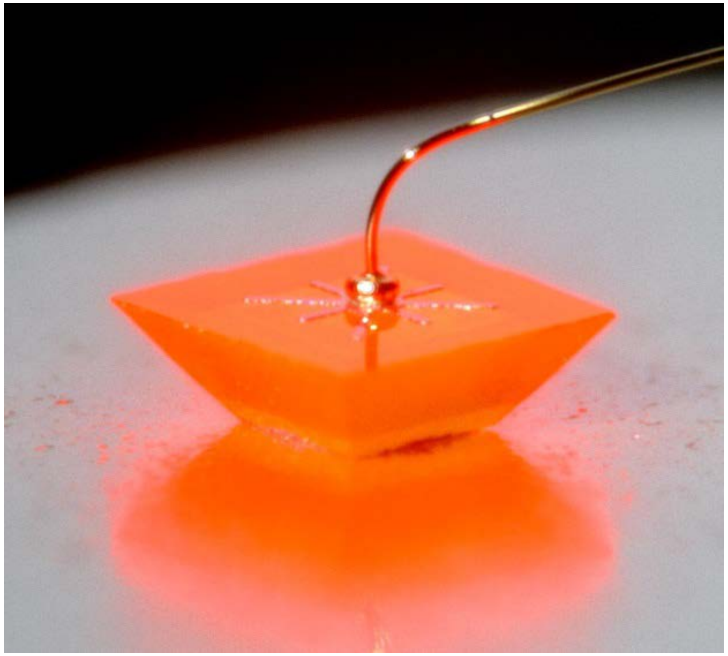
Improved Radiative Recombination in AlInGaP LEDs

(new project)



Lumileds
Ted Chung: Senior Manager
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Project Summary

Timeline:

Start date: October 1, 2017

Planned end date: September 30, 2019

Key Milestones

Year 1: 15% external quantum efficiency (EQE) for amber LED

Year 2: 20% EQE for amber LED,
60% EQE for red LED

Budget:

Total Project $ to Date (as of 2/18/2018)

- DOE: $187,403
- Cost Share: $57,370

Total Project $:

- DOE: $1,068,970
- Cost Share: $327,243

Key Partners:

Sub-recipient:

- Sandia National Laboratories: for defect characterization by DLTS/DLOS

Other collaborators:

- Stony Brook University: X-ray topography of GaAs substrate and epi layers
- MIT: STEM-CL characterization of AlInGaP die

Project Outcome:

- Design more efficient amber and red LEDs by characterizing and mitigating defects associated with high efficiency epitaxy designs
- Enable efficiency gains towards DOE SSL program goals for white lighting efficacy

Team

LUMILEDS

Member	Position	Expertise
Ted Chung	Senior Manager	Epitaxial growth & device physics
Juan Cai	MOCVD growth scientist	Epitaxial growth, TEM
Suk Choi	MOCVD growth scientist	Epitaxial growth, device physics
David Soltz	Characterization scientist	Time-resolved PL, electron beam induced current (EBIC)

Sandia National Laboratories

Member	Position	Expertise
Andy Armstrong	Senior Technical Staff	Deep-level transient spectroscopy (DLTS) Deep-level optical spectroscopy (DLOS)

Team

Additional collaboration with universities

Stony Brook University

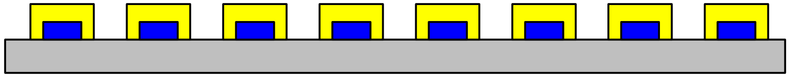
- Professor Dudley of Stony Brook University: X-ray topography:
  - Synchroton X-ray done at Argonne National Laboratory

- Professor Gradecak of Massachusetts Institute of Technology (MIT)
  - Cathodoluminescence (CL) with scanning transmission electron microscopy (STEM)

Challenge: White light LED efficacy

Phosphor-converted LEDs

Blue pump LED + phosphor

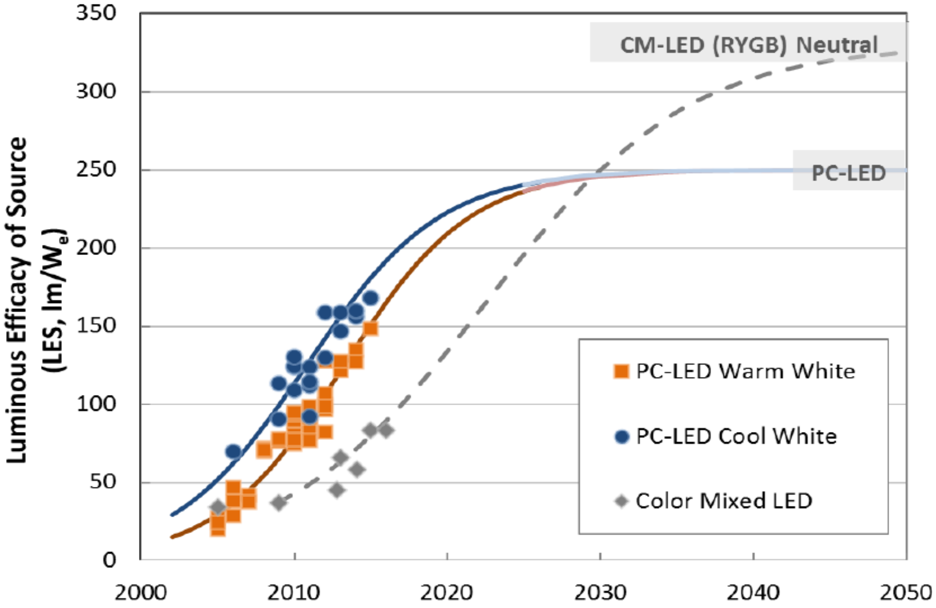


- LED architecture with highest efficacy <u>today</u>
- Used in majority of LED lighting applications
- Efficacy ultimately limited by phosphor down-version loss (“Stokes loss”)

