Carrier Dynamics of Polar, Semipolar, and Nonpolar InGaN/GaN LEDs Measured by Small-Signal Electroluminescence

Prof. Daniel Feezell

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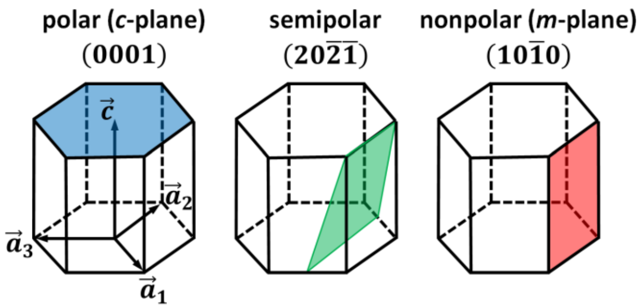
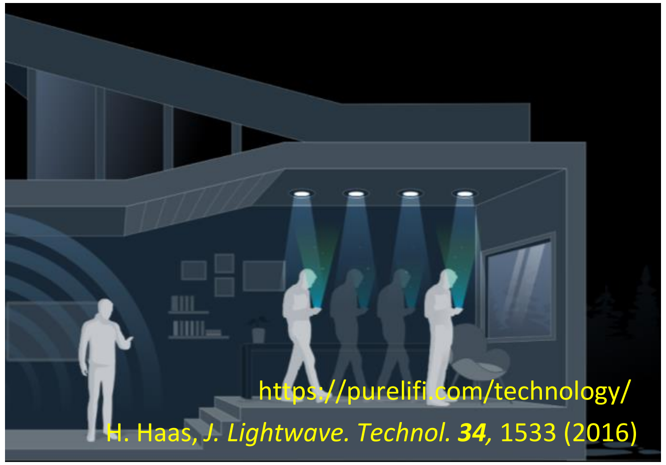


Outline

- Carrier dynamics measurements and modeling with small-signal EL
- *c*-Plane wavelength series on commercial epitaxy
- Crystal orientation series
- Core-shell nanostructure-based LEDs

