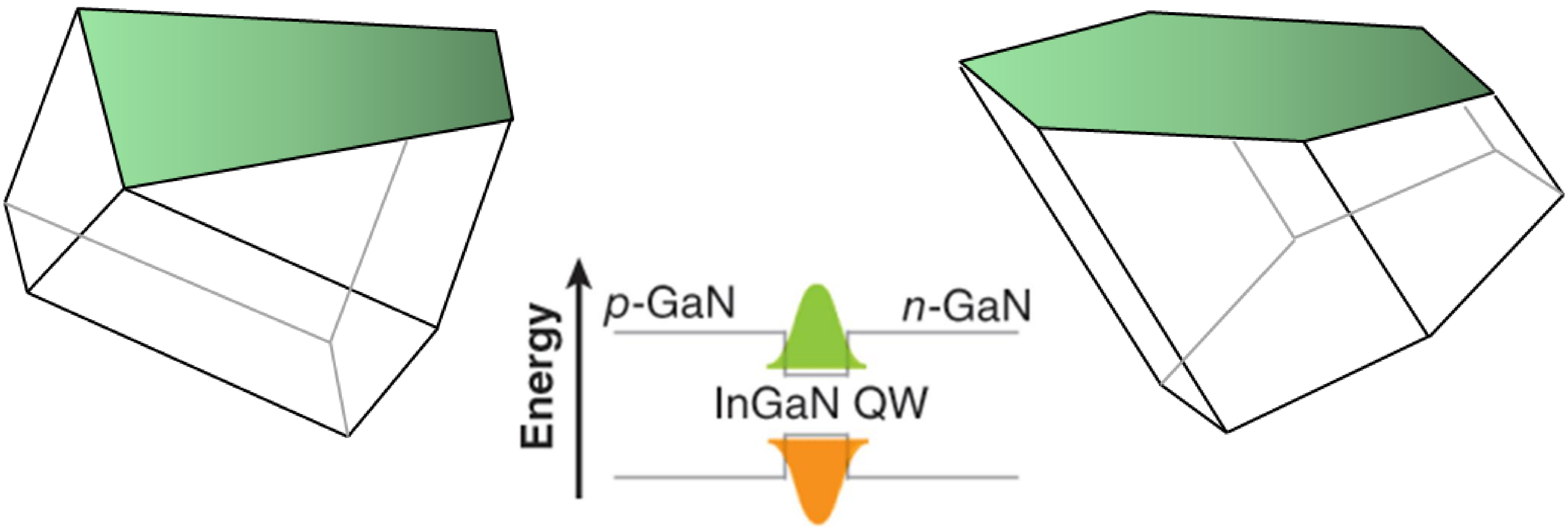
LEDs on Semipolar Bulk GaN Substrate with IQE > 80% at 150 A/cm^2 and 100 °C

2014 Building Technologies Office Peer Review



U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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Project Summary

Timeline:

Start date: **9/1/2011**

Planned end date: **8/31/2014**

Key Milestones

1. Yr 1: IQE >70% at 405 nm at 150 A/cm^2 and 100 ^{0}C
2. Yr 2: IQE >80% at 405 - 450 nm at 150 A/cm^2 and 100 ^{0}C

Budget:

Total DOE $ to date: **$462,167.33**

Total future DOE $: **$217,696.42**

Target Market/Audience:

Solid State Lighting

Key Partners: None

Project Goal:

Demonstrate Light Emitting Diodes on Semipolar Bulk GaN Substrates

1. With Internal Quantum Efficiency (IQE) > 80%
2. At a Current Density (J) of 150 A/cm2; and
3. At a Junction Temperature (T_j) of 100˚C

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Purpose and Objectives

Problem Statement: This project aims to address the issue related to steep reduction of optical efficiency of GaN based LEDs under high current density operation, commonly known as 'Current Droop'.

Target Market and Audience: The target market is Solid State Lighting (SSL).