Direct-emitting LEDs

Red, amber, green and blue LED

- LED architecture with highest efficacy <u>potential</u>
- Efficacy today limited by low efficiency of direct green, amber and red– not a fundamental limit
- **Need to improve to achieve DOE SSL program goals and full energy savings potential of SSL**



DOE SSL Program, “2017 Suggested Research Topics Supplement: Technology and Market Context,” edited by James Brodrick, Ph.D.

Challenge

Problem

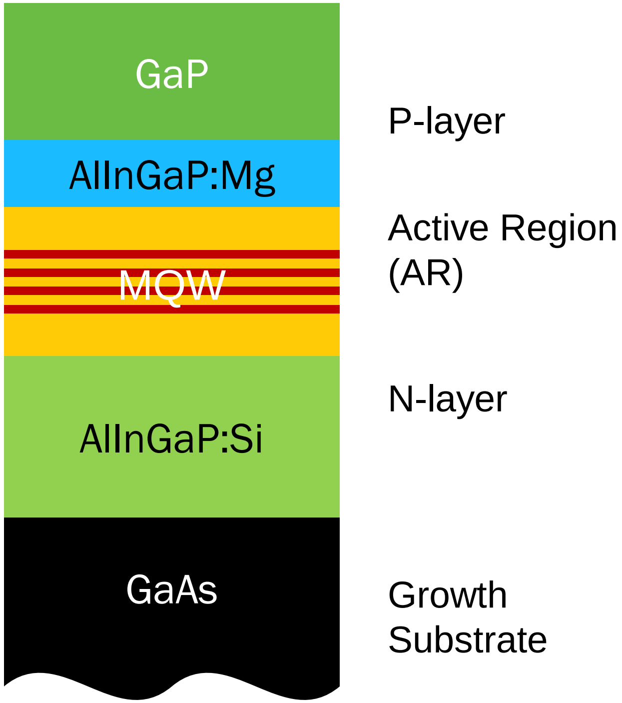
1) How to make red and amber LEDs brighter without sacrificing reliability?
   - Approaches for efficiency improvement are known but typically associated with faster LED degradation
2) How to make red and amber LEDs brighter despite the inherent limits of the band structure?

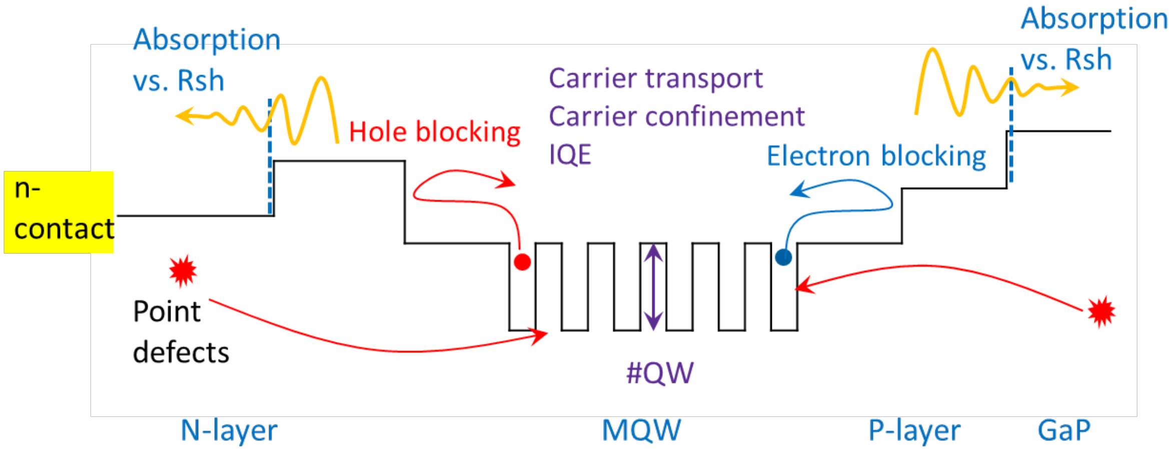
Approach

1) Determine the key root causes of degradation and establish a model
   - Establish boundary conditions using advanced characterization techniques including X-ray topography, cathodoluminescence, deep-level transient spectroscopy
2) Based on the model, design the LED structure using tensile strained barrier for better carrier confinement and higher flux

