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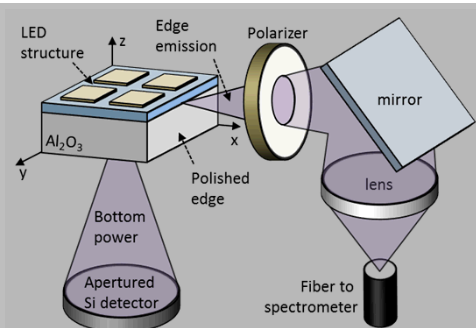

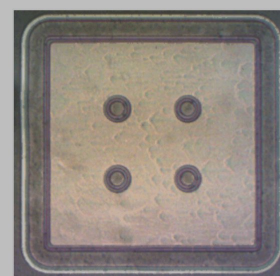

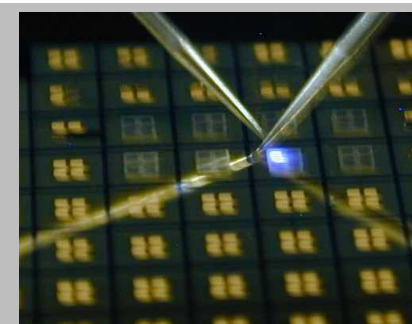

Anisotropic optical polarization of AlGaN based 275 nm light-emitting diodes due to quantum-size effects

J. J. Wierer, Jr., I. Montaño, M. H. Crawford, M. Moseley, and A. A. Allerman

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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Outline

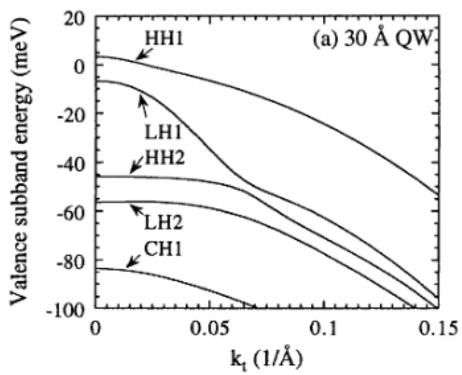
- Optical polarization in AlGaN based ultra-violet LEDs.
  - Anisotropic and influenced by many variables.
  - Used to determine internal emission patterns that affect light extraction.
- Experimental data on optical polarization and power (or efficiency) of ~275 nm LEDs.
  - Dependence on quantum well (QW) thickness
  - Dependence on current (carrier density)
- Theoretical simulations.
  - Created a model that matches experiential trends.
  - Complex changes in valence subbands change optical polarization

Optical polarization in AlGaN QWs

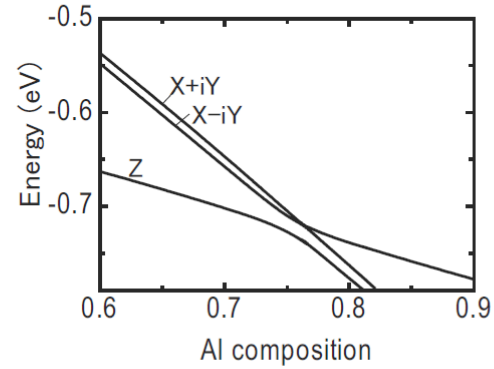
(In)GaN quantum well (QW)

$Al_{>0.3}GaN$ quantum well (QW)

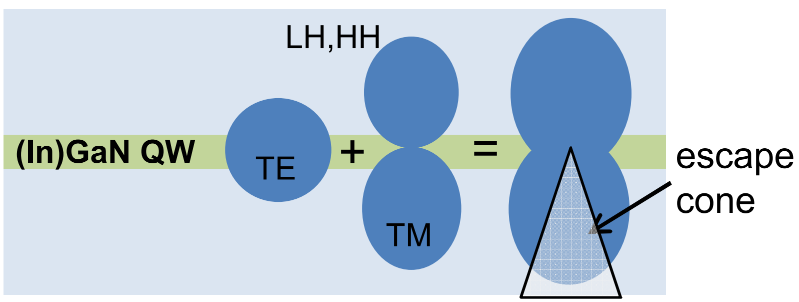
LH: light hole
HH: heavy hole
CH: crystal-field split-off hole

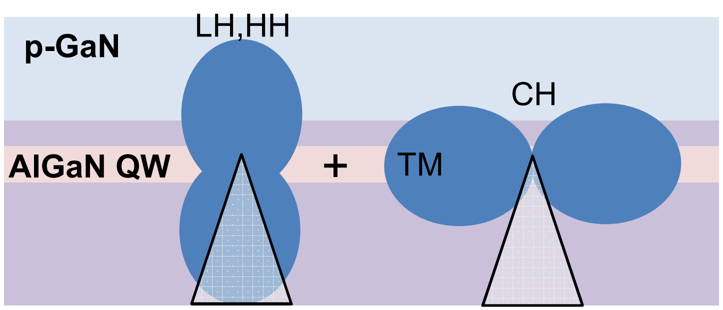


S. L. Chuang, SST 12, 252 (1997).



A. A. Yamaguchi, APL 96, 151911 (2010).





Extraction efficiencies ~80%!