Motivation for Carrier Dynamics/Modulation Studies

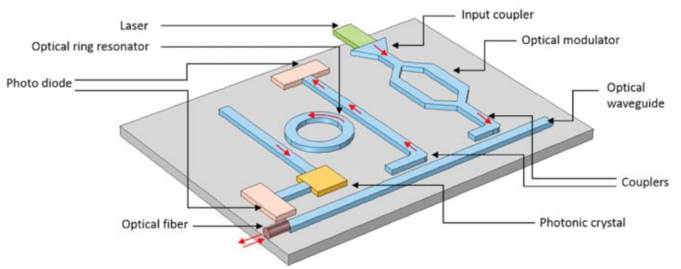
Visible-Light Communication



Augmented and Virtual Reality

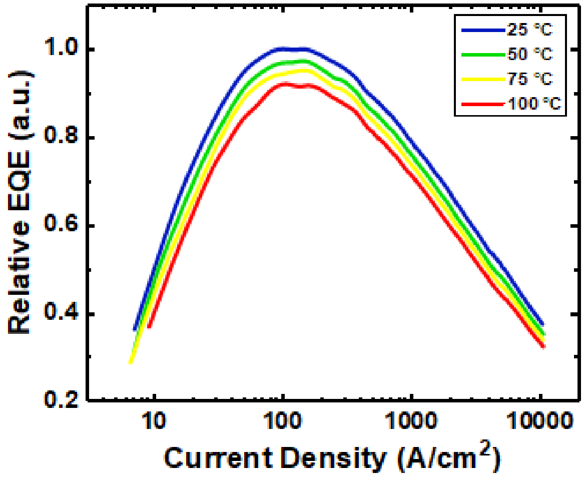
Micro-LED Displays

Photonic Integration

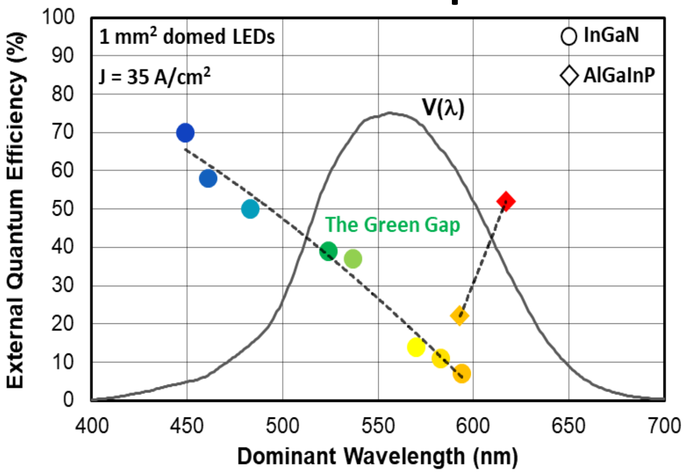


B.E.A. Saleh and M.C. Teich, *Fundamentals of Photonics*

Efficiency/Thermal Droop

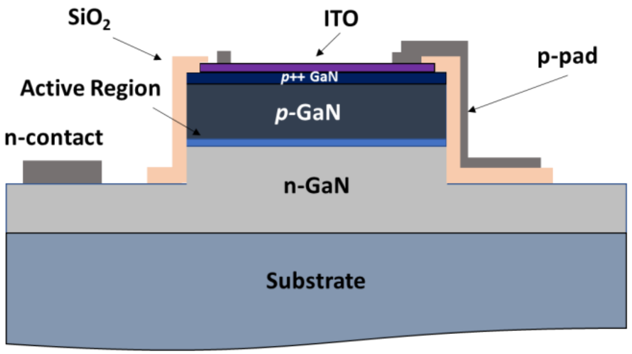


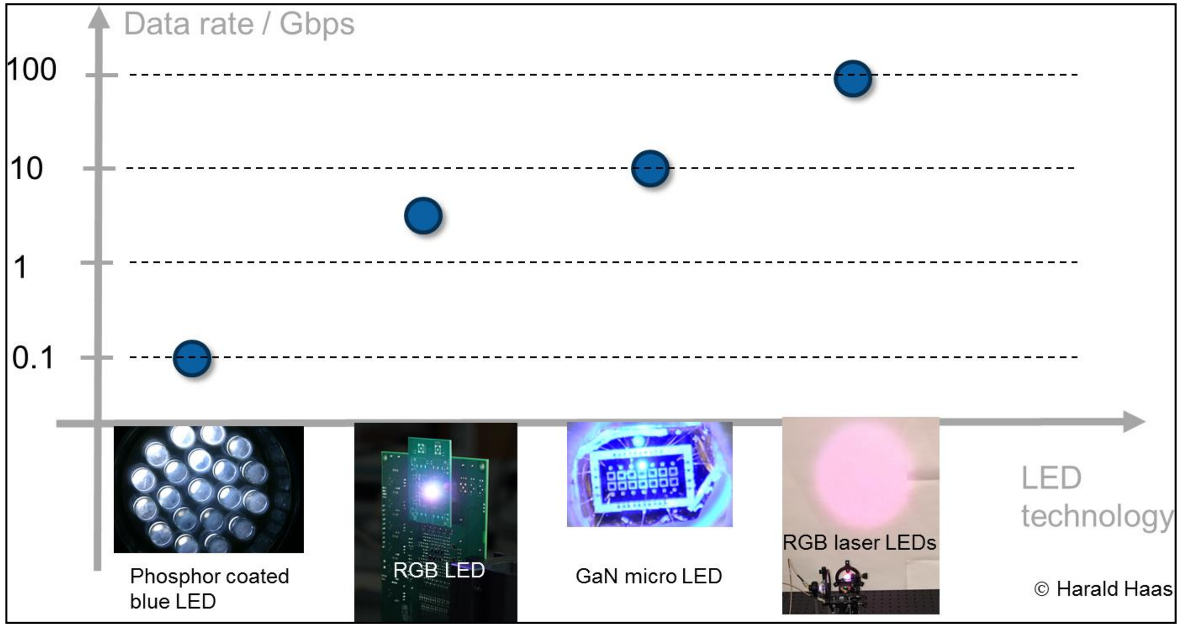
Green Gap



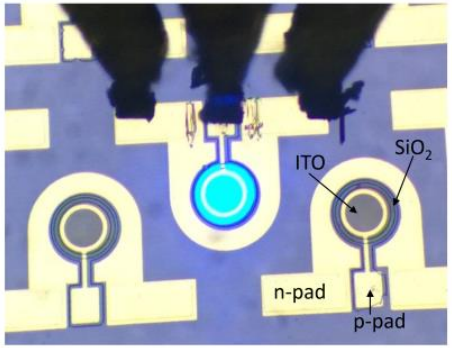
Small-Area GaN-Based LEDs

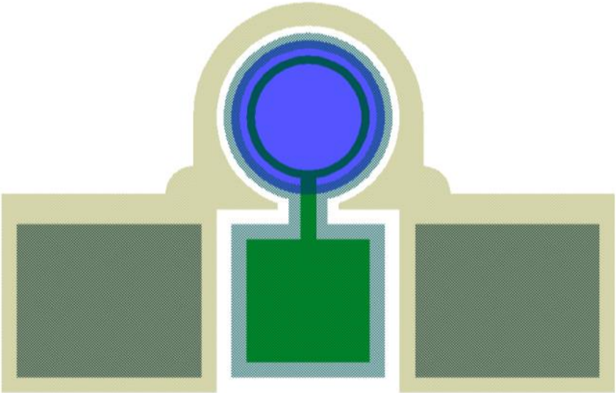
- Small area reduces RC parasitics
- 50 – 100 μm diameter
- Can be driven at high current density