Approach: Part 1

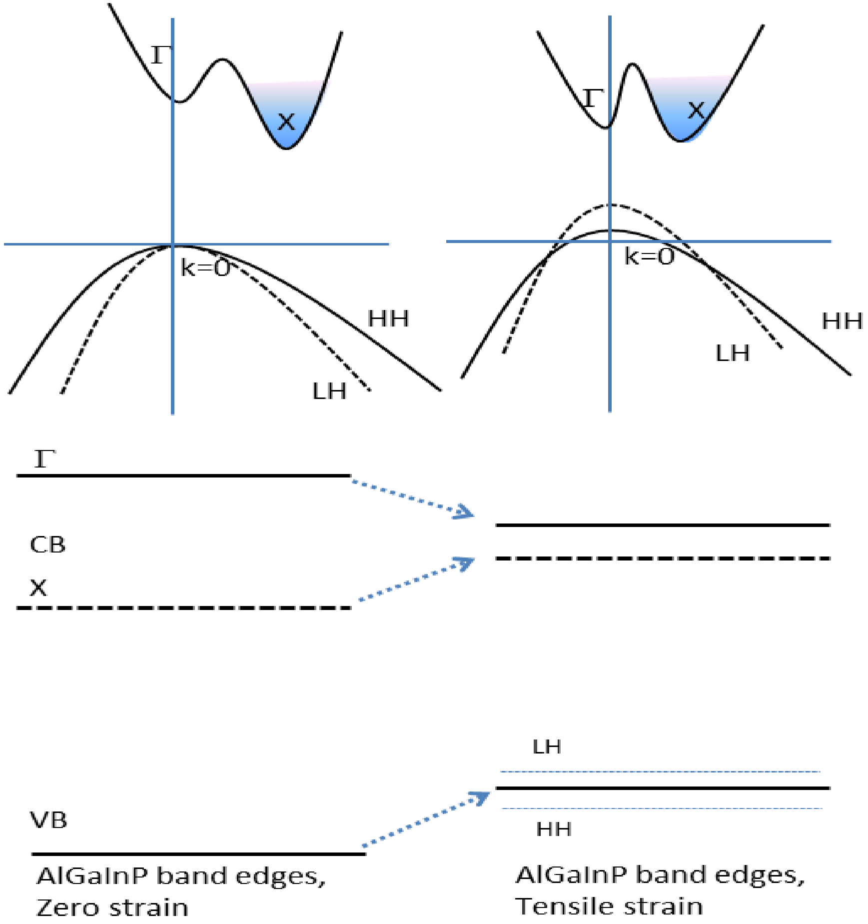
AlInGaP epi structure





- 1st part of the project is improve reliability by reduction of point defects
    - This determines the type of active region we can use

Approach: Part 2



Tensile strain increases the conduction band offset of the X-valley, increasing the energy barrier for electrons to overcome and reducing carrier overflow.

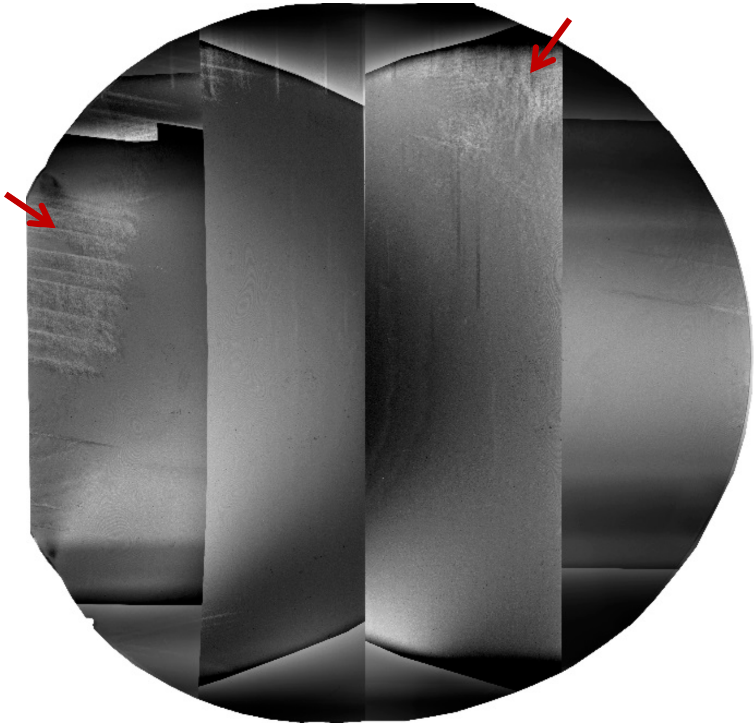
Secondary effect:

Splitting of light-hole and heavy hole bands in valence band

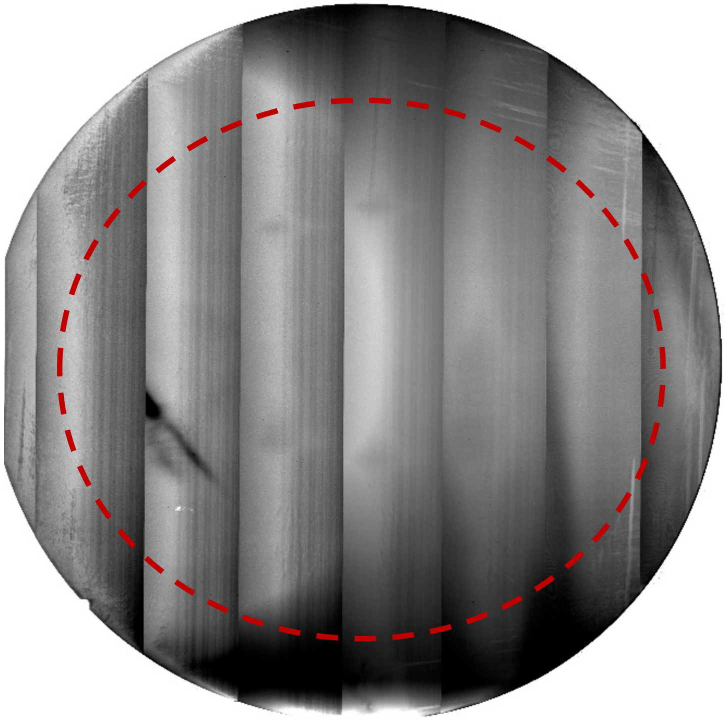
Goal: to increase EQE and H/C factor

X-ray topography: GaAs substrates

GaAs substrate
from vendor A



GaAs substrate
from vendor B

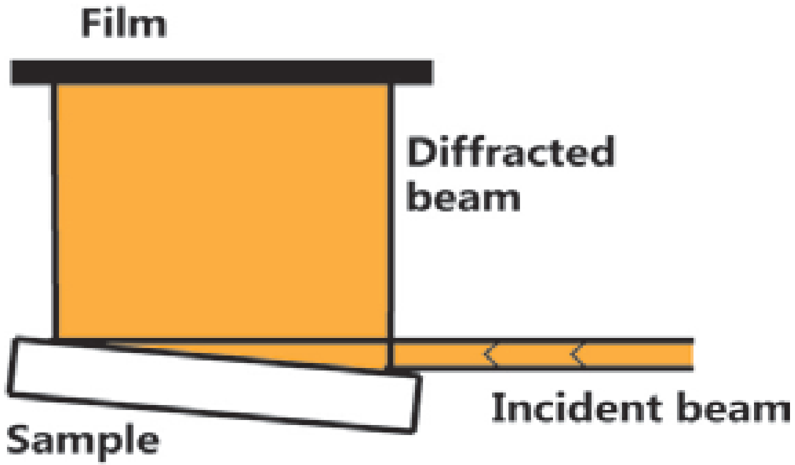


X-ray white beam transmission image of entire 150 mm GaAs substrates

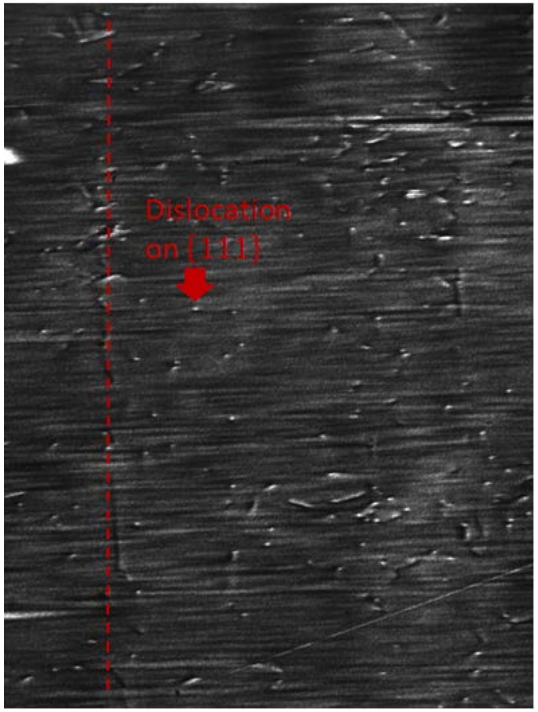
- Large number of dislocations at wafer edge
- Substrate from Vendor A has abnormally high number of dislocations at 2 locations

Grazing incident X-ray diffraction

Monochromatic X-ray topography using Grazing incident geometry (reflection mode)



