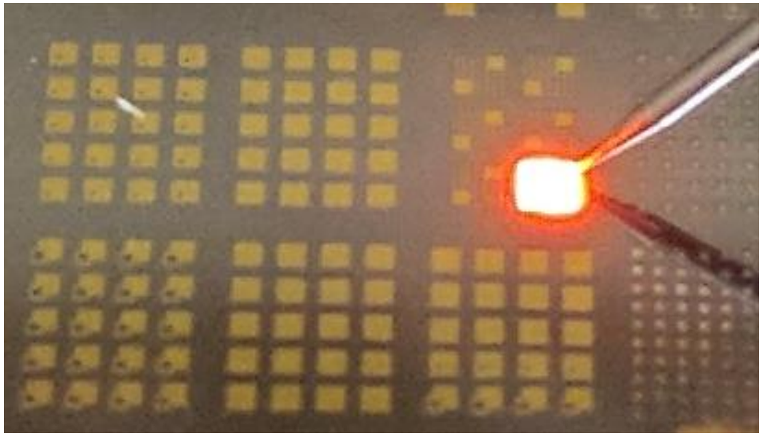
U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

AlInP-Based LEDs for Efficient Red and Amber Emission



National Renewable Energy Laboratory, MicroLink Devices, South Dakota School of Mines and Technology

Kirstin Alberi, Scientist

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Project Summary

Timeline:

Start date: 10/1/18

Planned end date: 9/30/20

Key Milestones

1. Demonstrate ordered $Al_xIn_{1-x}P$ (λ = 590 nm) with IQE = 75% (9/30/19)
2. Demonstrate $Al_xIn_{1-x}P$ LED (λ = 590 nm) on GaAs substrate with PCE = 1% and 0.5 hot/cold factor (9/30/20)

Key Partners:

MicroLink Devices

South Dakota School of Mines and Technology

Budget:

Total Project $ to Date:

- DOE: $500K
- Cost Share: $0

Total Project $:

- DOE: $1M
- Cost Share: $0

Project Outcome:

This project is focused on the development of a novel phosphide-based LED design that will increase the efficiency of direct-emitting amber LEDs by up to 4x. The objective is to fill in the "green gap" that exists in direct-emitting LEDs to enable color-mixed white LED architectures and color tuning functionality.

Team

NREL

Dr. Kirstin Alberi

Previously worked on BTO/SBIR-funded SSL projects
PI of BES, EERE, CRADA projects
DOE Early Career Award, 2012

Project Management
Optical Spectroscopy
Device Fabrication
Device Measurement

Dr. Brian Fluegel

Developed novel spectroscopy measurement techniques
Key contributor to understanding ordering phenomena in phosphide-based semiconductors.

MicroLink

Dr. Chris Stender

PI on several SBIR projects, including AlInP for SSL.
Expert on III-V semiconductor device fabrication.

Epitaxial growth
In-house characterization

Dr. Kamran Forghani

Specialist in epitaxial growth by MOCVD and the design of metamorphic buffers for growth on lattice-mismatched substrates.

SDSMT

Prof. Phil Ahrenkiel

Expert in transmission electron microscopy
Extensive experience in the development of phosphide semiconductors for optoelectronic devices, the design of metamorphic buffers and MOCVD growth of AlInP and GaInP

Transmission electron microscopy

Challenge

Tailoring the spectrum to the application can improve energy savings and end user experience

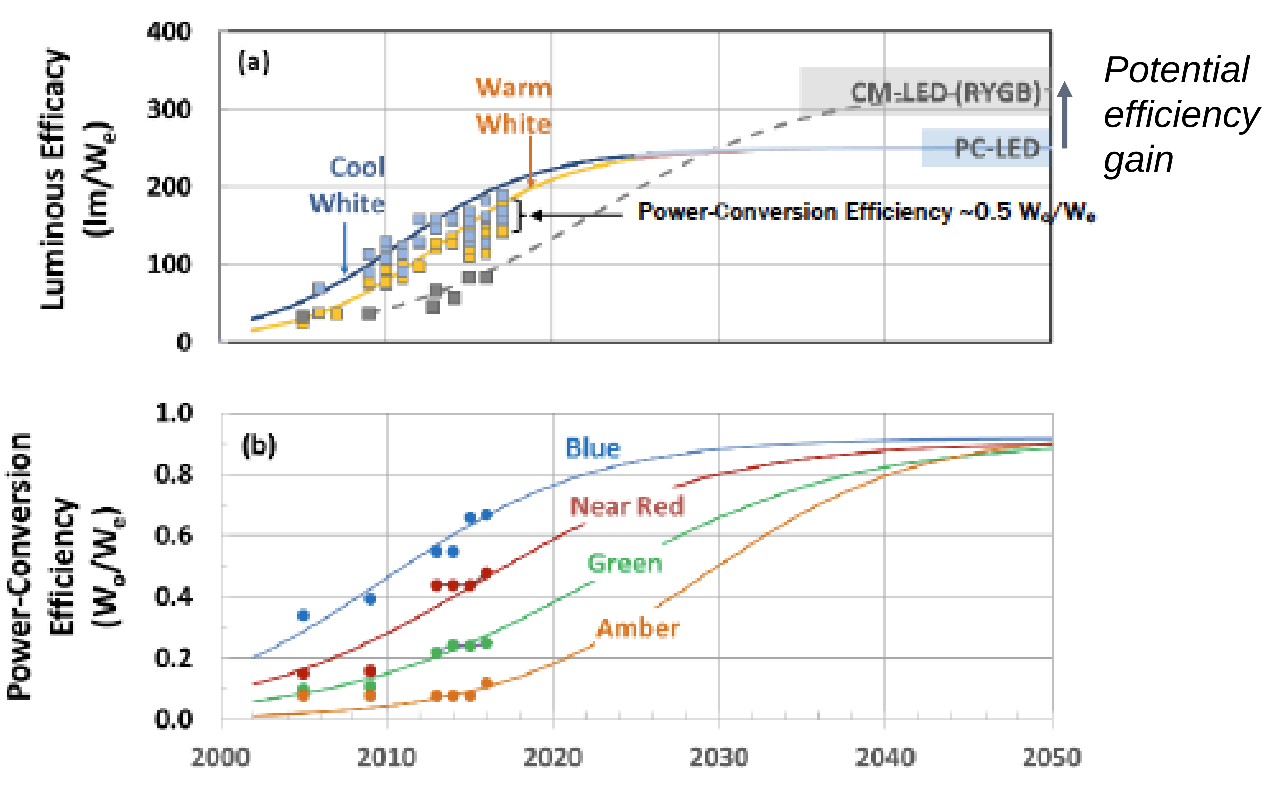
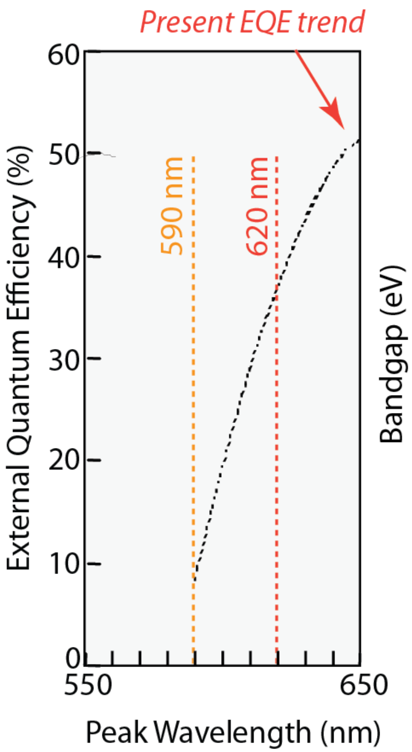