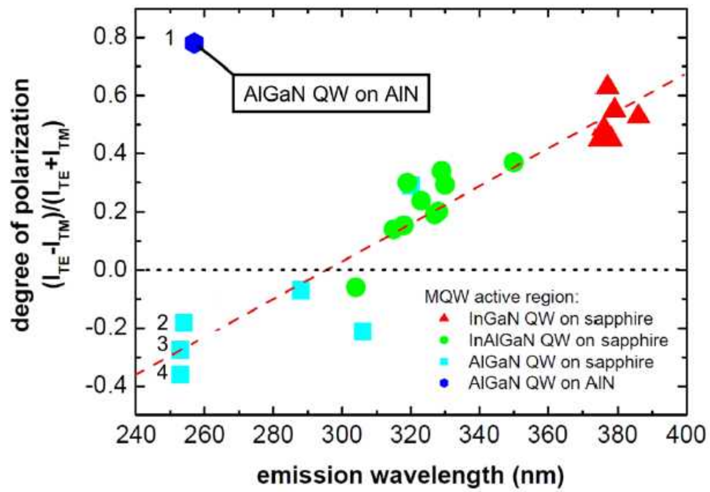
Extraction efficiencies ~0.1-10 %!

- Use optical polarization to determine the internal emission patterns.
- It is the emission patterns that affect light extraction efficiency.

Optical polarization in AlGaN QWs

Four known variables that affect optical polarization:

- Al concentration in the AlGaN alloy.
  - Lower Al content is favorable.
- Strain with respect to AlN.
  - Higher compressive strain is favorable.
- Quantum well thickness.
  - Thinner quantum wells are favorable.
- Carrier density.
  - Lower carrier density is favorable.



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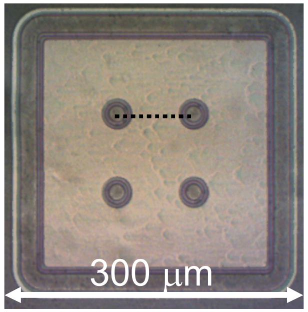
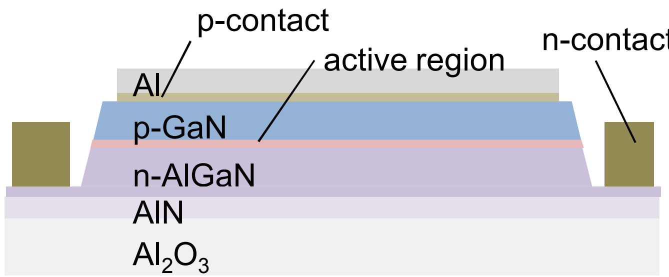
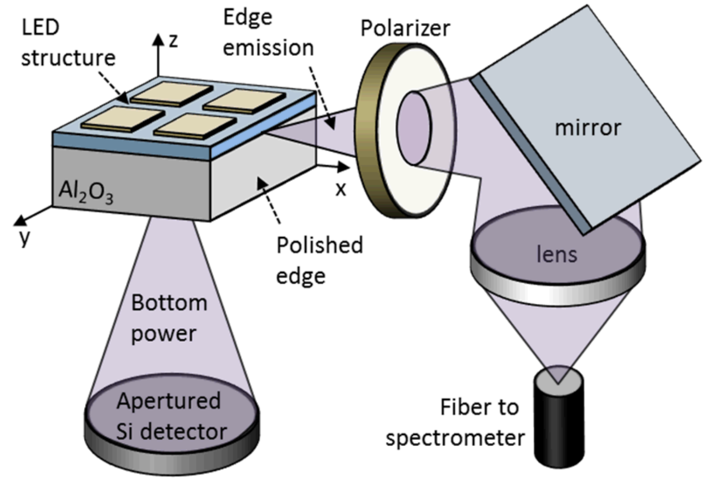
Experimental details