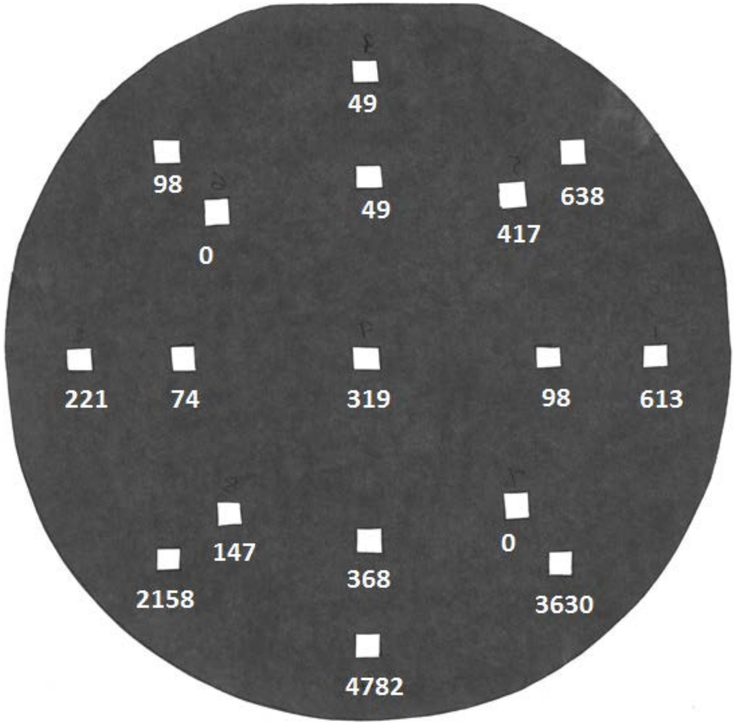
All box size: $2.33mm \times 1.75mm$



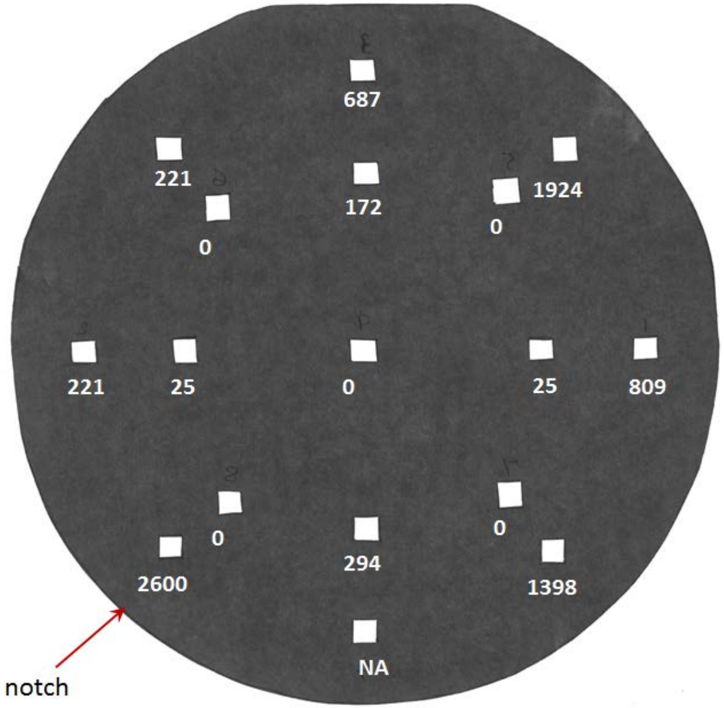
- Penetration depth of ~1 um
- Look at X-ray diffraction pattern of (3 3 -3) lattice planes
- Advantage: able to evaluate the dislocation density on the top wafer surface

Grazing incident X-ray diffraction

GaAs substrate
from vendor A



GaAs substrate
from vendor B



- Grazing-incident X-ray diffraction of (33-3) planes does show higher number of dislocations on the wafer surface at the wafer edge
- Correlates to vendors' EPD maps & understanding
  - dislocations are generated during cool-down of ingots (contraction)

On-going investigation: X-ray topography

GaAs substrates:

- Study different Si doping concentrations
- Does dislocation density difference explain the reliability difference?
- Need to establish whether there is causal relationship

AlInGaP film:

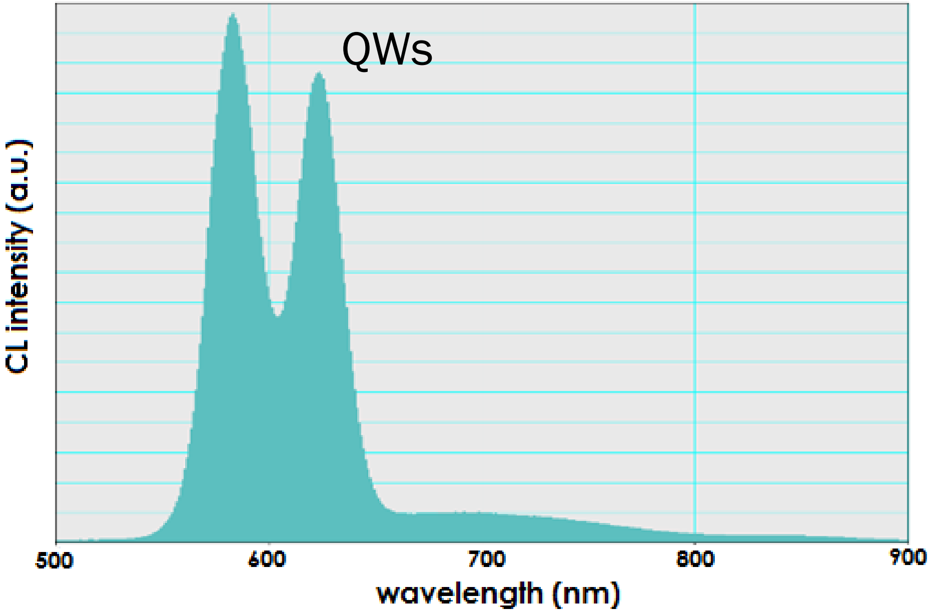
- Evaluate whether those dislocations propagate from GaAs substrates into AlInGaP epitaxial layers
- Does it change with Al% composition or doping in AlInGaP?

MOCVD growth conditions of AlInGaP film:

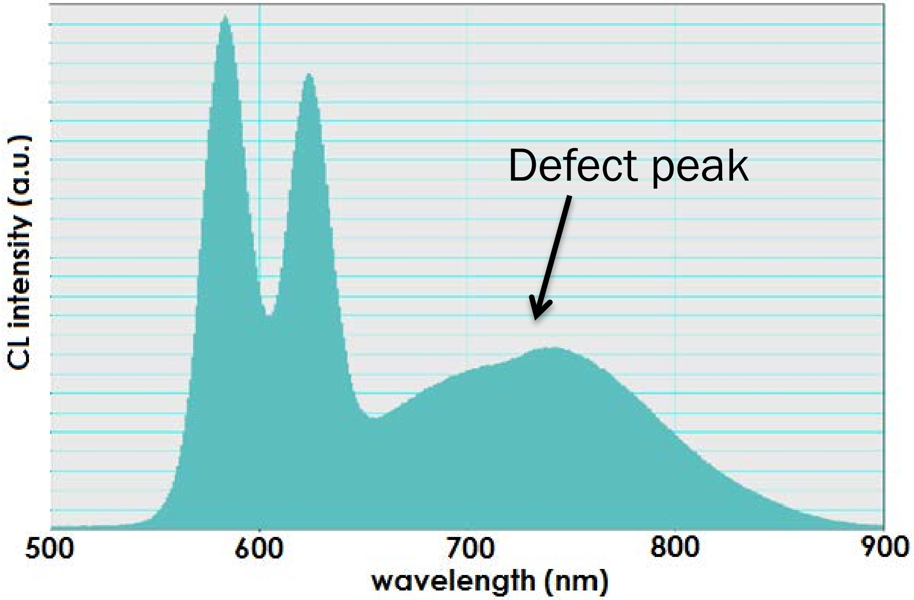
- Does growth condition change the dislocation density across the wafer?