- In the US, Lighting consumes 18% of the total site electricity use in 2010.
- SSL technology offers a potential saving of 217 TWh, or about one-third of lighting site electricity consumption, by 2025. *(Source: DOE SSL MYPP, Pg. 1)*

Impact of Project: Despite 20+ years of R&D, IQE of state-of-art LEDs is less than 65% under preferred operating condition set by DOE

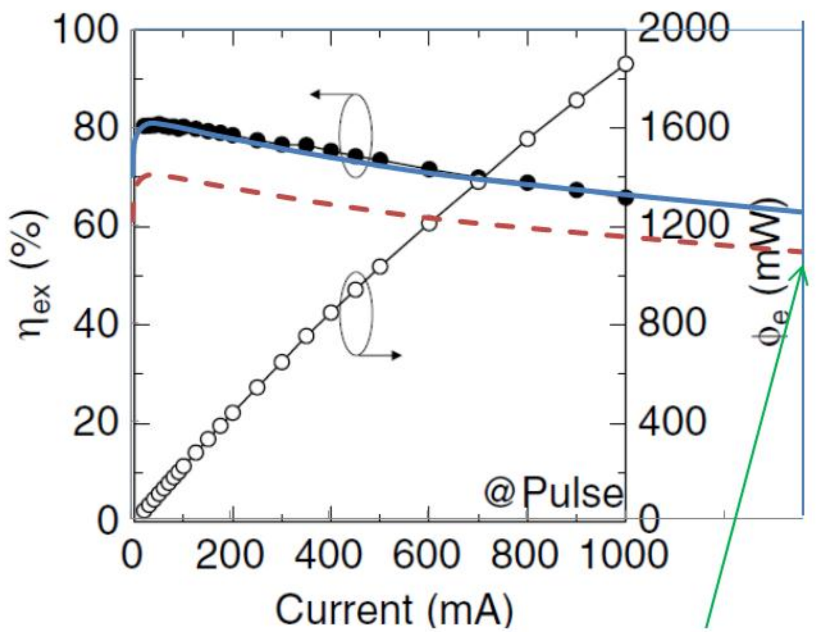
1. This project aims to achieve IQE > 80% under conditions specified in DOE MYPP

2. Impact path:
   a. Near-term: Establish proof-of-concept semipolar LED with IQE >80%
   b. Intermediate-term: Establish product quality semipolar LED with IQE >80%
   c. Long-term (3yr.+ after project): Manufacture semipolar LED with IQE >80%

Comparison with State-of-Art

Best Reported Nichia Data

- Narukawa et al., J. Phys D. Appl. Phys. 43 (2010) 354002



EQE = 60% (150 A/cm², 100 ˚C)

- Extrn. Efficiency assumed: 90% (fits well with IQE model)
- Used best hot/cold: Rebel ES (radiometric Nichia data not available)
- Hot/Cold = 92% at 100C

⇨ **IQE = 65%** (150 A/cm^2, 100 ˚C)