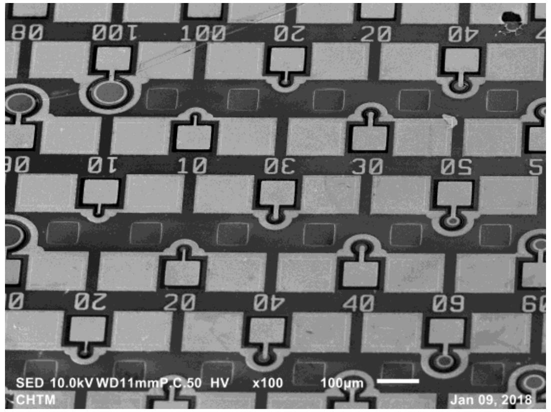


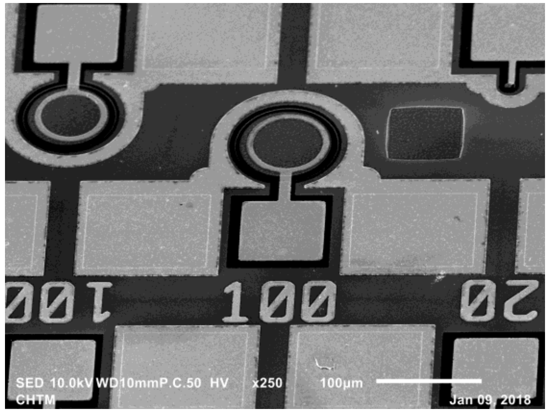


https://www.lifi.eng.ed.ac.uk/lifi-news/2015-11-28-1320/how-fast-can-lifi-be

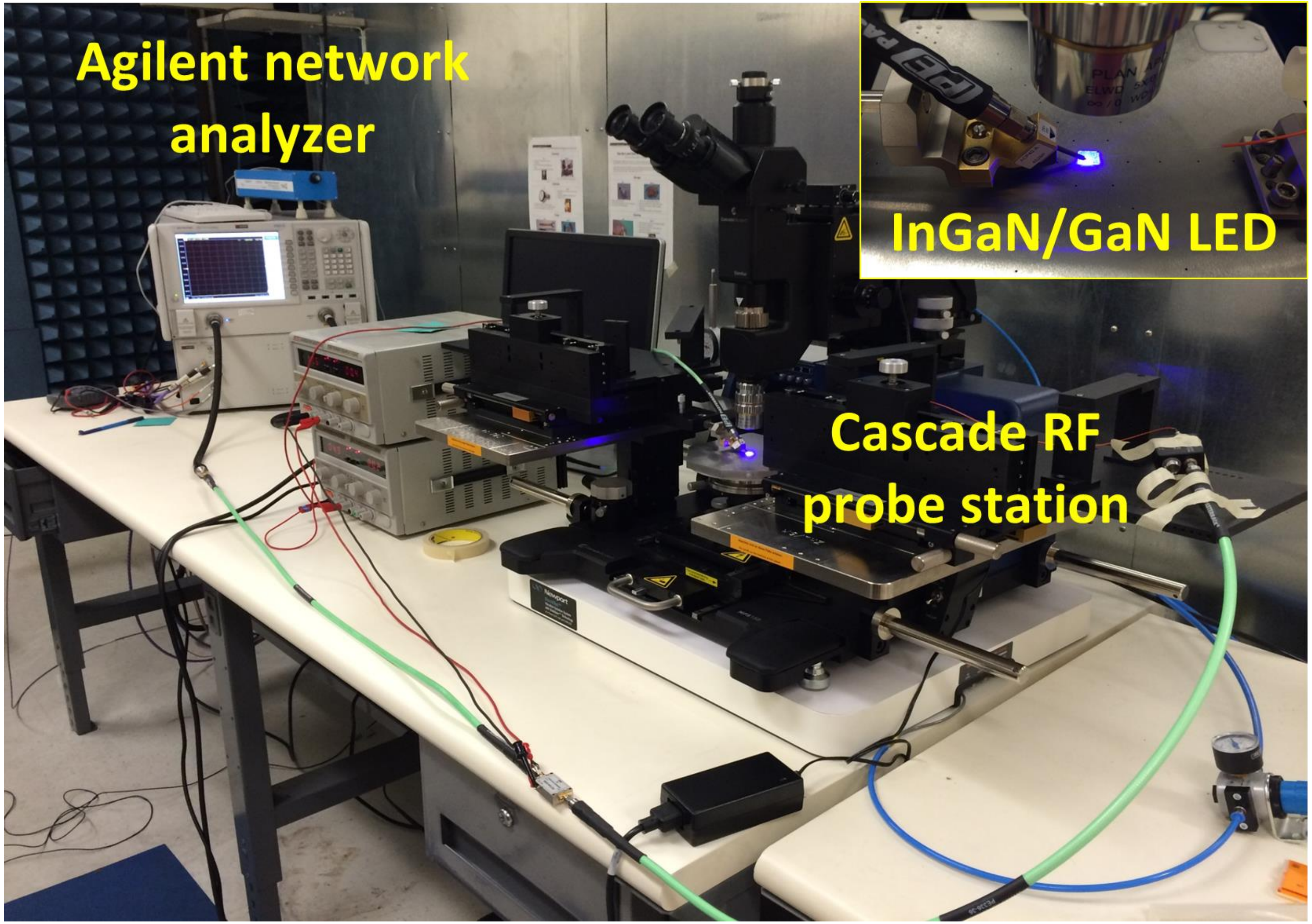


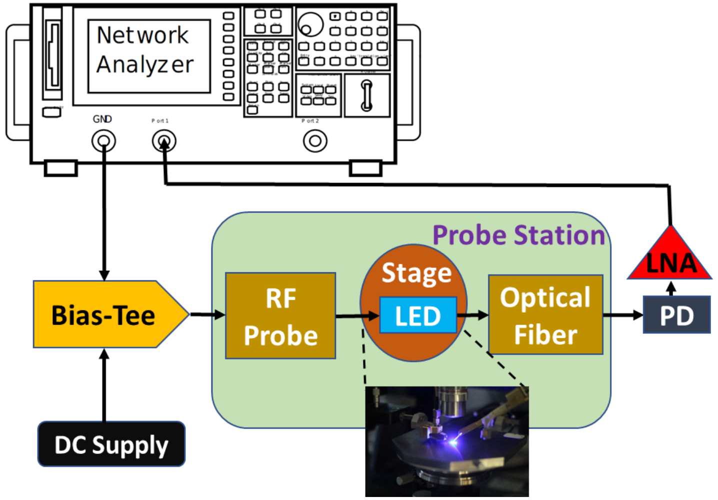


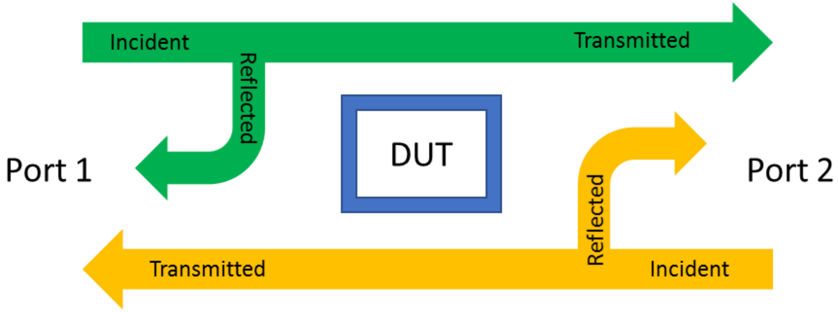




RF Measurement System





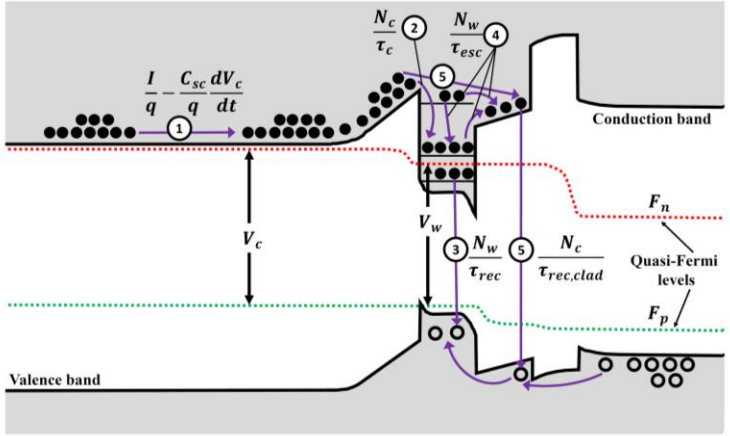


$S_{11} = \frac{Reflected}{Incident}$ Impedance = $Z = Z_0 \frac{1+S_{11}}{1-S_{11}}$

$S_{21} = \frac{Transmitted}{Incident}$ Frequency Response= S_{21}

Rate Equation Modeling of LED Carrier Dynamics

$A_i e^{-i\omega t}$



$A_t(\omega) e^{-i(\omega t + \varphi_t)}$

$A_r(\omega) e^{-i(\omega t + \varphi_r)}$

Considered carrier processes:

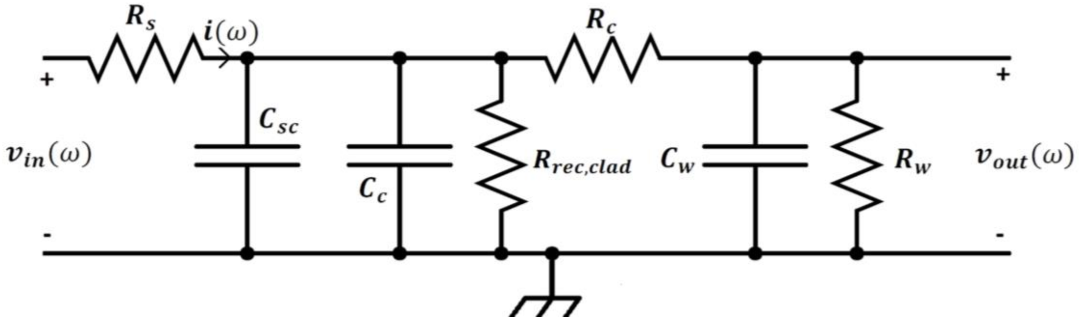
1. Carrier injection
2. Carrier diffusion and capture
3. Recombination in QW
4. Carrier leakage
5. Recombination in cladding and overshoot

Small-signal rate equations

$$j\omega n_w = -\left[\frac{1}{\tau_{\Delta rec}} + \frac{1}{\tau_{\Delta esc}}\right] n_w + \frac{n_c}{\tau_{\Delta c}}$$

$$j\omega n_c = \frac{i}{q} - j\omega v_c \frac{C_{sc}}{q} + \frac{n_w}{\tau_{\Delta esc}} - \frac{n_c}{\tau_{\Delta c}} - \frac{n_c}{\tau_{\Delta rec,clad}}$$

Small-signal equivalent circuit



Associated lifetimes

$$\tau_{\Delta rec} = R_w C_w \qquad \tau_{\Delta RC} = \frac{R_s}{R_s + R_c}\tau_{\Delta 0}$$

$$\tau_{\Delta esc} = R_c C_w \qquad \tau_{\Delta 0} = R_c C_{tot}$$

A. Rashidi, et al., *J. of Appl. Phys.* **122**, 3 (2017)

A. Rashidi et al., *Appl. Phys. Lett.*, **112**, 031101 (2018)

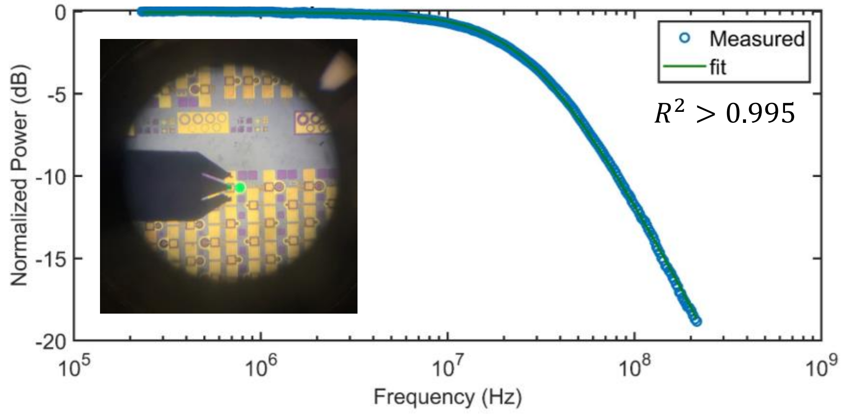
Fitting Equivalent Circuit Model

Simultaneous fitting of optical frequency response and impedance yields various carrier lifetime

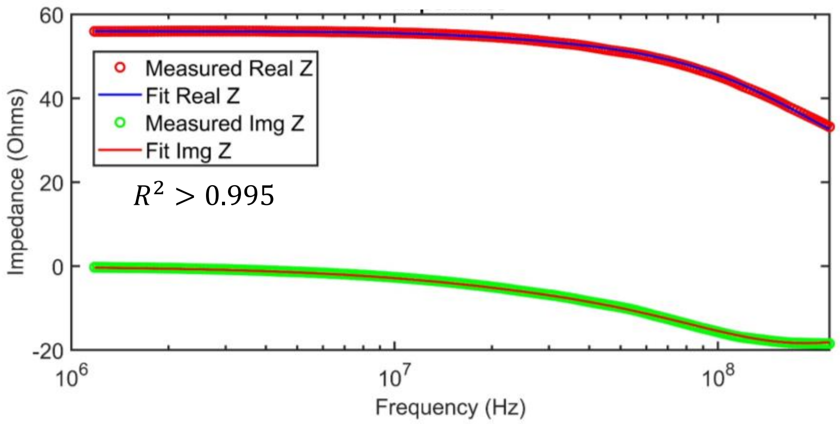
Optical response: $$\frac{v_{out}}{v_{in}} = \frac{R_w}{R_s(1+j\omega\tau_{rec})(1+j\omega\tau_0) + R_s(j\omega R_w C_{tot}) + R_c(1+j\omega\tau_{rec}) + R_w}$$