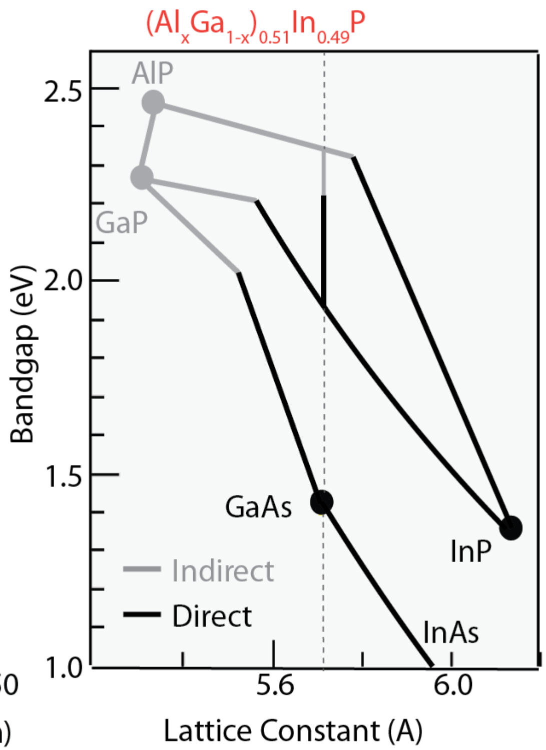
Figure 5-3. Efficacies and Efficiencies Over Time of White and Colored LED Packages

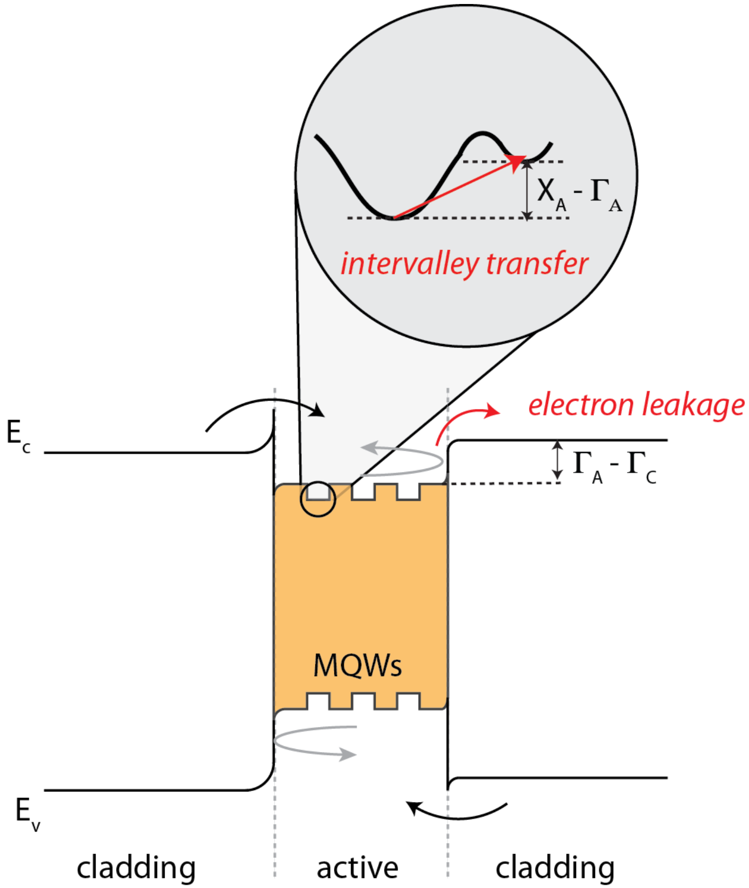
We must improve the efficiencies of amber, red and green LEDs to enable high efficiency and tunable color-mixing lighting.