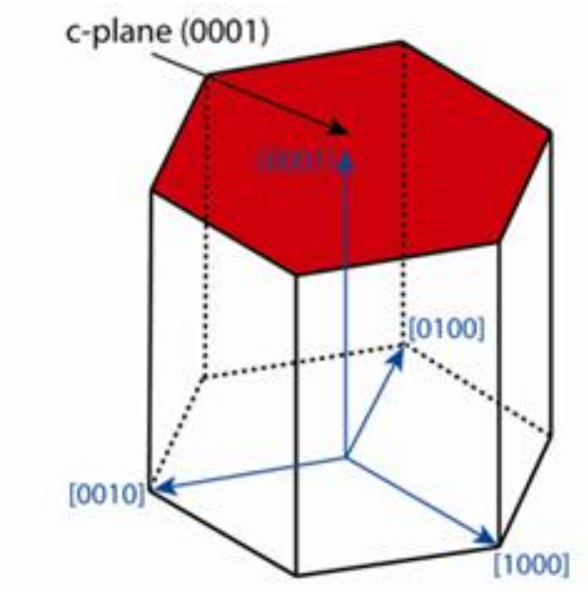
This Project

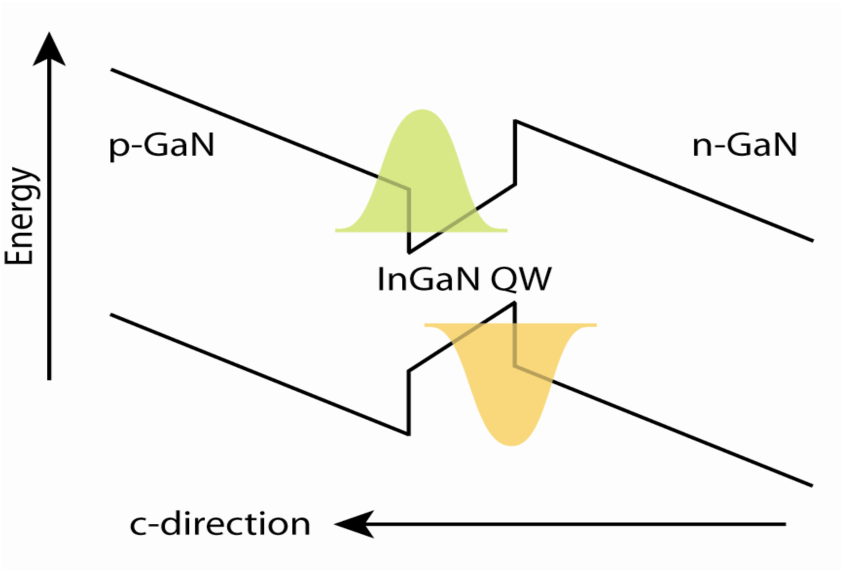
Metric	This Program (2013)	2020 MYPP
IQE (@35A/cm2)	90%	90%
RT QE Droop (Relative EQE at 150A/cm2 vs 35A/cm2)	95%	90%
RT QE Droop (Relative EQE at 300A/cm2 vs 35A/cm2)	90%	
Thermal Droop (Relative flux at 100C Tj vs 25C Tj)	95%	95%
HT QE Droop (Relative EQE at 150A/cm2 at 100C Tj vs 35A/cm2 at 25C)	90%	86%
IQE (@150A/cm2 @100C Tj)	81%	77%

The end of program milestones exceed the state-of-art performance level by >20% (20% increased energy saving)

Key Issue: Influence of Polarization induced Electric Field

Competition: Polar GaN Technology





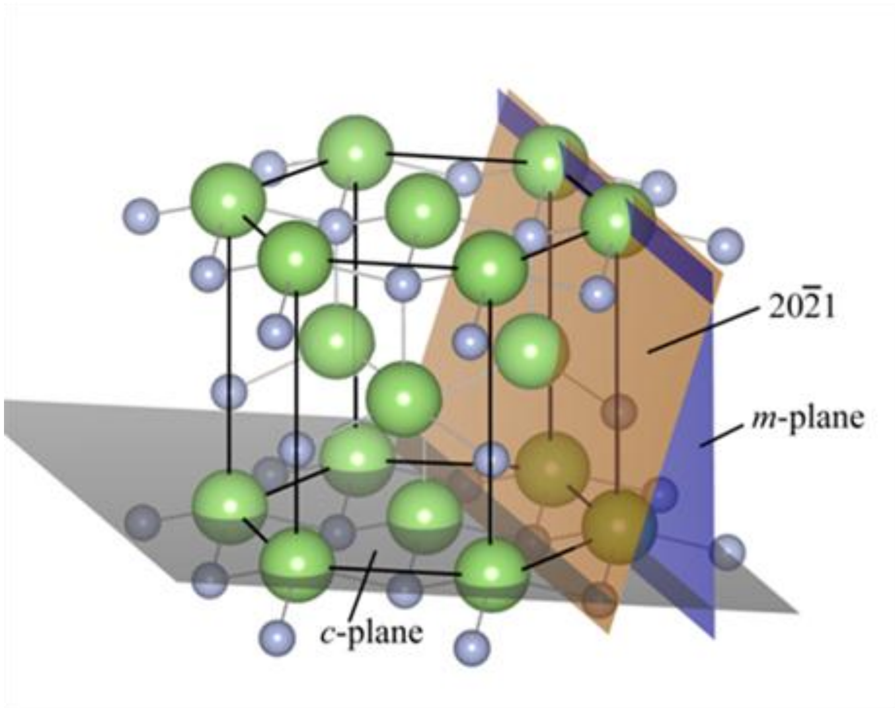
Reduced overlap of electron and hole wave-functions