Input impedance: $$Z_{in} = R_s + \frac{R_c(1+j\omega R_w C_w) + R_w}{(1+j\omega R_w C_w)(1+j\omega R_c C_{tot}) + j\omega C_{tot} R_w}$$

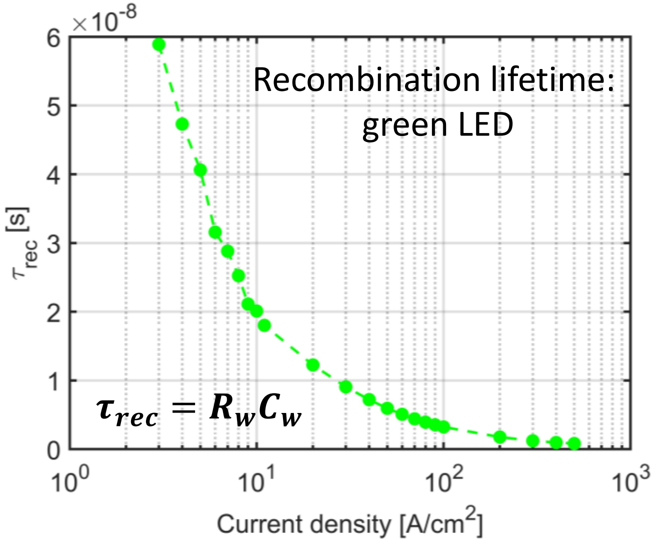
Fit to optical frequency response



Fit to input impedance



Extract differential lifetimes



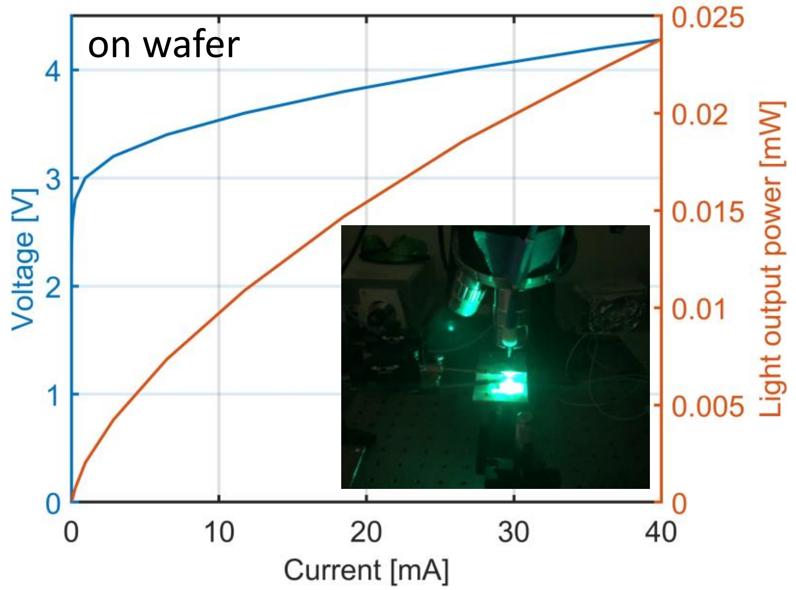
A. Rashidi, et al., *J. of Appl. Phys.* **122**, 3 (2017)

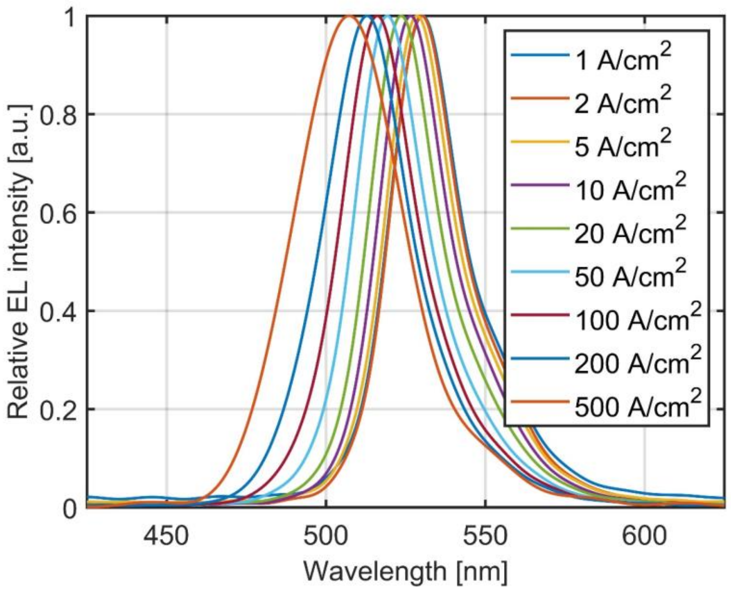
Wavelength Series on Lumileds Epitaxy

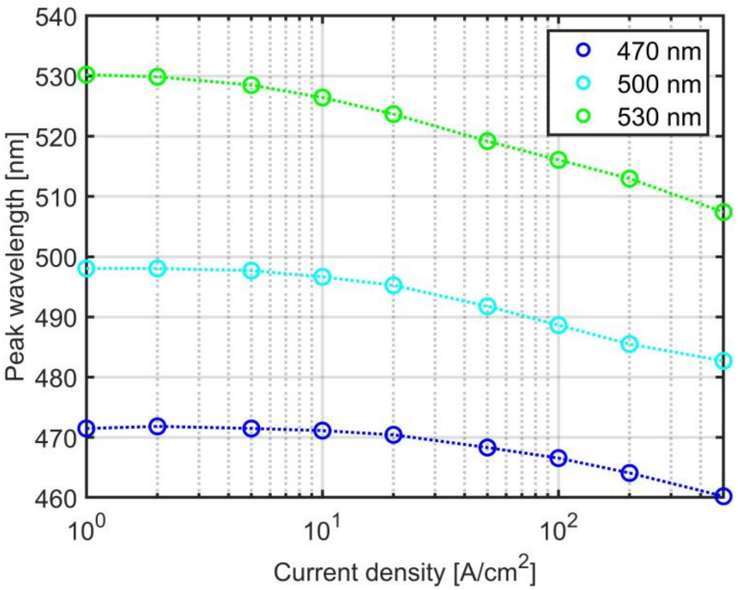
Color	Description
Blue	3 QWs, 3 nm, wavelength 470 nm
Cyan	3 QWs, 3 nm, wavelength 500 nm
Green	3 QWs, 3 nm, wavelength 530 nm

*LED mesa diameter = 100 µm

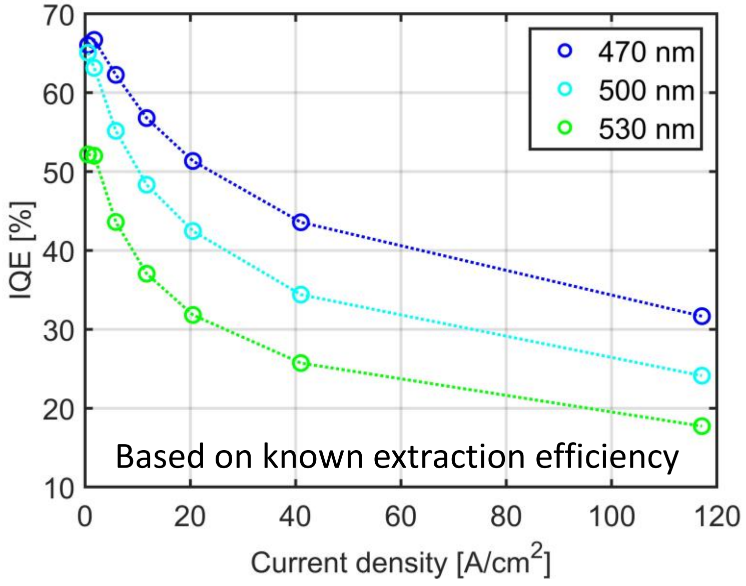
- Study of simplified commercial LED designs
- Representative of recombination behavior in “real” designs
- Design simplification restricts emission to one QW