Cathodoluminescence of AlInGaP die

Die with good reliability
Flux drops by < 1%

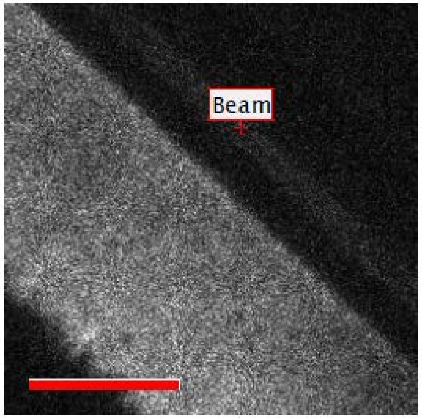


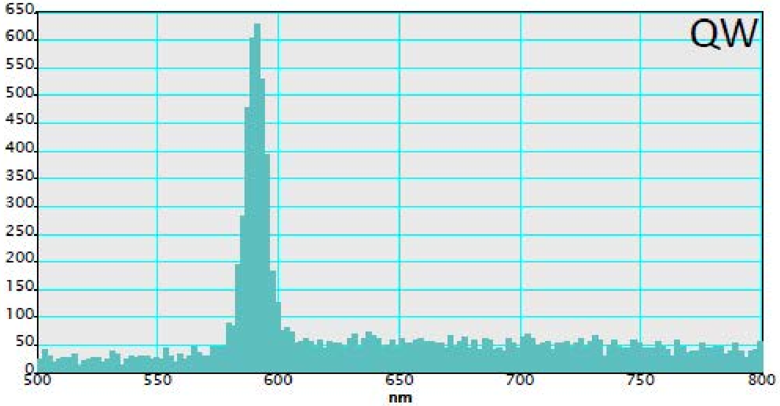
Die with poor reliability
Flux drops by >8%



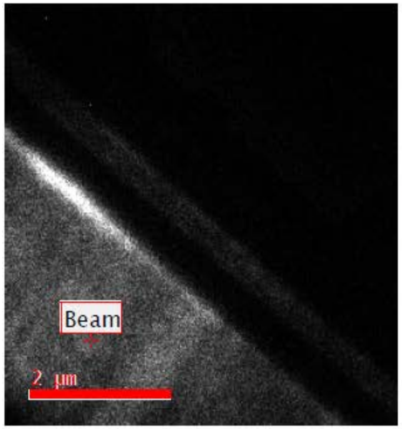
- Die with poor reliability (flux drop > 8%) shows a broad defect peak ~ 750 nm wavelength
- The appearance of CL peak at 750 nm correlates to flux degradation

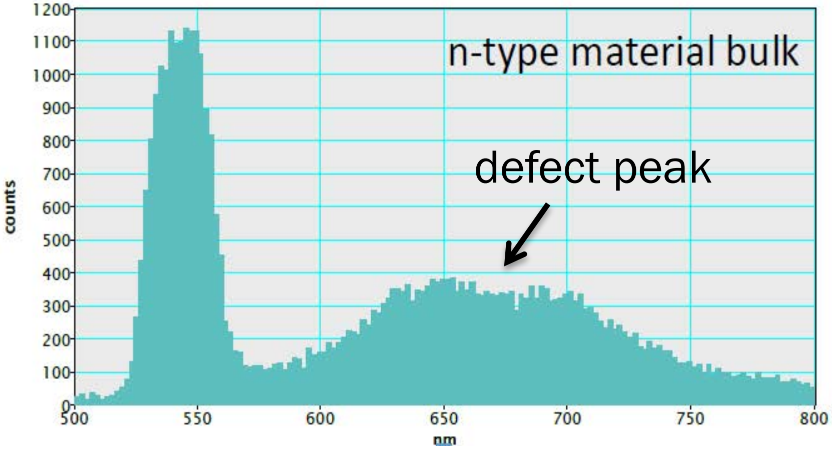
STEM CL of stressed die with flux drop> 20%