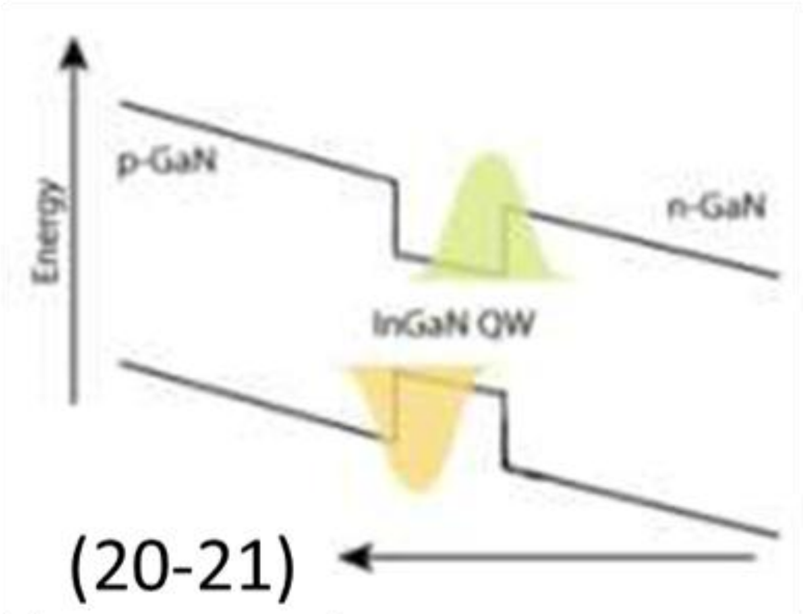
-> Quantum Confined Stark Effect (QCSE)

-> Reduces oscillator strength and recombination rate

Distinctive Approach: Use of Nonpolar and Semipolar GaN

Nonpolar/Semipolar GaN Technology





Increased overlap of electron and hole wave-functions

-> Increases oscillator strength

-> Increases radiative recombination rate

Approach

$$IQE = \frac{BN^2}{AN + BN^2 + CN^3}$$

Non-radiative Recomination Coefficient *(defect/trap related - minimized through use of low defect density bulk GaN substrates)*

Radiative Recomination Coefficient *(expected to be higher for nonpolar and semipolar planes)*

Auger Non-radiative Recomination Coefficient *(strong dependence on carrier density – nonpolar devices offer significant potential for low carrier density device designs)*

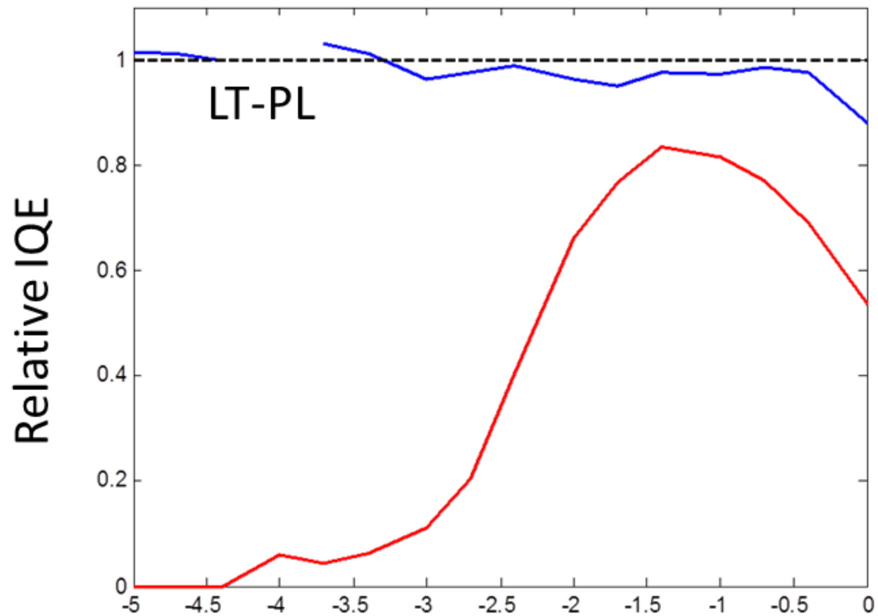
Soraa's approach for this program employs:

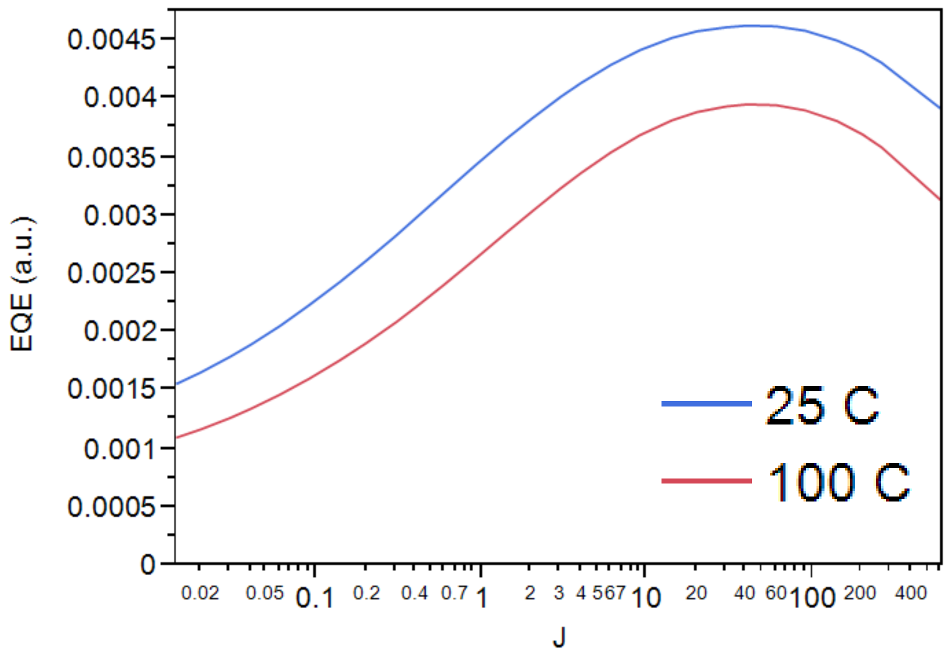
1. Bulk GaN substrates: Reduced defect related non-radiative recombination processes (reduced *A* coefficient) compared to heteroepitaxy
2. Semipolar orientation: Increased radiative recombination rates (higher *B* coefficient) due to improved electron-hole wavefunction overlap
3. Wider design space: Soraa's novel device design would enable lower carrier density (*N*) in the active region, resulting in reduced Auger recombination

Soraa's approach offers key advantages to address IQE roll-over

Progress and Accomplishments (End of Year 1)

Measurement of Internal Quantum Efficiency (IQE)





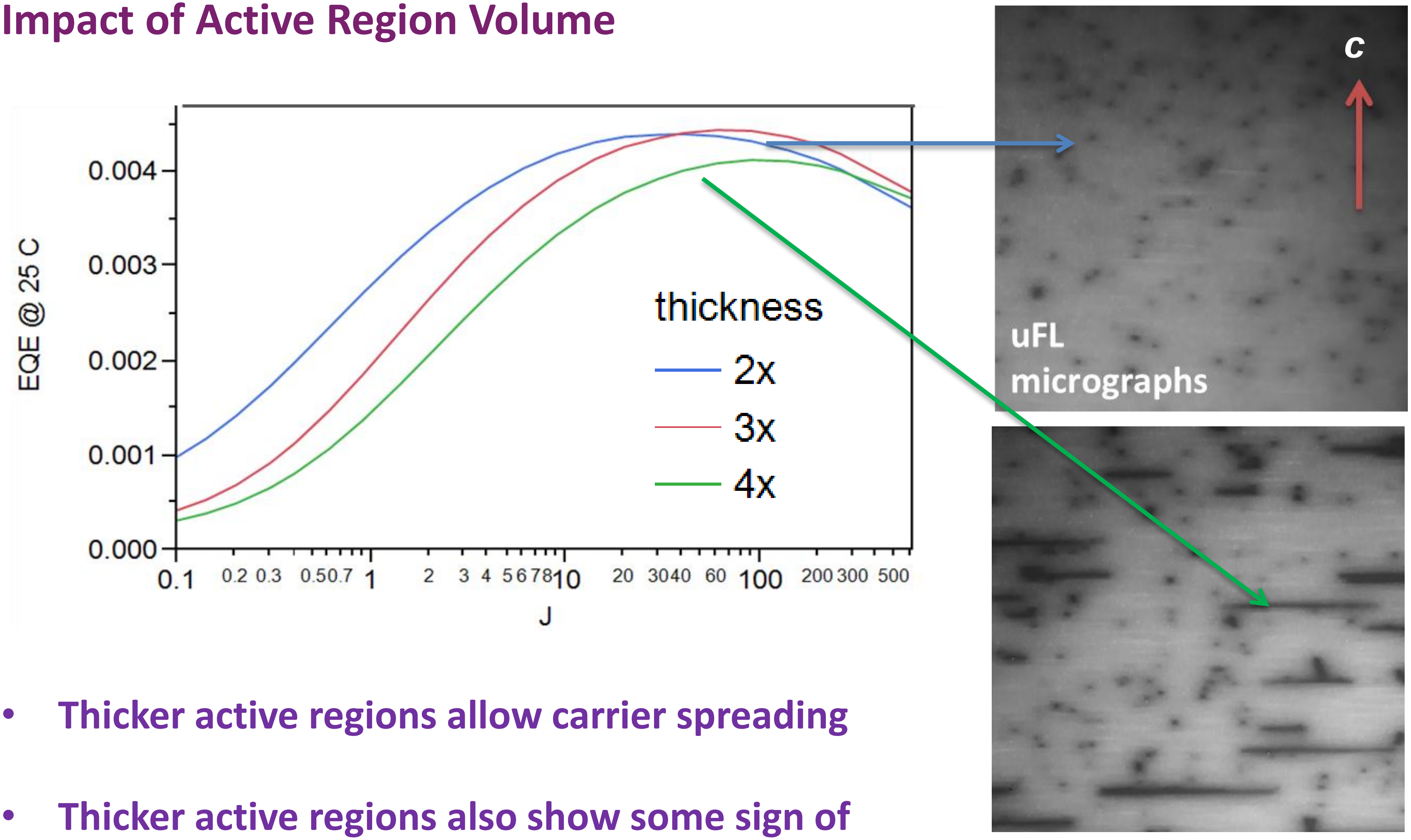
Peak IQE (measured using Low Temp Photoluminescence) = **85%** (407 nm)
Current droop (measured using Electroluminescence) = **97%**
Thermal droop (measured using High Temp Electroluminescence) = **85%** (to 100 ˚C)