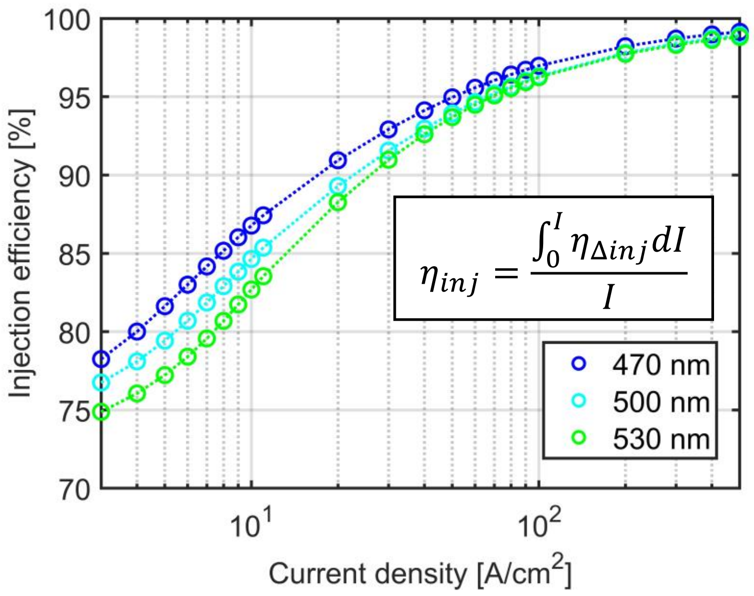


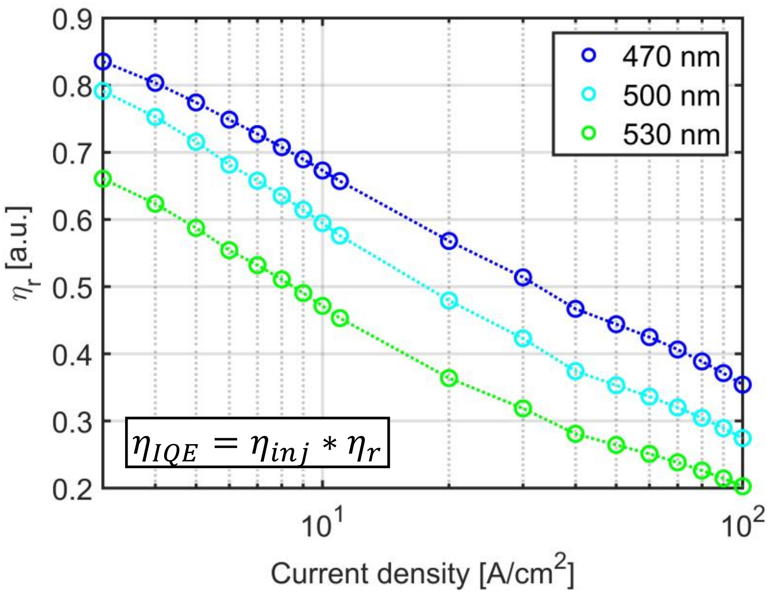




Internal Quantum, Injection, and Radiative Efficiency

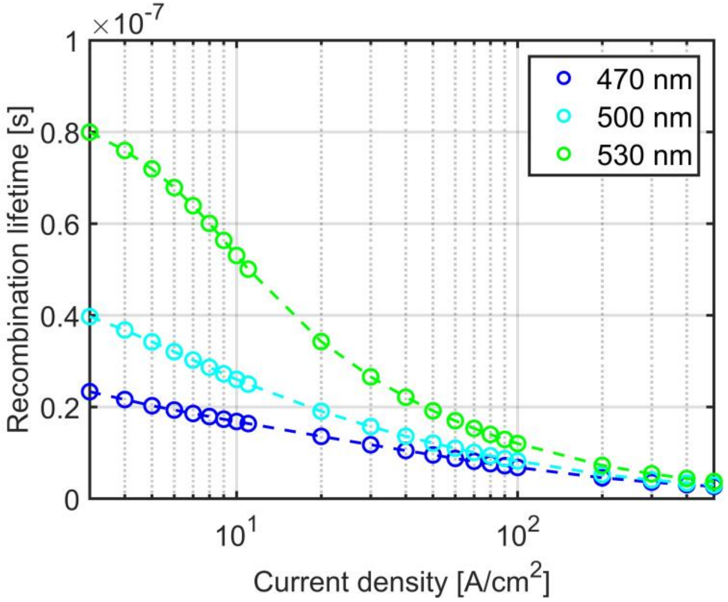


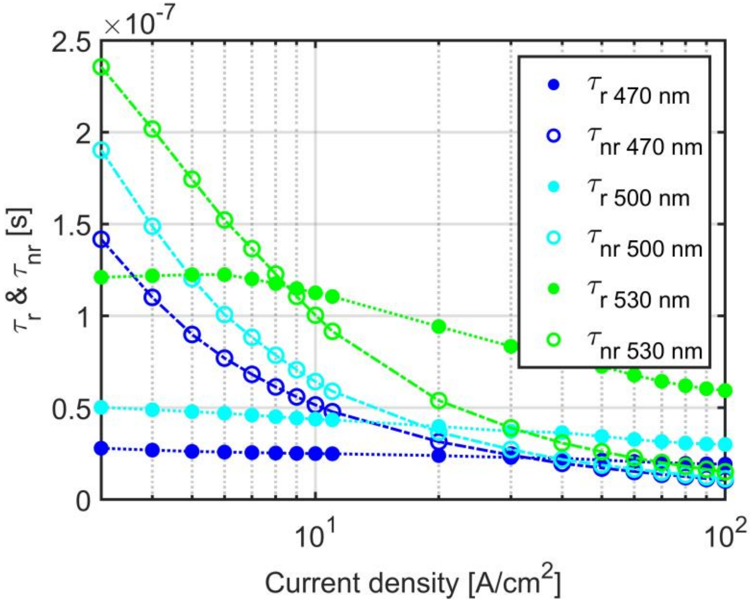




- Longer wavelength → lower IQE, lower injection efficiency, and lower radiative efficiency
- ***How much of the change in efficiency from blue to green is due to intrinsic effects (e.g., wave-function overlap and phase-space filling) vs. extrinsic effects (e.g., material degradation)?***