Only QW emission is visible in CL spectrum when e-beam is focused on QWs

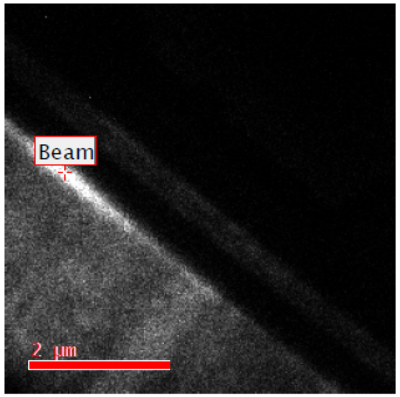


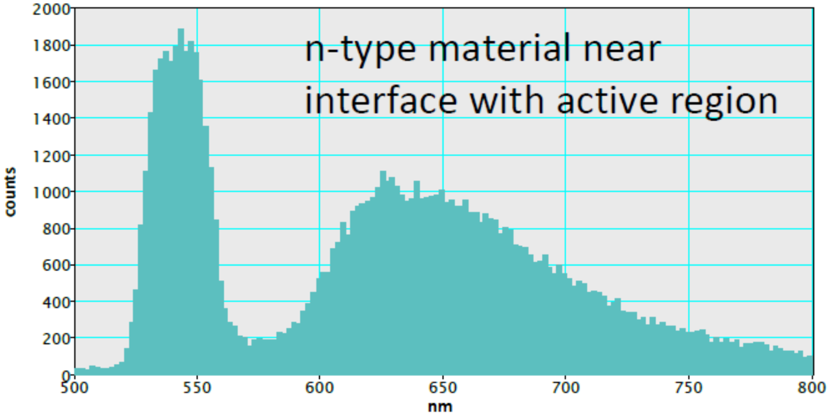


Defect peak appears when the electron beam is focused on n-layer

- No defect peak emission in QWs

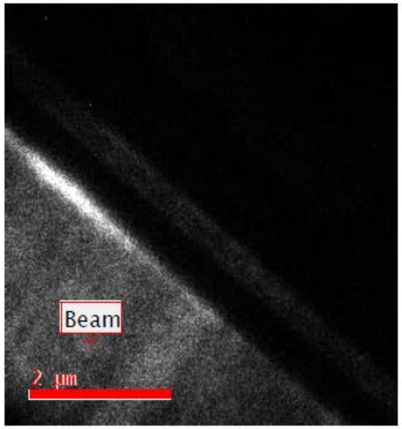
STEM CL of stressed die with flux drop> 20%

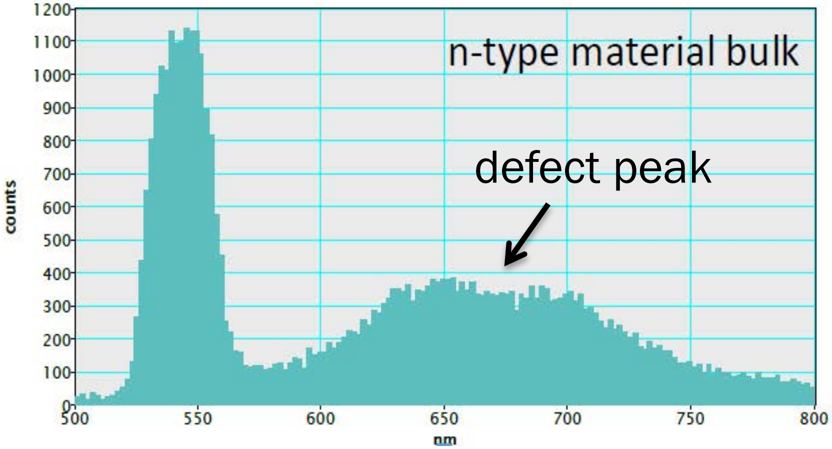




n-type material near interface with active region

Defect peak intensity increases when the electron beam rests on the n-layer closest to the QW active region





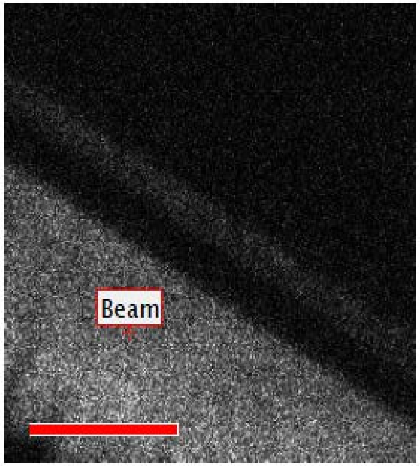
n-type material bulk

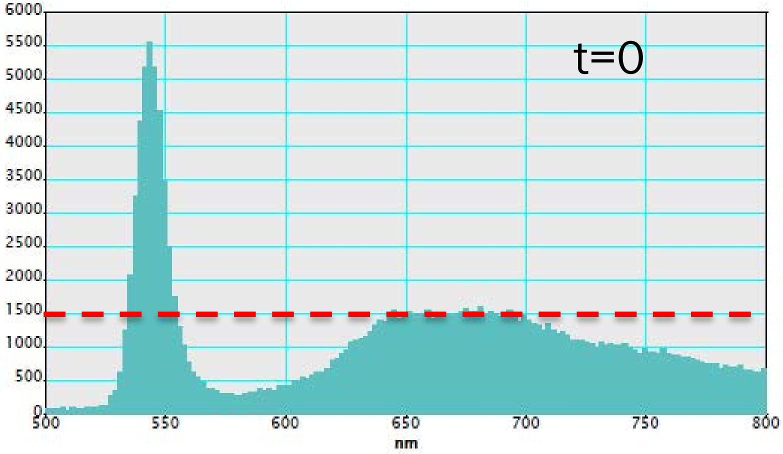
defect peak

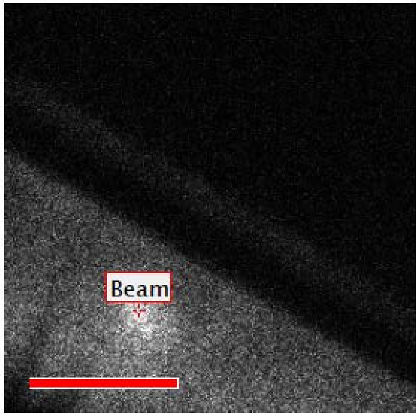
Defect peak appears when the electron beam is focused on n-layer