https://www.energy.gov/sites/prod/files/2019/01/f58/ssl_rd-opportunities_jan2019.pdf

Challenge



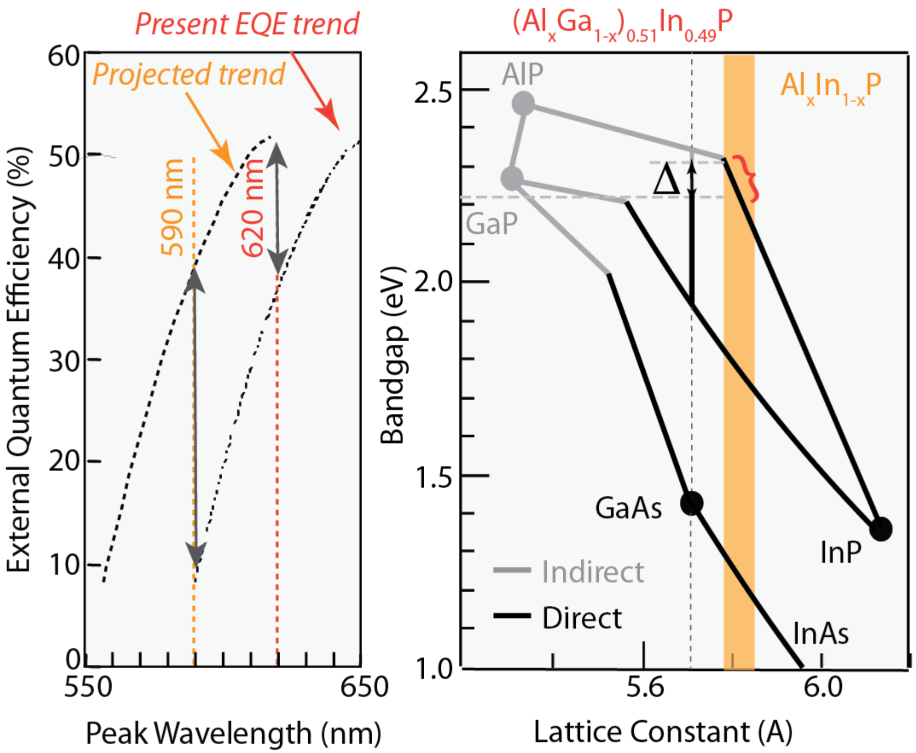


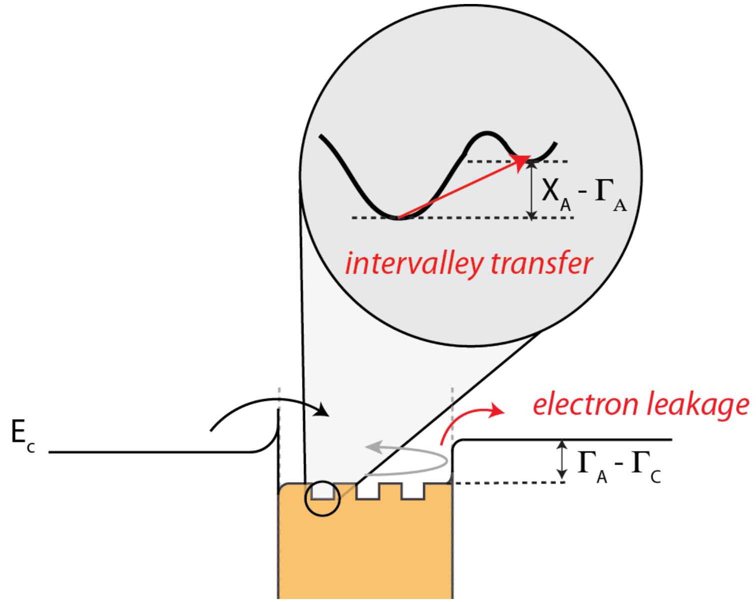


AlGaInP has a direct-indirect crossover in the amber wavelength range.

Low energetic barriers to intervalley transfer and electron leakage permit excessive carrier losses.