Radiative and Non-Radiative Lifetimes



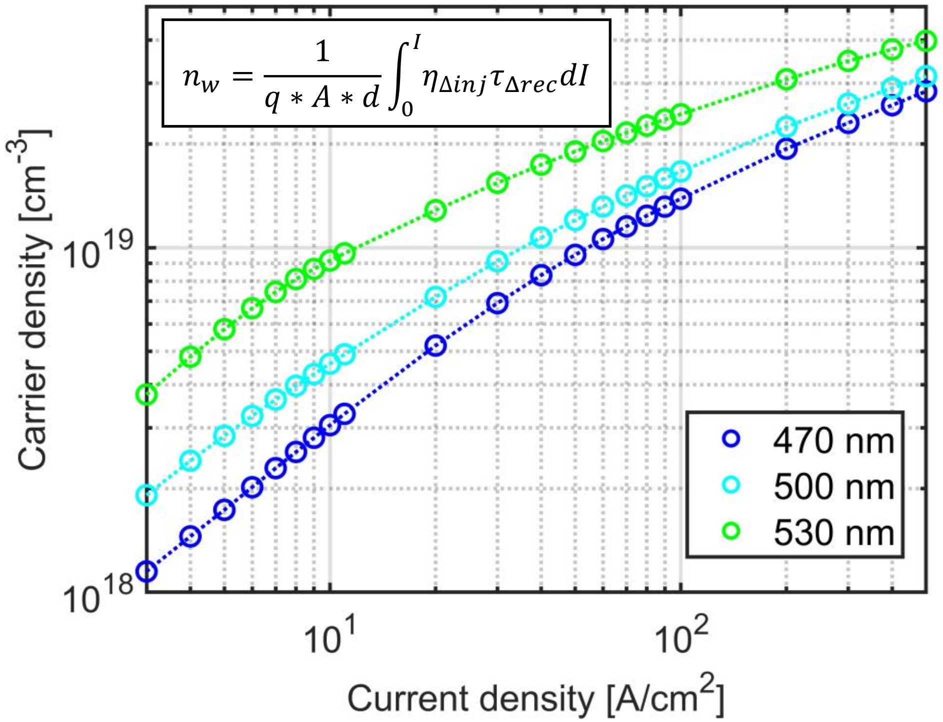


$$\eta_r = \frac{\tau_{nr}}{\tau_{nr} + \tau_r}$$

$$\tau_{rec} = \frac{\tau_{nr} * \tau_r}{\tau_{nr} + \tau_r}$$

- The total recombination lifetime is obtained by integrating the differential lifetime
- Radiative lifetime and non-radiative lifetime are separated using total lifetime and radiative efficiency
- Longer wavelength → longer total lifetime, longer radiative and non-radiative lifetimes
- ***Longer lifetimes at longer wavelengths expected from smaller wave function overlap***

Role of Carrier Density vs. Current Density



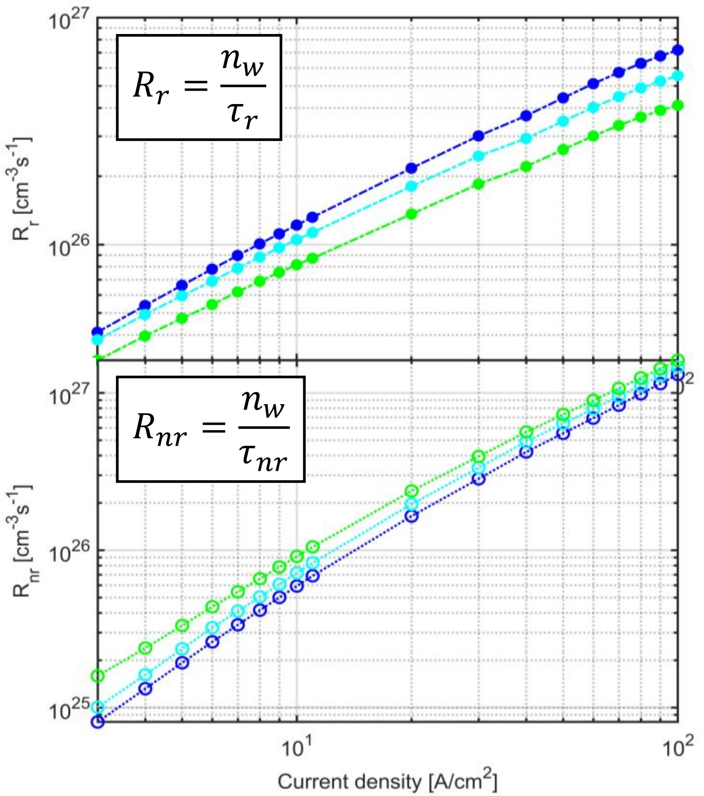
$$J \propto A(n)n + B(n)n^2 + C(n)n^3$$

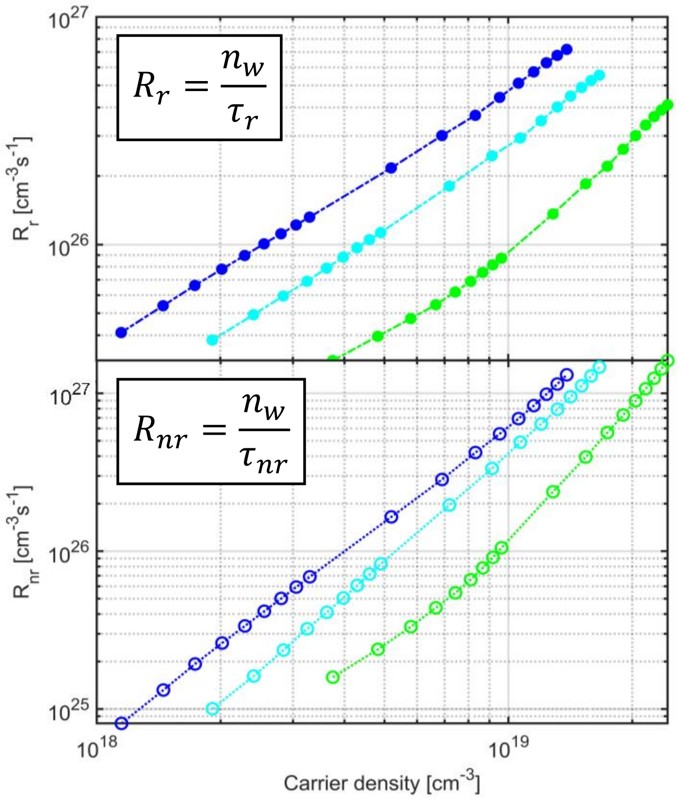
- Longer wavelengths have lower $A(n)$, $B(n)$, $C(n)$ at a given n due to stronger QCSE
- Reduces efficiency of converting carriers to current
- ***Longer wavelengths have higher n at a given J***
- ***Increases the relative strength of the Auger term***