IQE @ 150 A/cm² and 100 ˚C: 70%

Year 1 results exceed State-of-Art performance level by ~10%

Key Lessons Learnt

Impact of Active Region Volume



- Thicker active regions allow carrier spreading
- Thicker active regions also show some sign of reduced crystal quality

Project Integration and Collaboration

Project Integration:

Relevant results from the program are disseminated to a broader audience at the annual DOE Solid State Lighting R&D Workshops.

Communications:

Results from this program have been presented in the following workshops:

- DOE Solid State Lighting R&D Workshop, Jan 29 – 31, 2013, Long Beach, CA (both Oral and Poster presentation)
- DOE Solid State Lighting R&D Workshop, Jan 28 – 30, 2014, Tampa, FL (Poster presentation only)

Next Steps and Future Plans

Year 2 Goals:

- Optimize IQE (at 150 A/cm^2, 100 ^0C) as a function of wavelength (400-450 nm)
- Identify primary physical mechanism behind IQE degradation at high current densities and high temperature as function of wavelength
- Demonstrate IQE >80% at 150A/cm^2 and 100 ^0C in the wavelength range 400-450nm
- Fabricate LED lamps using optimized semipolar LED structures

REFERENCE SLIDES

Project Budget

Project Budget:

			Total (DOE + Soraa)	DOE	Soraa
	Cost Share: 30%				
PROJECT BUDGET	*PHASE 1 + 2 (9/1/11 - 8/31/14)*	*TOTAL*	*$968,355.00*	*$679,863.75*	*$288,491.25*
PHASE 1 BUDGET	*PHASE 1 (9/1/11 - 8/31/12)*	*TOTAL*	*$483,115.00*	*$339,188.13*	*$143,926.88*
PHASE 1 SPENDING	*PHASE 1 (9/1/11 - 8/31/12)*	*TOTAL*	*$535,732.32*	*$377,865.31*	*$157,867.01*
PHASE 2 BUDGET	*PHASE 2 (9/1/12 - 8/31/13)*	*TOTAL*	*$485,240.00*	*$340,675.63*	*$144,564.38*
PHASE 2 SPENDING	*PHASE 2 (9/1/12 - 2/28/14)*	*TOTAL*	*$105,377.52*	*$84,302.02*	*$21,075.50*
REMAINING	*YEAR 2 (10/1/13 - 8/31/14)*	*TOTAL*	*$327,245.16*	*$217,696.42*	*$109,548.74*