Approach

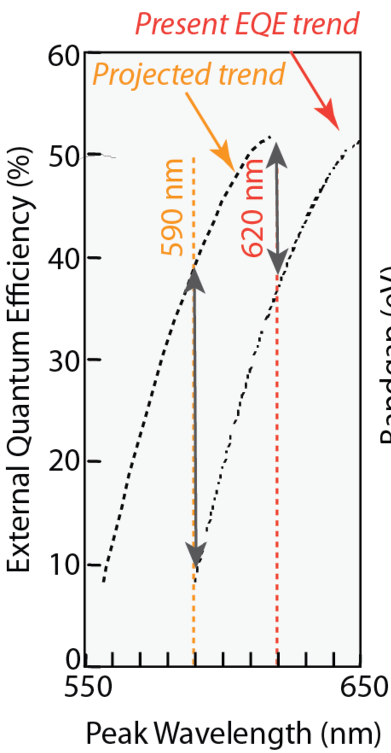


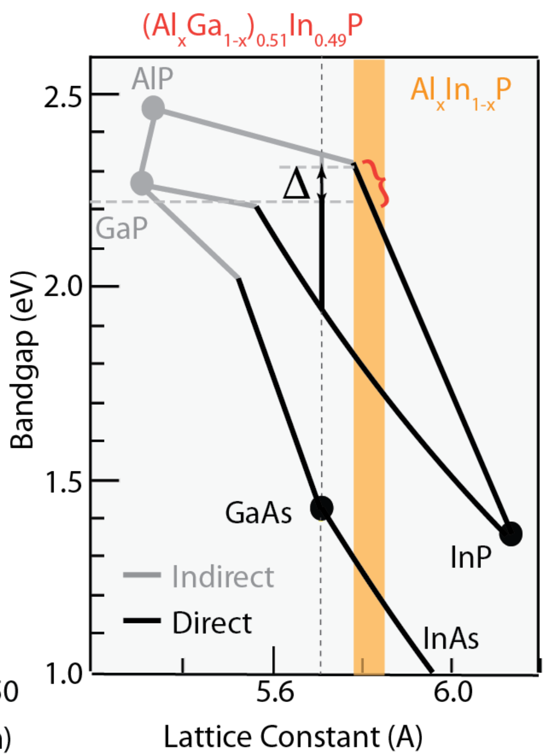


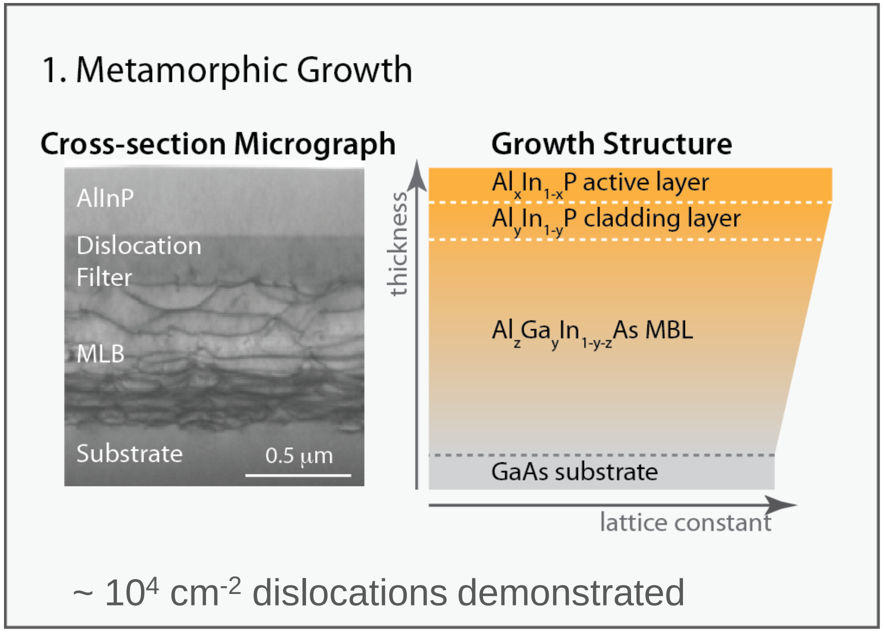
Our approach is to utilize Al$_x$In$_{1-x}$P with a higher direct-indirect crossover energy. This will increase the potential barriers to carrier loss and shift the EQE trend to shorter wavelengths.

It also has the advantage that it builds on existing red/amber LED designs and manufacturing infrastructure.