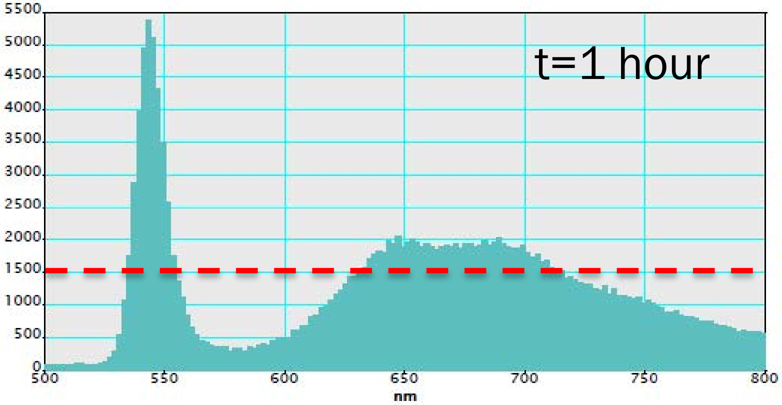
- This indicates the present of defects in n-layer closest to the active region

STEM CL of unstressed die









Defect peak intensity increases when the electron beam rests on the n-layer closest to the QW active region for 1 hour

- This indicates CL can replicate the aging effect under reliability stress test

Remaining Project Work

Characterization:

1) Deep-level transient & optical spectroscopy (DLTS & DLOS)
   - Done by Andy Armstrong of Sandia National Laboratories
   - Determine type of defect states next to active region
2) X-ray topography of AlInGaP film
   - Professor Dudley of Stony Brook University
3) Explore other characterization techniques
   - Transient-lifetime photoluminescence (TLPL)
   - Positron annihilation lifetime spectroscopy (PALS)

Active region design of LEDs:

- Incorporate tensile-strained barrier into the LED active region
  - Study performance and reliability
  - Achieve amber and red LED performance targets

Stakeholder Engagement

- **Project partners for advanced characterization**
  - Professor Dudley of Stony Brook: X-ray topography
  - Andy Armstrong of Sandia National laboratories
    - Characterize defect states in AlInGaP
    - Deep-level transient spectroscopy (DLTS)
    - Deep-level optical spectroscopy (DLOS)
    - 2 samples per month starting in April - in progress
- **Lumileds epitaxy manufacturing**
  - Qualification and release of new epitaxy technology
  - Manufacturing located in San Jose, California
- **Lumileds product development**
  - Implementation in new LED products or upgrades of existing LED products
  - Established market channel and comprehensive color LED product portfolio

Thank You

Lumileds

Ted Chung, Senior Manager

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REFERENCE SLIDES

Project Budget

Project Budget: $1,396,213
Variances: On track - no significant variance to date
Cost to Date: $244,773 as of 2/18/2018
Additional Funding: $240,000 for Sandia work (funded directly by DOE)

Budget History

FY 2017 (past)		FY 2018 (current)		FY 2019 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
-	-	$535,025	$163,756	$533,945	$163,487

Project Plan and Schedule

		10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9
		2017			2018												2019								
	Task / Subtask / Milestone Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	**Defect characterization in GaAs substrate and unstrained AlGaInP**																								
1.1	Survey measurement of defects in GaAs substrate and GaAs buffer	🟦	🟦	🟦	🟦	🟦	🟦																		
1.1.1	Establish defect characterization capability			🟥																					
1.1.2	Establish dependence of defects on Si doping						🟥																		
1.2	Growth and characterization of lattice-matched AlGaInP				🟦	🟦	🟦	🟦	🟦	🟦															
1.2.1	Identify origin of defects in AlGaInP vs. Al content and Si doping									🟥															
2	**Defect characterization in strained AlGaInP structures**																								
2.1	Growth of lattice-mismatched bulk AlGaInP layer on GaAs						🟦	🟦	🟦	🟦	🟦	🟦	🟦												
2.1.1	Identify atomistic origin of defects vs. reduced In content												🟥												
2.2	Characterization of baseline defects in state-of-the art LED					🟦	🟦																		
2.2.1	Establish baseline defects in full LED devices						🟥																		
2.3	Introduction of strained AlGaInP EBL in LED device										🟦	🟦	🟦												
2.3.1	Mid-project EQE gain demonstration in amber LED												🟥												
3	**Development of full LED structure with strained EBL**																								
3.1	Growth of lattice-mismatched bulk AlGaInP layer vs. thickness													🟦	🟦	🟦									
3.1.1	Confirm absence of defects below critical thickness															🟥									
3.2	Optimization of strained AlGaInP EBL in LED device													🟦	🟦	🟦	🟦	🟦	🟦						
3.2.1	Establish defect density vs. strain in EBL																		🟥						
3.2.2	Establish strain vs. performance relation																		🟥						
3.3	Development of growth condition for optimized epi													🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦			
3.3.1	Demonstrate targeted EQE gains for red and amber																					🟥			
4	**Finalization of epi structure and recipe**																								
4.1	Process manufacturability validation																				🟦	🟦	🟦	🟦	🟦
4.1.1	Process freeze and epi qualification																								🟥