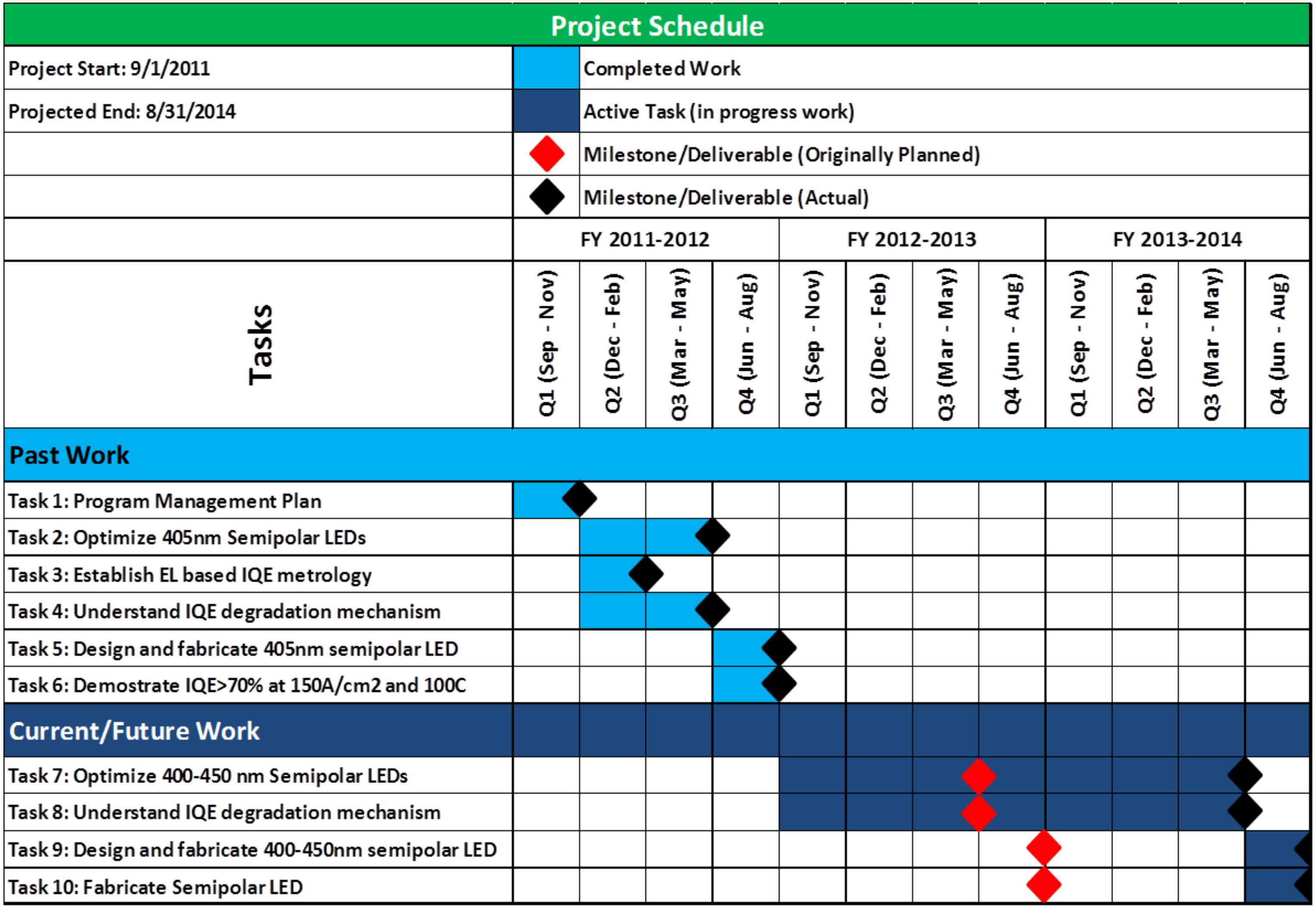
Variances: None

Cost to Date: 66%

Additional Funding: None

Budget History			
9/1/2011 – FY2013 (past)		FY2014 (End date: Aug 31, 2014)	
DOE	Cost-share	DOE	Cost-share
$462,167.33	$178,942.51	$217,696.42	$109,548.74

Project Plan and Schedule



Phase II work has been delayed due to relocation of work site and substrate quality issues