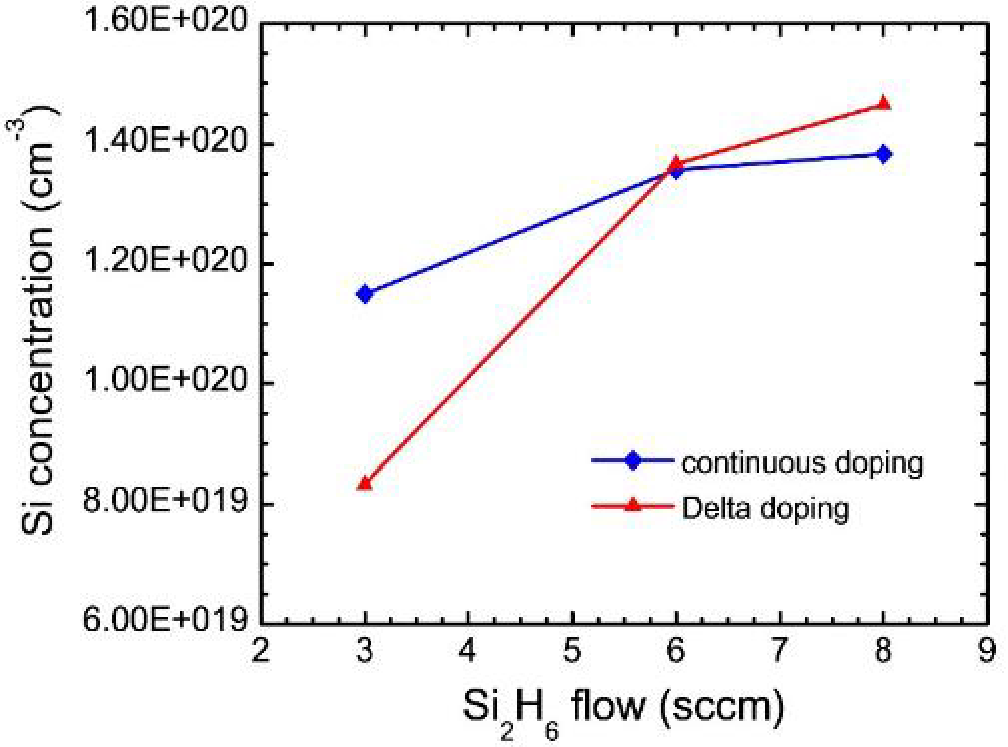
Polarization screened QWs and polarization matched QB (using quaternary alloys) will be implemented

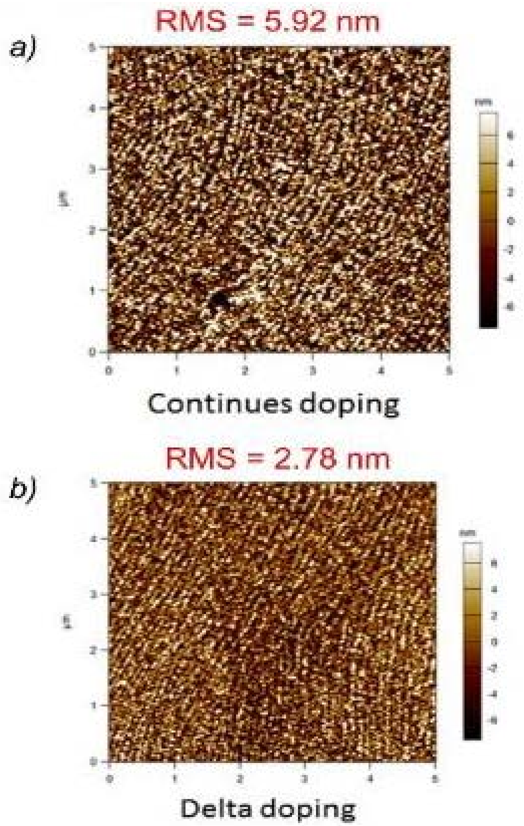
Wavefunction overlap will be optimized



Remaining Project Work

Doping optimization for the polarization-field screened QWs





Thank You

University of California, Santa Barbara
Professor Jim Speck
speck@ucsb.edu

References

1. “*Solid-State Lighting Research and Development: Multi-Year Program Plan*,” U.S. Department of Energy, April 2012.
2. M. Auf der Maur, A. Pecchia, G. Penazzi, W. Rodrigues, and A. Di Carlo, “Efficiency Drop in Green InGaN/GaN Light Emitting Diodes: The Role of Random Alloy Fluctuations,”*Physical Review Letters*, vol. 116, p. 027401, Jan. 2016.
3. C.-K. Li, M. Piccardo, L.-S. Lu, S. Mayboroda, L. Martinelli, J. Peretti, J. S. Speck, C. Weisbuch, M. Filoche, and Y.-R. Wu, “Localization landscape theory of disorder in semiconductors. III. Application to carrier transport and recombination in light emitting diodes,” *Physical Review B*, vol. 95, p. 144206, Apr. 2017.