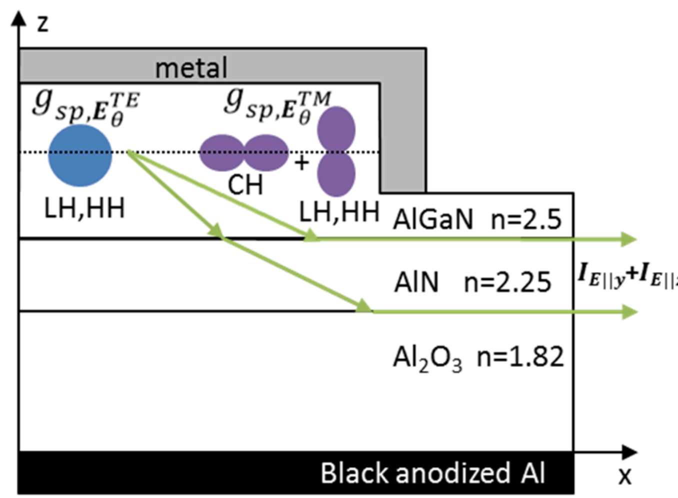




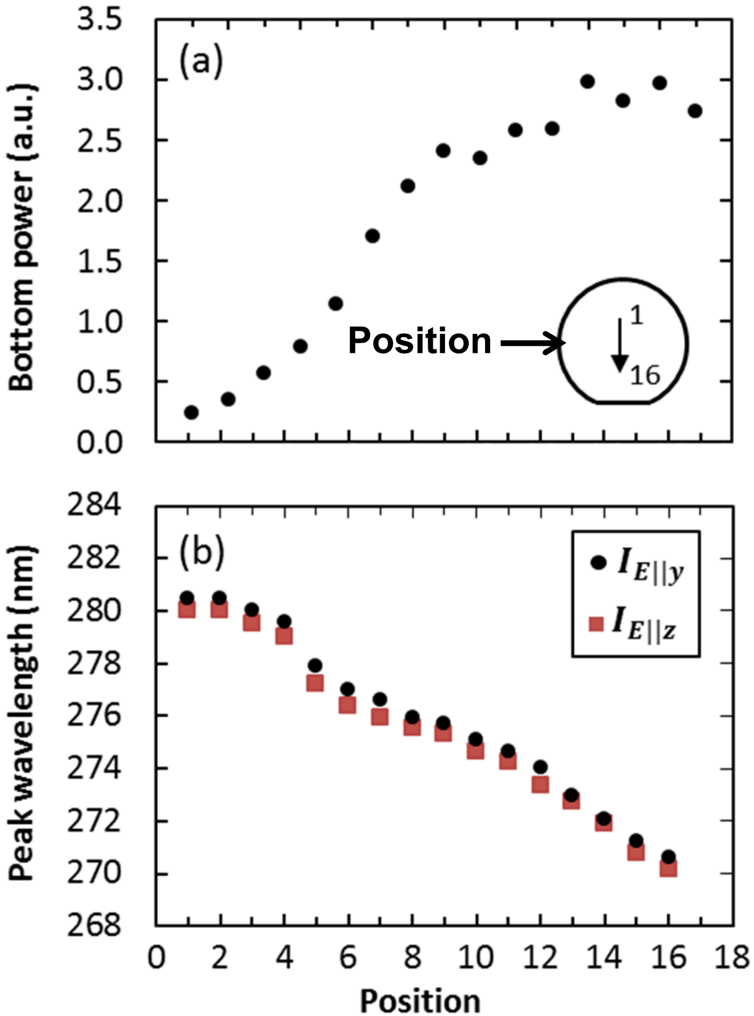


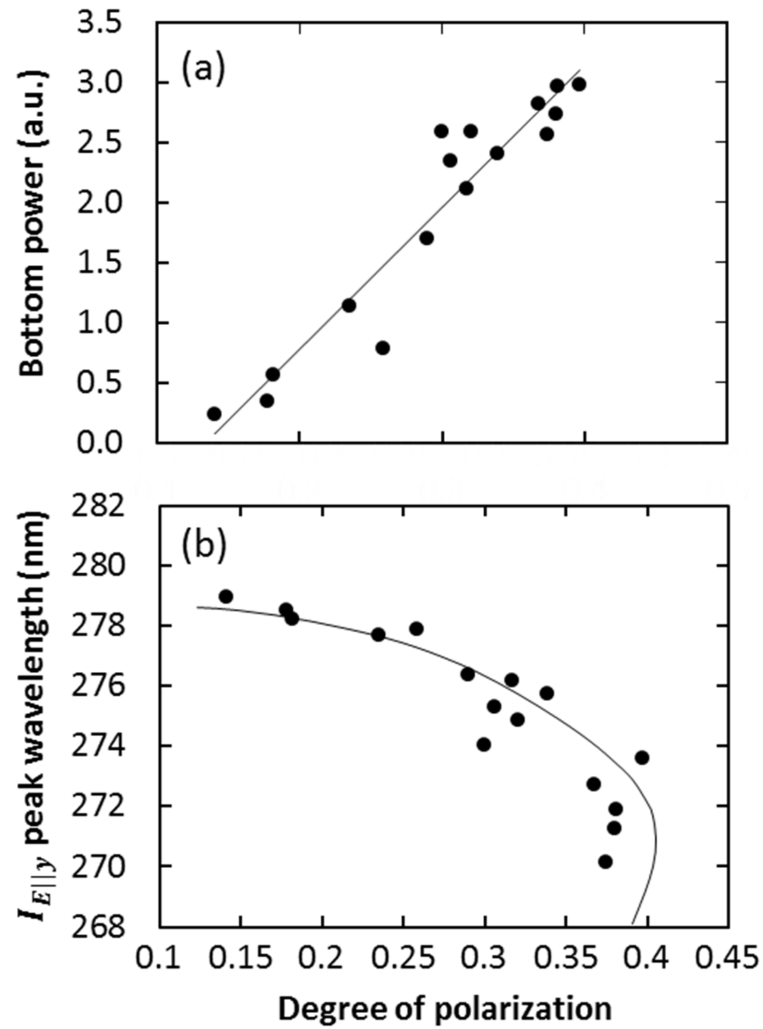
- ~275 nm AlGaN flip-chip LEDs.
- Active region:
  - 3 periods of $Al_{0.44}Ga_{0.56}N/Al_{0.55}Ga_{0.45}N$
  - ~2.6 nm and ~2.9 nm thick, respectively.
  - ~78% compressively strained to AlN.
- Measured two ways:
  - Power from the bottom. (Efficiency of the LED.)
  - Polarized power from the side. (Internal emission of the active region.)
  - Degree of polarization = $(I_{E||y} - I_{E||z})/(I_{E||y} + I_{E||z})$