Approach



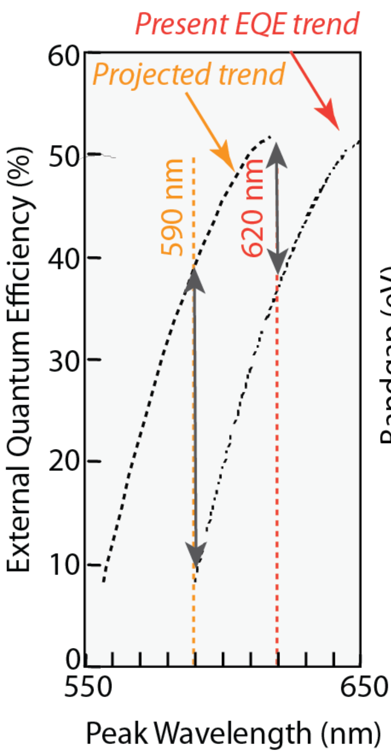


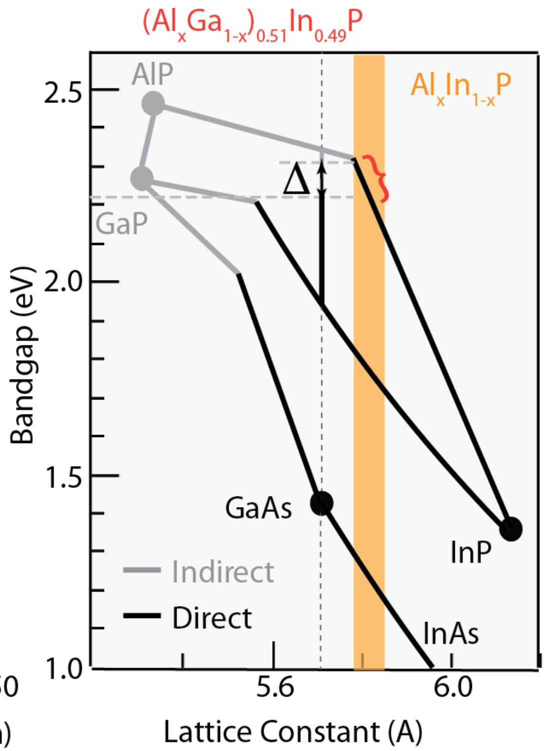


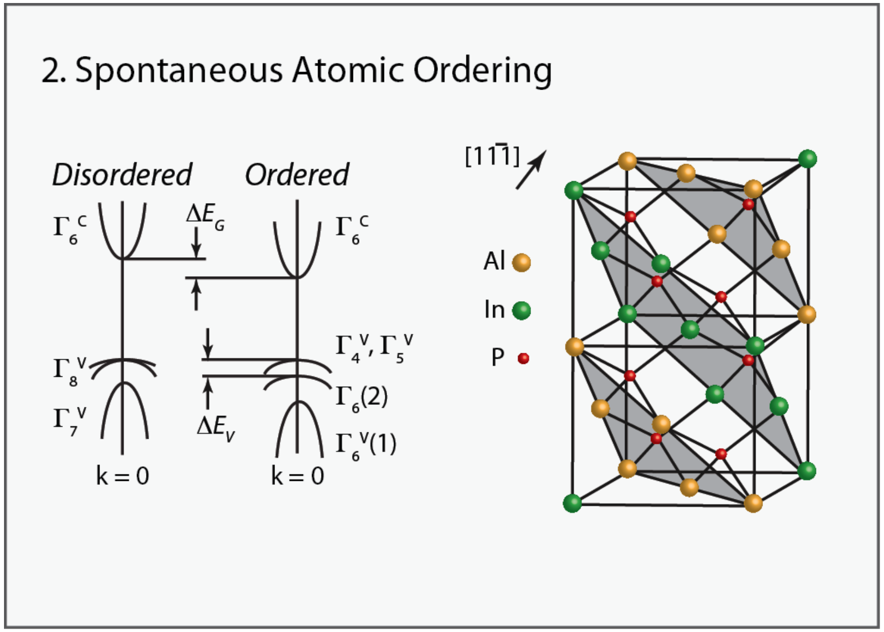
A metamorphic buffer layer (MBL) enables the growth of AlInP on lattice-mismatched GaAs substrates.

- The lattice constant is continuously graded between GaAs and AlInP
- Dislocations are confined to the MBL, resulting in low dislocation densities in the device layers.

Approach





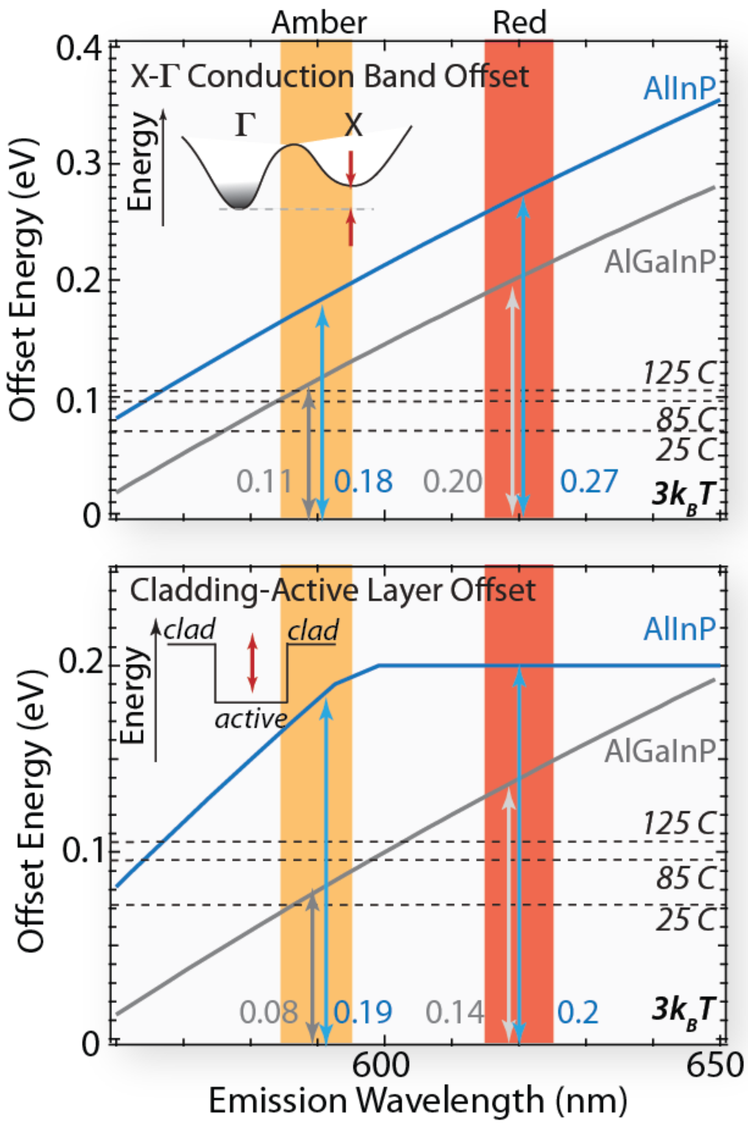


T.M. Christian, *et al.*, *J. Appl. Phys.*, **114**, 074505 (2013)

Control of spontaneous atomic ordering of Al and In atoms allows us to engineer high electron confinement barriers between AlInP active and cladding layers.

- Ordering causes a reduction in the conduction band by ≥ 200 meV
- Disordered/ordered/disordered heterostructures produce electron confinement without having to substantially change the AlInP composition between cladding and active layers.

Approach



An increase in the direct-indirect crossover for AlInP compared to AlGaInP will result in a larger barrier to intervalley transfer loss.

The potential Γ conduction band reduction we can achieve with ordering (≥ 200 meV) will allow us to design high offset barriers to electron leakage from ordered active layers to disordered cladding layers.

At shorter wavelengths, the offset barrier between these layers is limited by the X conduction band edge in the cladding layer.