Radiative and Non-Radiative Recombination Rates

$$R_{rec} = \int_0^{n_w} \frac{dn_w}{\tau_{\Delta rec}}$$

$$\tau_{rec} = \frac{n_w}{R_{rec}}$$

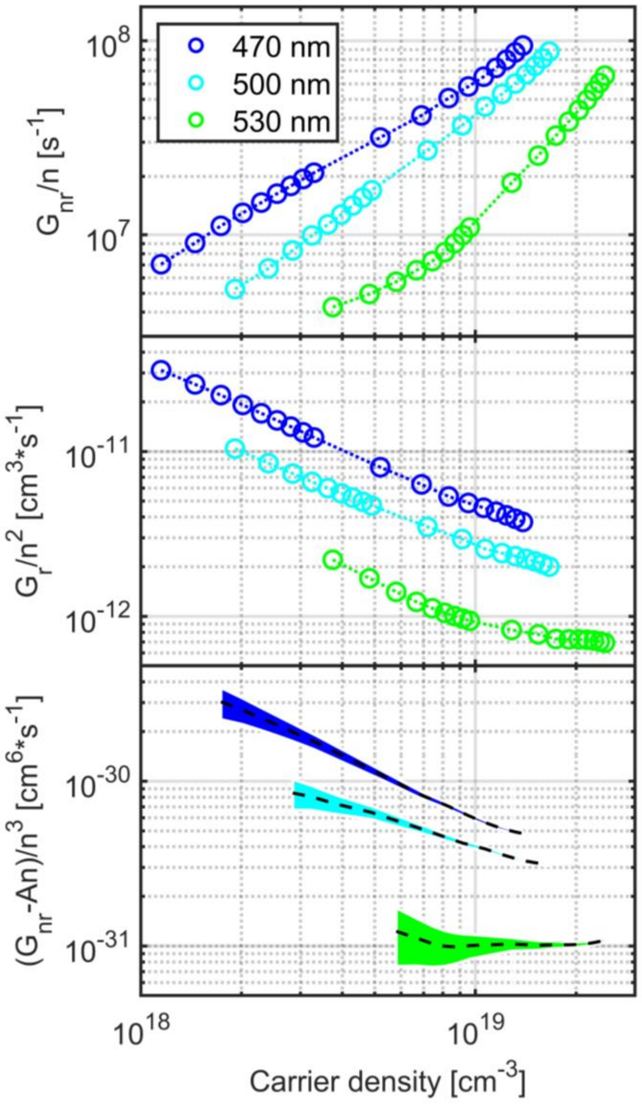




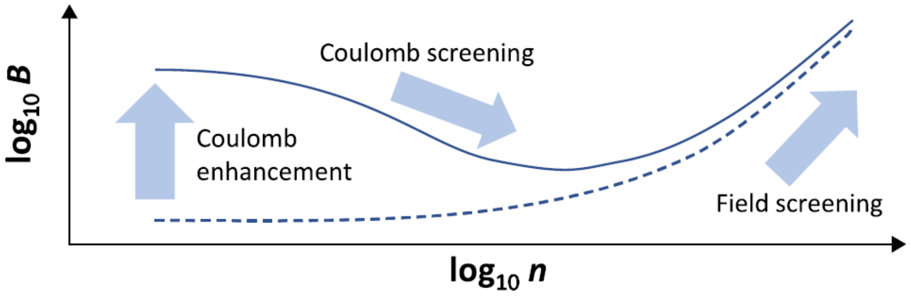
- Longer wavelength → stronger polarization in QWs → lower wave function overlap → smaller A, B, and C*
- At longer wavelength, n is higher, but B and C are lower
- ***R_{nr}(530 nm) > R_{nr}(470 nm) but R_r(530 nm) < R_r(470 nm) since $R_r \propto n^2$, while $R_{nr} \propto n^3$***
- ***In addition to increased Auger, reduction in radiative rate is an important factor for green gap***

*E. Kioupakis et al ., *Appl. Phys. Lett.*, **101**.23 (2012): 231107.

ABC Parameters

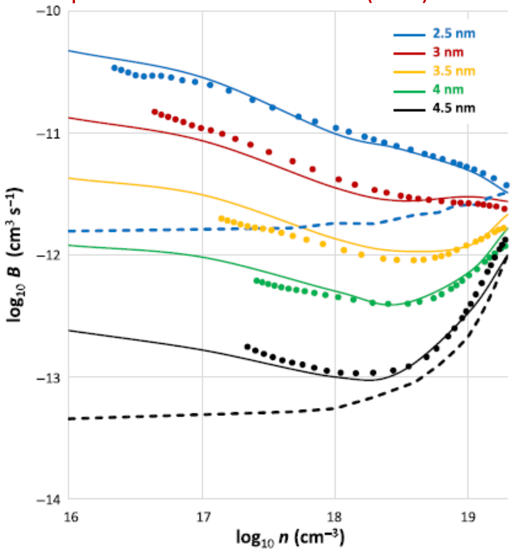


- Mechanisms that affect $A(n)$, $B(n)$, and $C(n)$: QCSE (field screening), phase-space filling (PSF), and Coulomb enhancement/screening
- G_{nr}/n doesn't converge at low n, so can only bracket $A(n)$
- Increase of G_r/n^2 and $(G_{nr} - An)/n^3$ at low n attributed to Coulomb enhancement
- Strong field screening not observed in these 3-nm-thick QWs
- Difficult to decouple the different effects but ***ratios can provide insight***

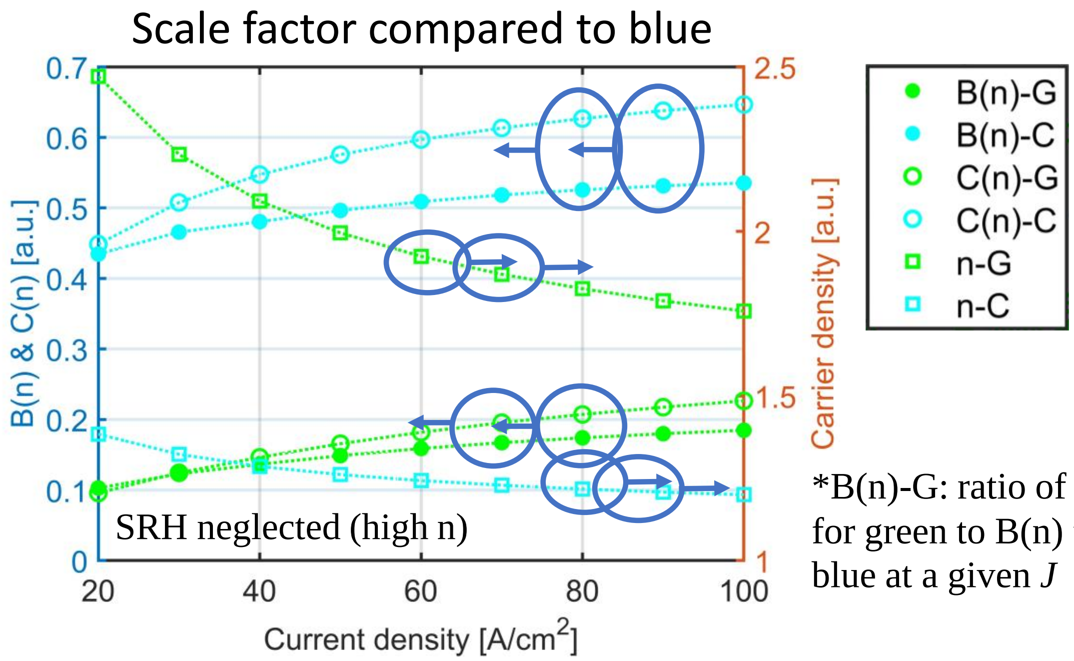


A. David et al., *Phys. Rev. Appl.*, 12.4 (2019): 044059.

Optical differential lifetime (ODL) method



n, B(n), and C(n) Compared to Blue at 40 A/cm^2



*B(n)-G: ratio of B(n) for green to B(n) for blue at a given *J*

Definition of $B(n)$ & $C(n)$

$$R_r = B(n) * n^2$$

$$R_{nr} \approx C(n) * n^3 \quad \text{(at high } n\text{)}$$

Normalized to blue:

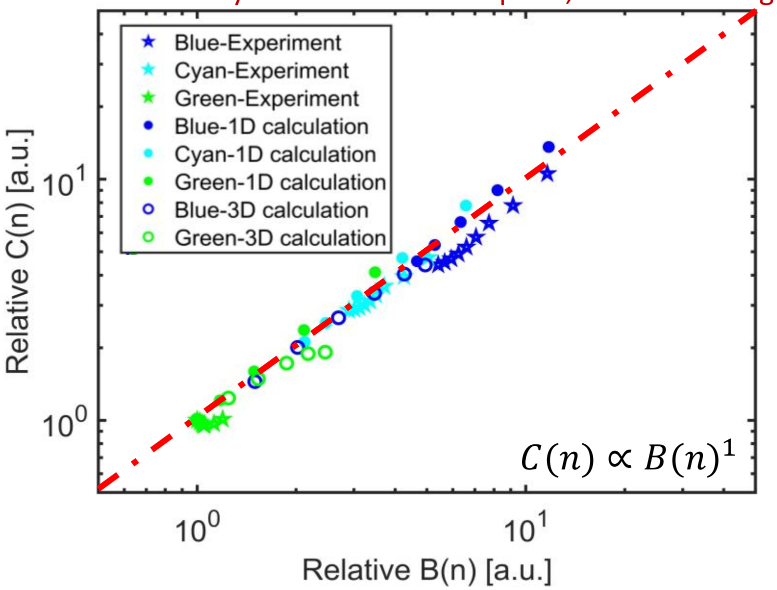
	R_r	R_{nr}	n	B(n)	C(n)
Blue	1	1	1	1	1
Cyan	0.80	1.16	1.29	0.48	0.55
Green	0.60	1.34	2.09	0.14	0.15

$$\eta_r \approx \frac{B(n)n^2}{B(n)n^2 + C(n)n^3} \quad \text{(at high } n\text{)}$$