    $I_{E||y}$: TE; $I_{E||z}$: TM



Optical polarization and power

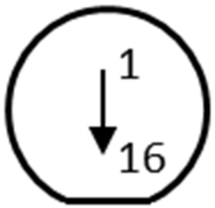


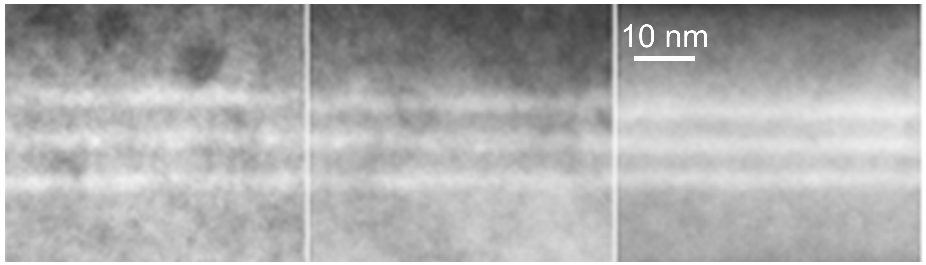


- Large dependence of bottom power and degree of polarization with position.

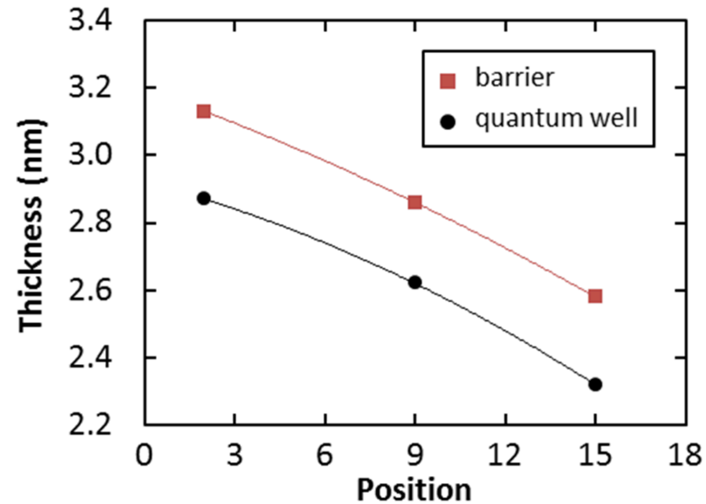
Quantum well thickness varies

Position: 2 9 15



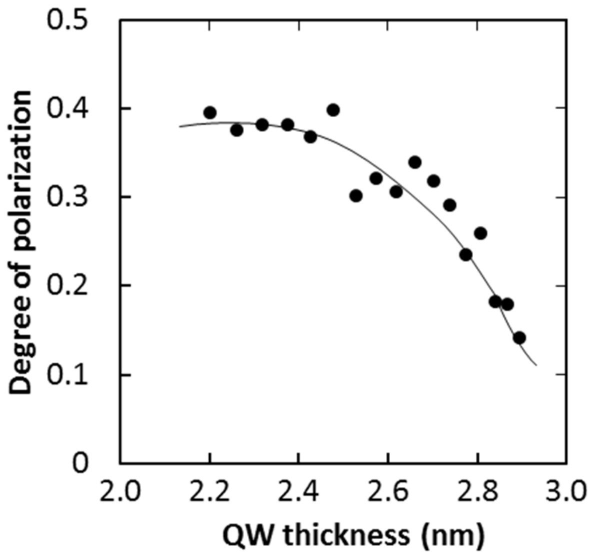


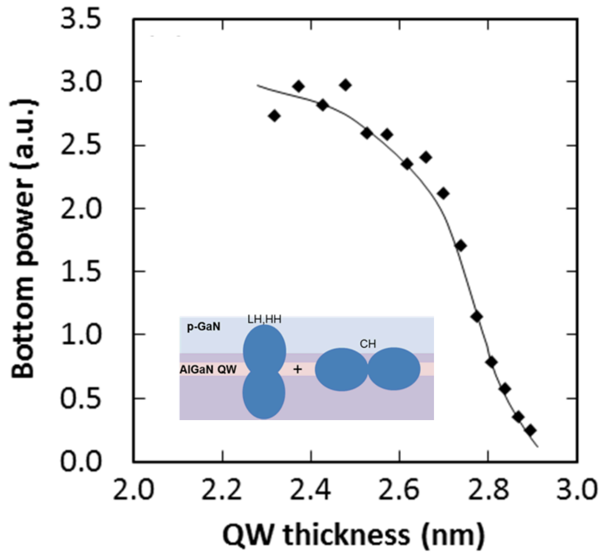
STEMs

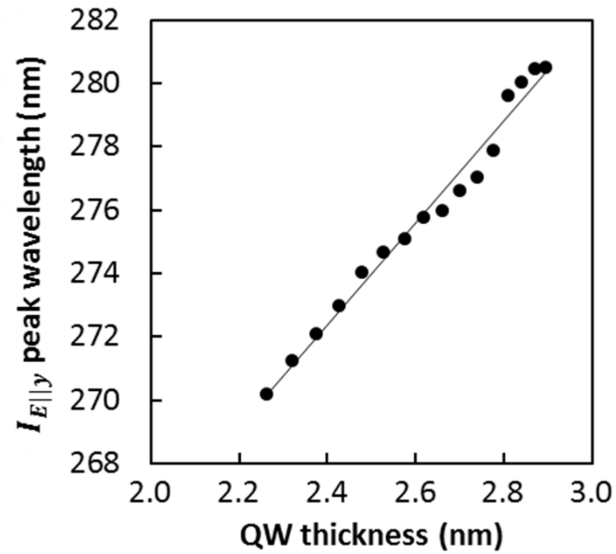


- Growth variations produce thickness variations across the wafer.
- Therefore polarization and light extraction vary across the wafer.