Impact: Improvement Potential

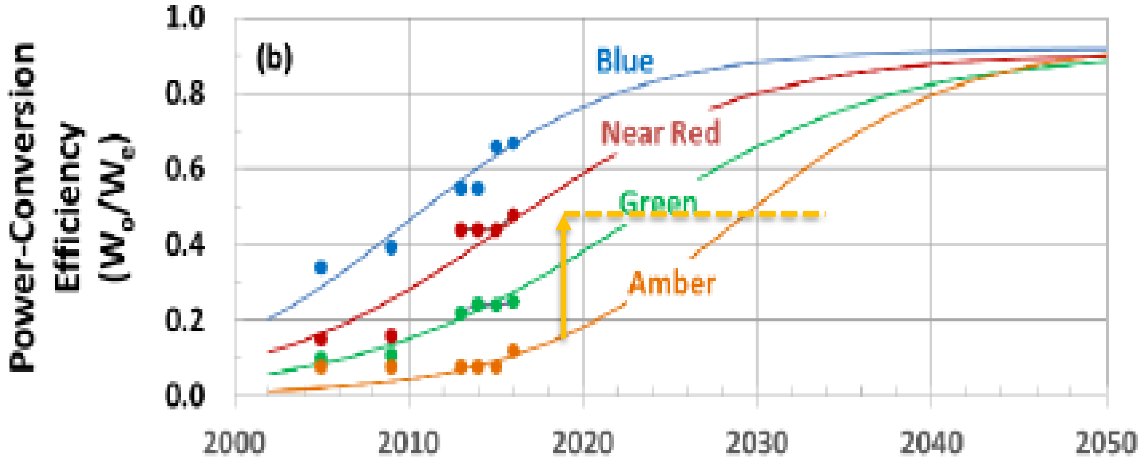


Figure 5-3. Efficacies and Efficiencies Over Time of White and Colored LED Packages

Our approach has the potential to improve direct-emitting amber LED efficiency by up to 4x.

This improvement will help to fulfill the DOE's long-term mission of closing the green gap and realizing color mixing architectures with high efficiency and color-tuning capabilities.

Impact: Comparison to Other Technologies

Pc-Amber LEDs

Efficiency ~25-30%
FWHM ~ 75nm

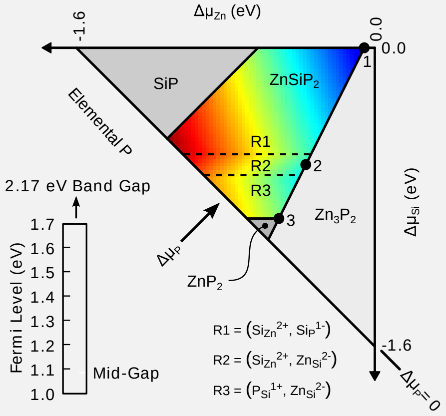
www.lumileds.com/

Quantum Dot LEDs

Down-conversion limited
Narrow FWHM

cleantechnica.com/

New Materials



Perovskites, II-IV-V
Earlier stage research

Adele Tamboli, NREL

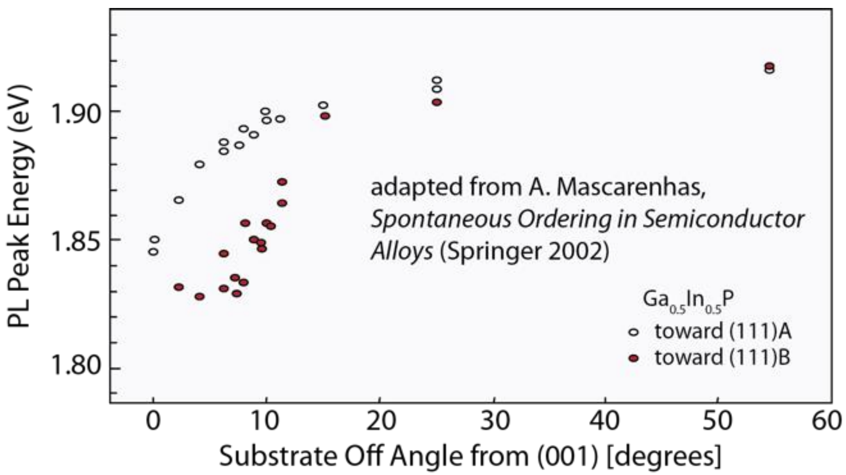
Compared to alternative amber LED solutions, our approach has the following aspects:

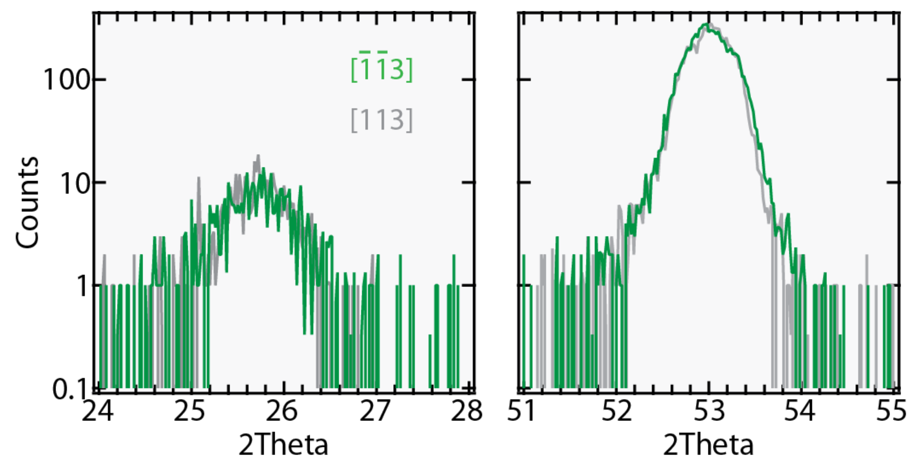
- Potential for the highest efficiency (no down conversion)
- Narrow FWHM
- Long lifetime
- Utilizes existing manufacturing methods and is a drop-in replacement for existing LEDs
- Shorter anticipated development time compared to new materials

Progress

In the **early state** of this project, we are focused on optimizing the energetic barriers through control of the order parameter.