Project Budget

Project Budget:
- DOE: $999,996
- Cost Share: $250,130

Variances: W2018, S2018 – personnel added to take program to level spending

Cost to Date:
- DOE: $178,370.76
- Cost Share: $35,674.15

Additional Funding: None

Budget History			
FY 2018 (current)		FY 2019 – 9/30/19 (planned)	
DOE	Cost-share	DOE	Cost-share
178,370	35,674	500,000	125,065

Project Plan and Schedule

<table>
<tr><th></th><th colspan="8">Timeline in Months</th></tr>
<tr><th>Task</th><th>1-3</th><th>4-6</th><th>7-9</th><th>10-12</th><th>13-15</th><th>16-18</th><th>19-21</th><th>22-24</th></tr>
<tr><td>Task 1</td><td colspan="8">Engineering Against SRH</td></tr>
<tr><td>1.1</td><td colspan="2">InGaN QW: MO</td><td colspan="6"></td></tr>
<tr><td>1.2</td><td colspan="2"></td><td colspan="2">InGaN QW: carrier gas</td><td colspan="4"></td></tr>
<tr><td>1.3</td><td colspan="4"></td><td colspan="2">AlGaN cap</td><td colspan="2"></td></tr>
<tr><td>1.4</td><td colspan="5"></td><td colspan="2">High T GaN barrier</td><td></td></tr>
<tr><td>1.5</td><td colspan="8">Thermal droop</td></tr>
<tr><td>Task 2</td><td colspan="8">Advanced Design</td></tr>
<tr><td>2.1</td><td colspan="2">Bulk B, C</td><td colspan="6"></td></tr>
<tr><td>2.2</td><td colspan="2">QW BC</td><td colspan="6"></td></tr>
<tr><td>2.3</td><td colspan="2"></td><td colspan="2">QW BC with E-field</td><td colspan="4"></td></tr>
<tr><td>2.4</td><td colspan="2">EBL</td><td colspan="6"></td></tr>
<tr><td>2.5</td><td colspan="2"></td><td colspan="2">Transport</td><td colspan="4"></td></tr>
<tr><td>2.6</td><td colspan="4"></td><td colspan="4">Balanced e and h injection</td></tr>
<tr><td>Task 3</td><td colspan="8">Polarization Engineering</td></tr>
<tr><td>3.1</td><td colspan="8">Polarization-screened QW</td></tr>
<tr><td>3.2</td><td colspan="2"></td><td colspan="6">Polarization-matched QBs</td></tr>
<tr><td>3.3</td><td colspan="2"></td><td colspan="6">Polarization-matched QBs with field screening</td></tr>
<tr><td>3.4</td><td></td><td colspan="7">Staggered QWs</td></tr>
<tr><td>3.5</td><td colspan="8">Current injection droop</td></tr>
<tr><td>Task 4</td><td colspan="8">Voltage Reduction</td></tr>
<tr><td>4.1</td><td>EBL</td><td colspan="7"></td></tr>
<tr><td>4.2</td><td></td><td colspan="2"># of QWs</td><td colspan="5"></td></tr>
<tr><td>4.3</td><td colspan="2"></td><td colspan="6">Reduce internal barriers to transport</td></tr>
<tr><td>4.4</td><td colspan="8">Detailed electrical measurements</td></tr>
<tr><td>Task 5</td><td colspan="8">Advanced Characterization</td></tr>
<tr><td>5.1</td><td colspan="2">APT local doping</td><td colspan="6"></td></tr>
<tr><td>5.2</td><td colspan="4">Polarization-matched QBs</td><td colspan="4"></td></tr>
<tr><td>5.3</td><td colspan="4">Staggered QWs</td><td colspan="4"></td></tr>
</table>

Go/No-Go Decision Point Summary:
The Go/No-Go decision point at 12 months is to realize MQW green LED with ΔV_F (35 A/cm^2) $<$ 0.5 V and performance (EQE) comparable to our current standard reference.