- Use a polynomial fit to determine thickness vs. position.
  - Find dependence of bottom power, peak wavelength, and degree of polarization vs. quantum well thickness.

QW thickness dependence



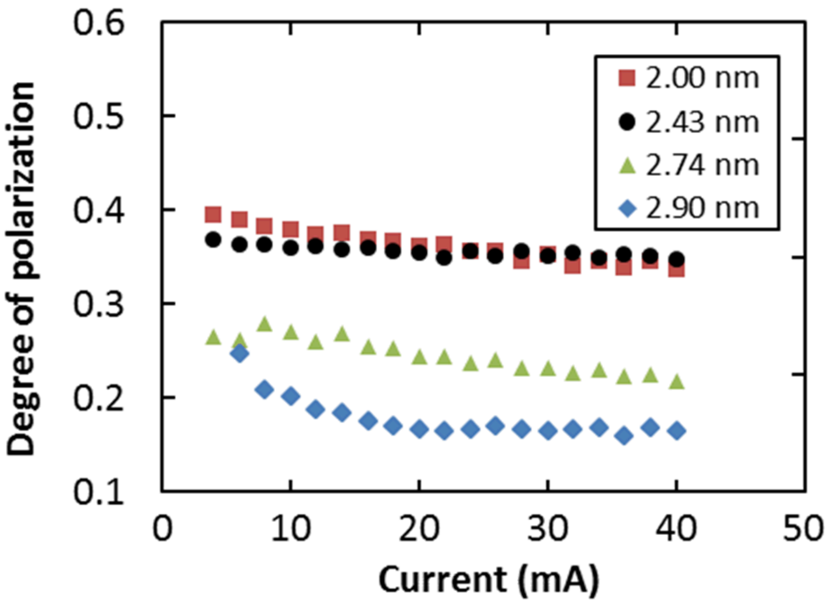


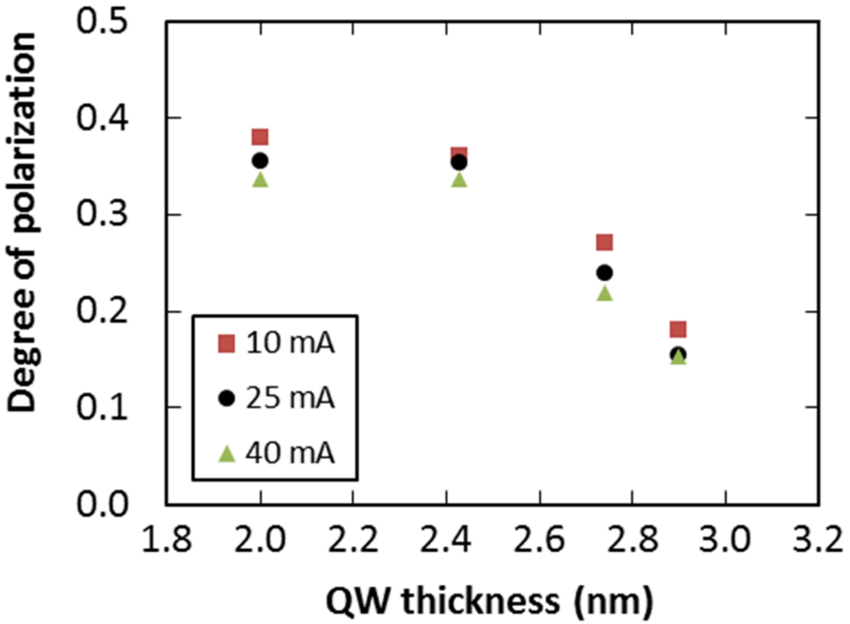


Thinner quantum wells have:

- Higher and more favorable degree of polarization.
- Increased bottom power (improved extraction efficiency).
  - Internal emission pattern better overlaps with escape cone.
- Shorter peak wavelengths.
  - Opposes Al composition trend on optical polarization.