Quarterly Progress Measure (Q1)	Accomplishment
Maximize ordering in $Al_xIn_{1-x}P$ (λ = 590 nm) to be > 0.45.	Measured total order parameter of 0.387 so far.





Order parameter is influenced by:

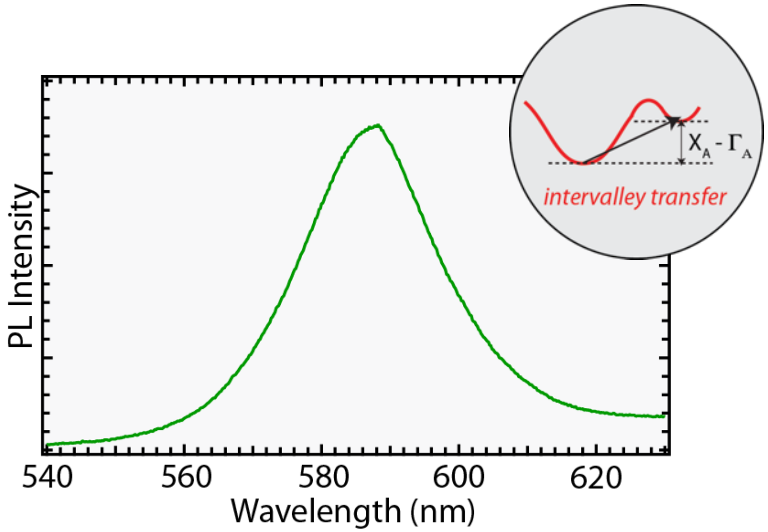
- substrate temperature
- Orientation
- V/III gas ratio

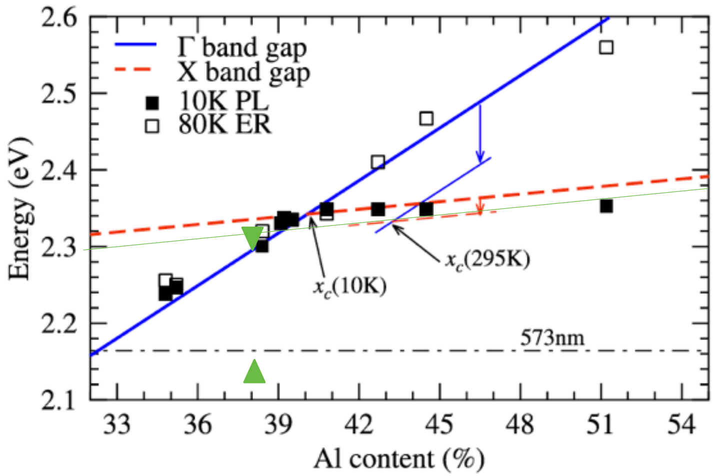
Order parameter is determined from XRD

$$S=\left\{\frac{I_{(1/2)(1/2)(3/2)}}{I_{113}}\,\frac{4\left[\left[|f_P|^2+|x_{Ga}f_{Ga}+x_{In}f_{In}|^2\right]\left(\frac{1+\cos^2 2\theta}{\sin 2\theta}\right)\left(1-e^{-2\mu L/\sin\theta}\right)\right]_{113}}{\left[|f_{Ga}-f_{In}|^2\left(\frac{1+\cos^2 2\theta}{\sin 2\theta}\right)\left(1-e^{-2\mu L/\sin\theta}\right)\right]_{(1/2)(1/2)(3/2)}}\right\}^{1/2}$$

Progress

Quarterly Progress Measure (Q2)	Accomplishment
Demonstrate internal Γ-X offsets of 130 meV in ordered $Al_xIn_{1-x}P$ (λ = 590 nm)	Measured 180 meV





D.A. Beaton, *et al., J. Appl. Phys.*, **114**, 203504 (2013)

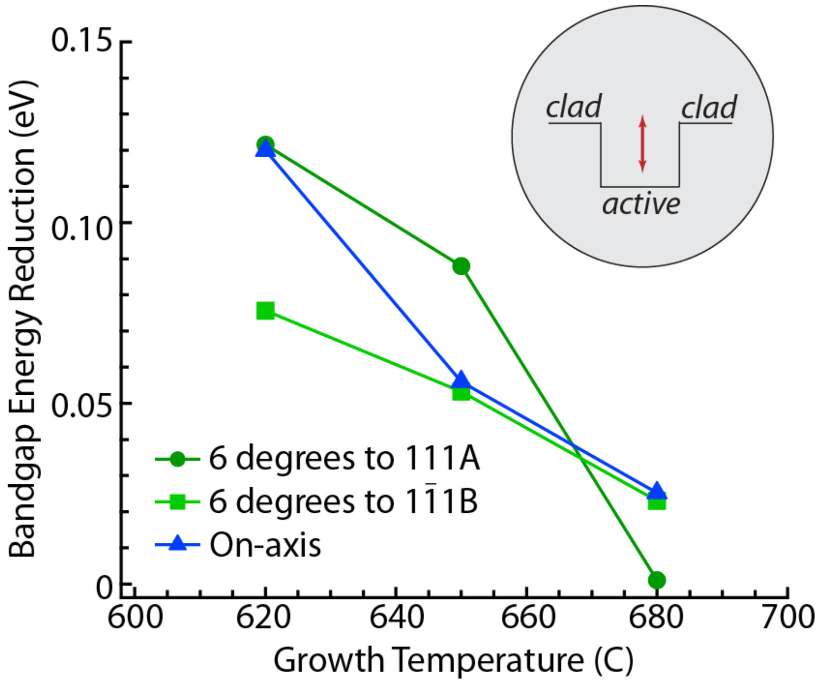
Γ-X offset measured in an ordered AlInP epilayers (λ = 580 nm) grown at 650 C:

$$2.319 \text{ eV (X)} - 2.138 \text{ }(\Gamma) = 0.180 \text{ eV}$$

We have demonstrated that we can obtain exceedingly high energetic barriers to intervalley transfer in AlInP.

