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/cm², 9/30/2019
2. Green LEDs with ≥ 46% external quantum efficiency (EQE) at 35 A/cm², 9/30/2019
3. Green LEDs with ≥ 35% power conversion efficiency at 35 A/cm², 9/30/2019

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

Budget:
Total Project $ to Date:
• DOE: $178,370.76
• Cost Share: $35,674.15

Total Project $:
• DOE: $999,996
• Cost Share: $250,130

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.
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 $\Delta V_F$ much larger than in blue
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 NH₃ flow

Use peak EQE and EQE at 35 A/cm² as metrics for improvement of material quality

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
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

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

p-AlGaN EBL has a negative effect on $V_\text{F}$, however increasing the Al% in the EBL improves the output power.
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/cm²:
- 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

\[ X = 0, 0.11, 0.20 \text{ and } 0.33 \]

- p++contact layer
- p-GaN
- HT GaN barrier
- 2 nm Al\(_x\)Ga\(_{1-x}\)N cap layer
- 3 nm InGaN QW
- GaN UID
- n-(In\(_{0.05}\)GaN\(_{0.95}\)/GaN) S.L
- 5 um UID GaN/n-GaN
- Patterned Sapphire Substrate (PSS)

\[ X = 0, 0.11, 0.20 \text{ and } 0.33 \]
Subtask 4.4 Detailed I-V measurement and analysis

Optimizing p++,GaN contact layer

- Pd/Au
- P-GaN

Unoptimized contact

Optimized contact

Current (mA) vs. Voltage (V)

Current density (A/cm²) vs. Voltage (V)
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

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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

- p++-GaN
- UID AlInGaN
- InGaN SQW
- UID AlInGaN
- n++-GaN

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

![Graph showing Si concentration vs. Si$_2$H$_6$ flow (sccm).]

- Continuous doping
- Delta doping

- RMS = 5.92 nm (Continues doping)
- RMS = 2.78 nm (Delta doping)
Thank You

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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

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### Budget History

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## Project Plan and Schedule

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

### Timeline in Months

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