Current (carrier density) dependence





- Degree of polarization decreases with current (or carrier density).
  - Therefore extraction efficiency decreases with current.
  - Identified efficiency droop mechanism in AlGaN QWs.
- Occurs for all investigated quantum well thicknesses.

Theoretical simulations

- Schrodinger-Poisson solver to calculate the spontaneous emission spectrum.
- Accounts for:
  - Spontaneous and piezoelectric polarization.
  - Screening potential introduced by charged carriers
  - Many-body effects.
- Transform the spontaneous emission from inside to outside the semiconductor to compare with experiment.
- Details in:

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Effect of thickness and carrier density on the optical polarization of $Al_{0.44}Ga_{0.56}N/Al_{0.55}Ga_{0.45}N$ quantum well layers

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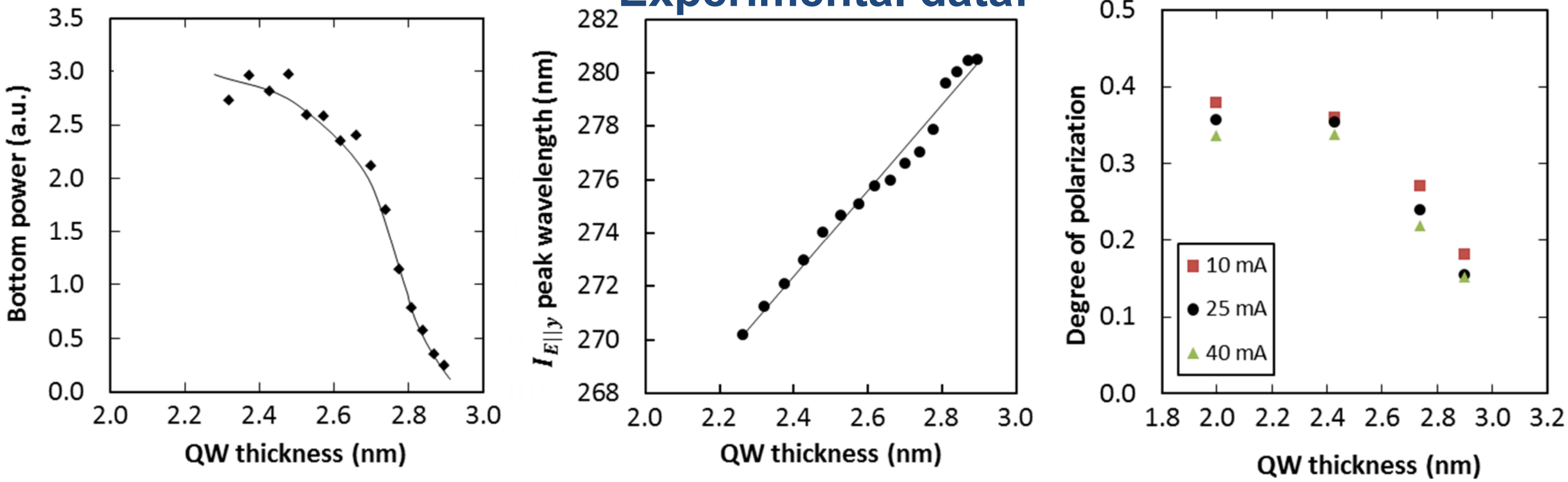
Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