Progress

Quarterly Progress Measure (Q3)	Accomplishment
Demonstrate electron confinement potentials of 130 meV in ordered/disordered $Al_xIn_{1-x}P$ heterostructures (λ = 590 nm)	Measured 128 meV



Γ (disordered) – Γ(ordered) for AlInP epilayers grown under different conditions suggests we still have room to improve the bandgap reduction due to ordering.

Stakeholder Engagement

MicroLink Devices

We are working with MicroLink Devices to demonstrate our LED technology using commercial MOCVD reactors for epitaxy.

MicroLink is also contributing their metamorphic buffer layer technology to the development of the devices.

DOE Energy I-Corps

We are participating in this program to identify commercialization pathways for our technology. As part of this program, we are interviewing the following parties along the value chain to understand how our technology will impact lighting applications and meet their needs:

- LED chip manufacturers
- Module and luminaire manufacturers
- Lighting designers and subject matter experts
- End users

Remaining Project Work

Quarter	Progress Measure	Purpose
Q3	Demonstrate electron confinement potentials of 130 meV in ordered/disordered $Al_xIn_{1-x}P$ heterostructures (λ = 590 nm)	Demonstrate $Al_xIn_{1-x}P$ heterostructure LEDs (λ =590 nm) with a MQW active layer that exhibit 50% higher EQE than equivalent $(Al_xGa_{1-x})_{0.51}In_{0.49}P$ LEDs (λ = 590 nm)
Q4	Demonstrate ordered $Al_xIn_{1-x}P$ (λ = 590 nm) with IQE = 75%	
Q5	Demonstrate $(Al_xGa_{1-x})_{0.51}In_{0.49}P$ active layers (λ = 590 nm) with IQE = 75%	Experimentally evaluate the efficiency potential of AlInP LEDs
Q6	Compare simulated device efficiencies for $Al_xIn_{1-x}P$ and $(Al_xGa_{1-x})_{0.5}In_{0.5}P$	
Q7	Demonstrate $Al_xIn_{1-x}P$ (λ = 590 nm) with MQWs	
Q8	Demonstrate unpackaged $Al_xIn_{1-x}P$ (λ = 590 nm) LED on GaAs substrate with 1% PCE and 0.5 hot/cold factor	

The end goal of this project is to demonstrate the feasibility of improving amber LED efficiency with AlInP and de-risk it for industry.

Thank You

National Renewable Energy Laboratory, MicroLink Devices, South Dakota School of Mines and Technology

Kirstin Alberi, Scientist

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REFERENCE SLIDES

Project Budget

Project Budget: $500K/year for two years
Variances: No significant variances to date.
Cost to Date: To date, 32% of the budget for FY 2019 has been spent
Additional Funding: None.

Budget History					
10/1/18– FY 2018 (past)		FY 2019 (current)		FY 2020 – 9/30/20 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
		$500K	$0	$500K	$0

Project Plan and Schedule

Project Schedule								
Project Start: 10/1/18		Completed Work						
Projected End: 9/30/20		Active Task (in progress work)						
		Milestone/Deliverable (Original)						
		Milestone/Deliverable (Actual)						
	FY2019				FY2020			
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: Maximize ordering in AlxIn1-xP (λ = 590 nm) to be η > 0.45								
Q2 Milestone: Demonstrate internal Γ-X offsets of 130 meV in ordered AlxIn1-xP (λ = 590 nm)								
Current/Future Work								
Q3 Milestone: Demonstrate electron confinement potentials of 130 meV in ordered/ disordered AlxIn1-xP heterostructures (λ =590 nm).								
Q4 Milestone: Demonstrate ordered AlxIn1-xP (λ = 590 nm) with IQE = 75%.								
Q1 Milestone: Demonstrate (AlxGa1-x)0.51In0.49P active layers (λ = 590 nm) with IQE = 75%								
Q2 Milestone: Compare simulated device efficiencies for AlxIn1-xP and (AlxGa1-x)0.51In0.49P LEDs using measured properties and including current spreading and light extraction features								
Q3 Milestone: Demonstrate AlxIn1-xP heterostructure LEDs (λ =590 nm) with a MQW active layer that exhibit 50% higher EQE than equivalent (AlxGa1-x)0.51In0.49P LEDs (λ = 590 nm)								
Q4 Milestone: Demonstrate an unpackaged AlxIn1-xP amber LEDs (λ =590 nm) on a GaAs substrate with 1% PCE and 0.5 hot/cold factor.								

We missed the FY 2019 Q1 milestone due to delays in setting up the subcontract agreements with MicroLink Devices and SDSMT. We are close to completing it. We also selected an aggressive quantitative order parameter value for this milestone because we thought we needed it to enable achievement of the Q2 and Q3 milestones. We have already met those milestones, so such a high order parameter value may not be needed.

← Go/no-go decision