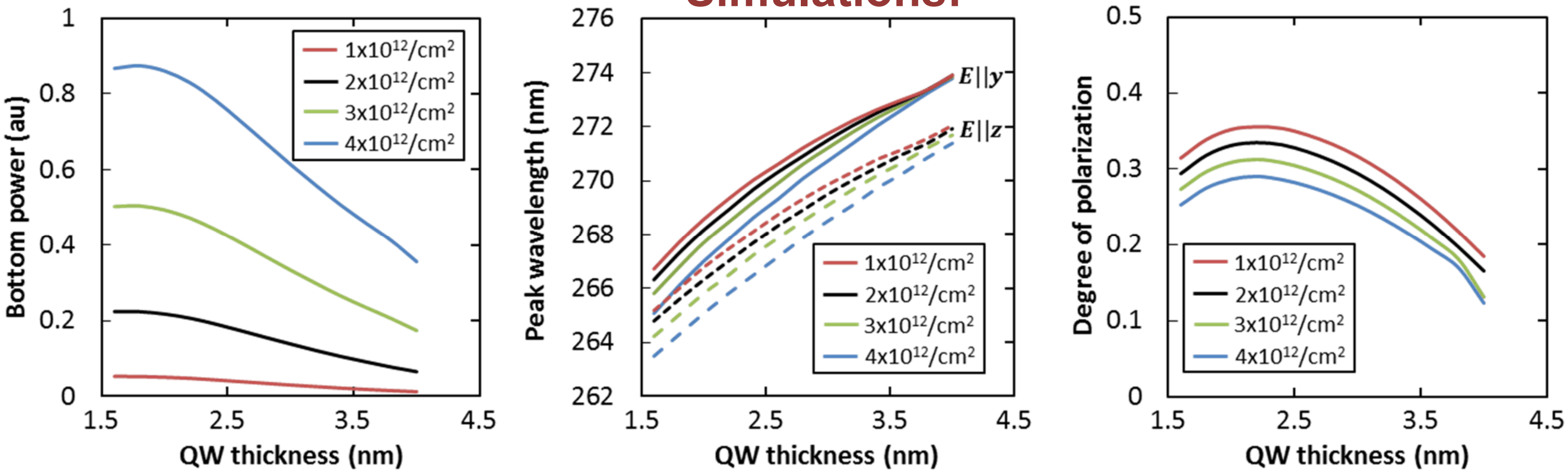
Comparing experiment and theory

Sandia National Laboratories

Experimental data:



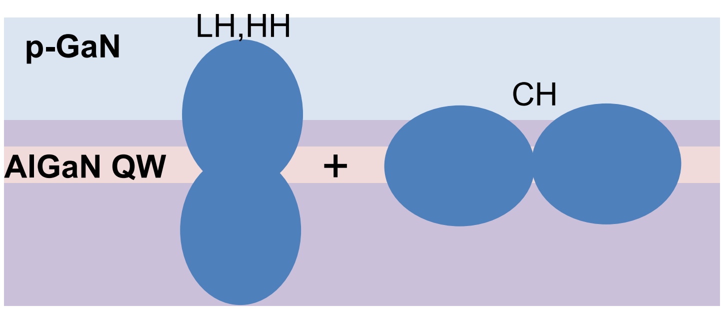
Simulations:

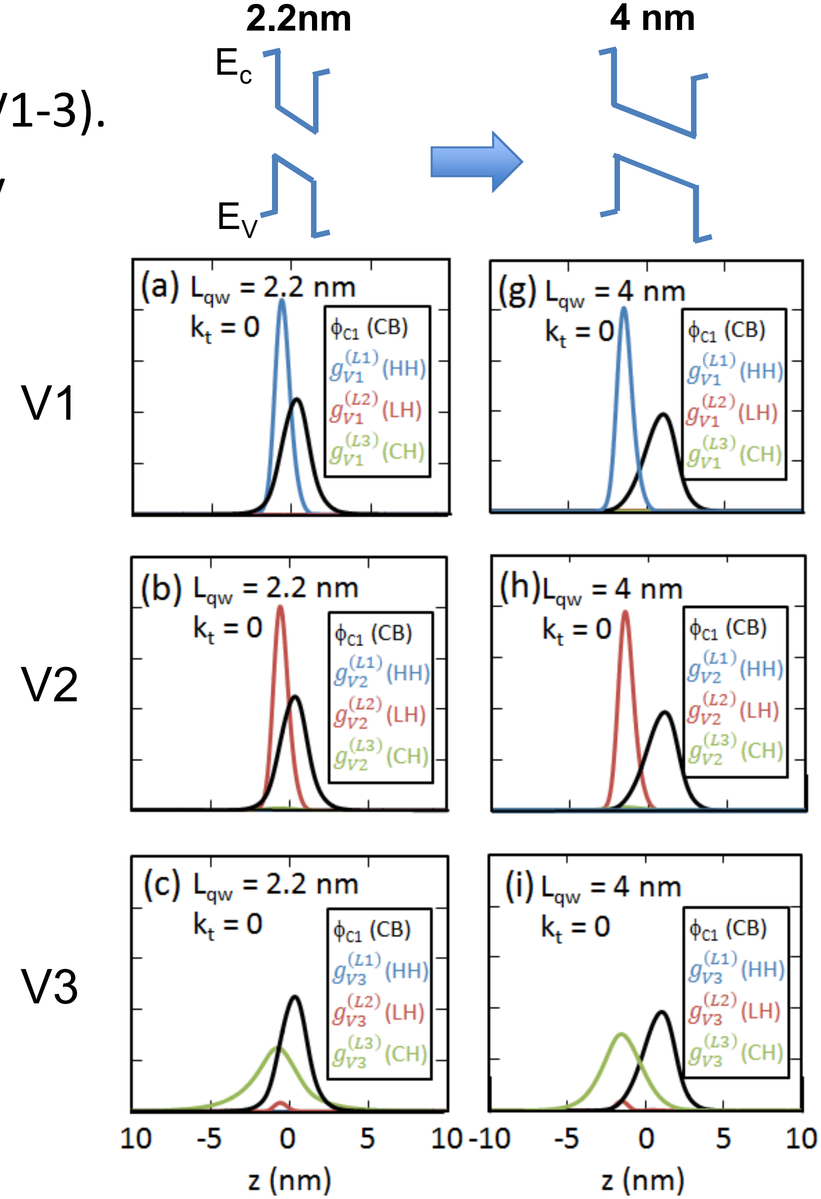


- Simulations match the experimental trends.

QW thickness dependence

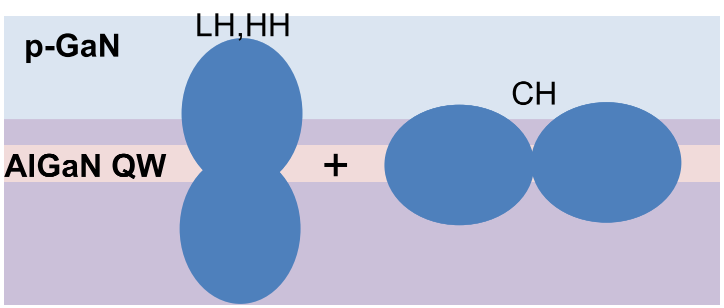
- Three lowest valence subbands participate (V1-3).
- Electron and hole wavefunctions are spatially separated.
  - Caused by piezoelectric and spontaneous polarization induced fields.
- When QW thickness increases:
  - Separation of electron and HH, LH, and CH wavefunctions increases.
  - CH is not as localized and has better overlap.
  - Results in more in-plane light, and reduced extraction efficiency.

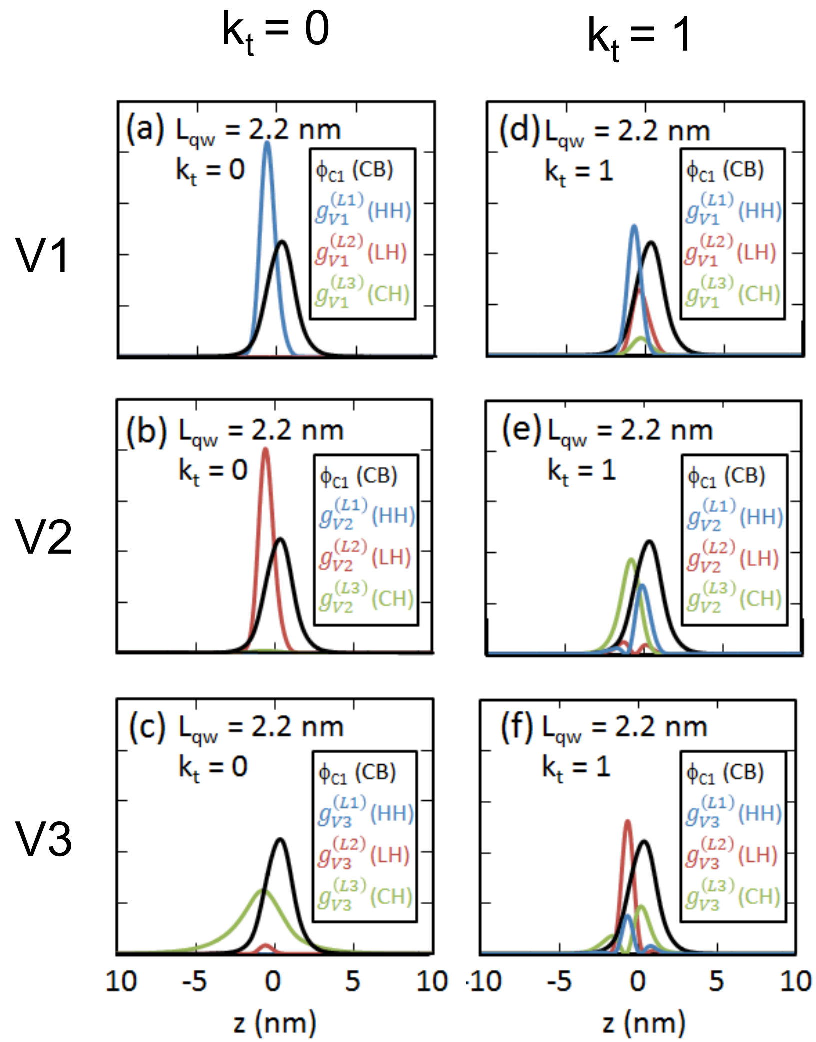




Carrier density dependence

- Subband coupling leads to CH envelope wavefunction in higher valence subbands.
- When carrier density increases:
  - Amount of carriers in lower valence subbands increases.
  - Carriers populate higher k_t.
- Therefore transitions to CH increase.
  - Results in more in-plane light, and reduced extraction efficiency.





Conclusion

- Measuring optical polarization of AlGaN based ultra-violet LEDs allows for:
  - Determining the internal emission patterns.
  - Understanding light extraction.
- Demonstrated experimentally and theoretically that quantum well thickness and carrier density affect optical polarization.
  - Are a result of changes in the valence subbands.

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