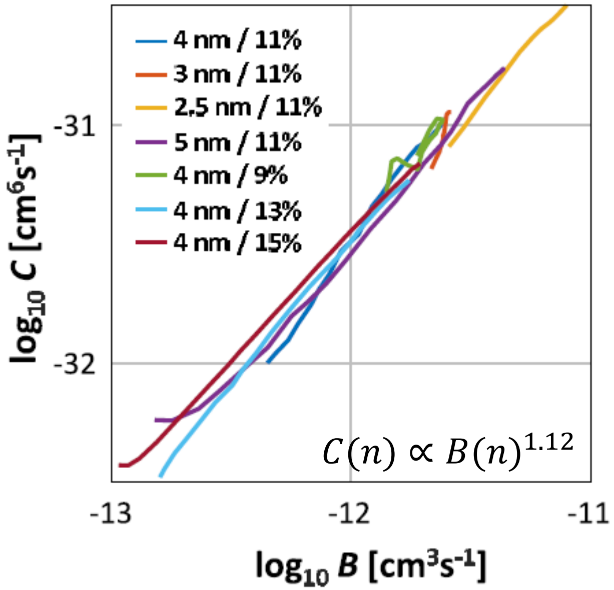
- Blue → Green: R_r decreases but R_{nr} increases
- Blue → Green: Carrier density increases by 2X
- Blue → Green: $B(n)$ and $C(n)$ both decrease by 7X
- ***Efficiency reduction for high n in longer wavelength LEDs not dominated by large relative increase in $C(n)$ compared to $B(n)$***

Scaling Law Between C(n) & B(n) at High n

Simulations by N. Pant and E. Kioupakis, Univ. of Michigan



Optical differential lifetime (ODL) method

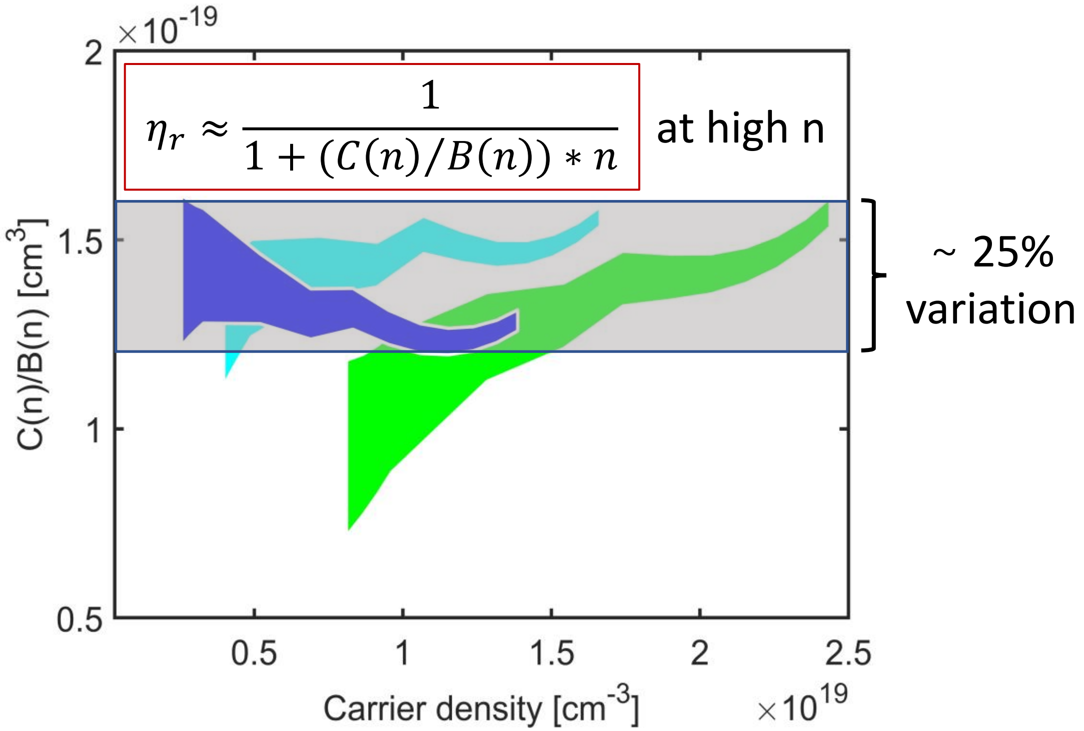


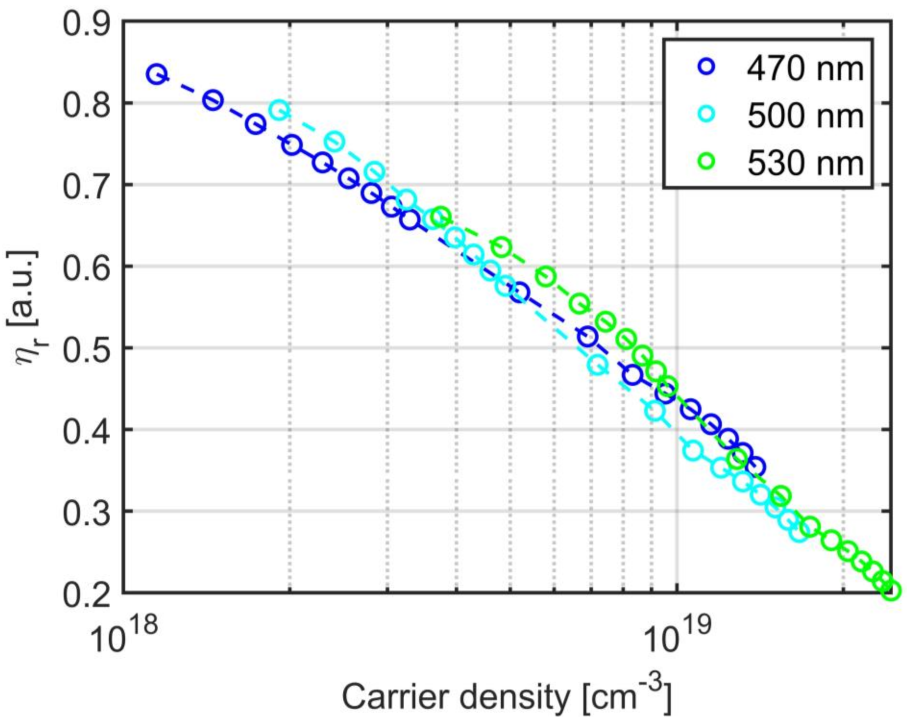
A. David et al., *Appl. Phys. Lett.*, 115.19 (2019): 193502.

$$\eta_r \approx \frac{1}{1 + (C(n)/B(n)) * n}$$ at high n

- $C(n) \propto B(n)$ at high n from experiment and Schrödinger-Poisson simulations from Univ. of Michigan
- Simulations capture variations in QCSE, PSF, and alloy disorder
- Same power law obeyed for all wavelengths at high n under varying polarization fields and PSF
- ***Variations in $C(n)$ and $B(n)$ due to QCSE (field screening) and PSF cancel out at high n if we consider $C(n)/B(n)$***
- ***Whatever differences exist in $C(n)/B(n)$ should mainly capture any material-quality differences***

C(n)/B(n) Approaches Similar Value at High n

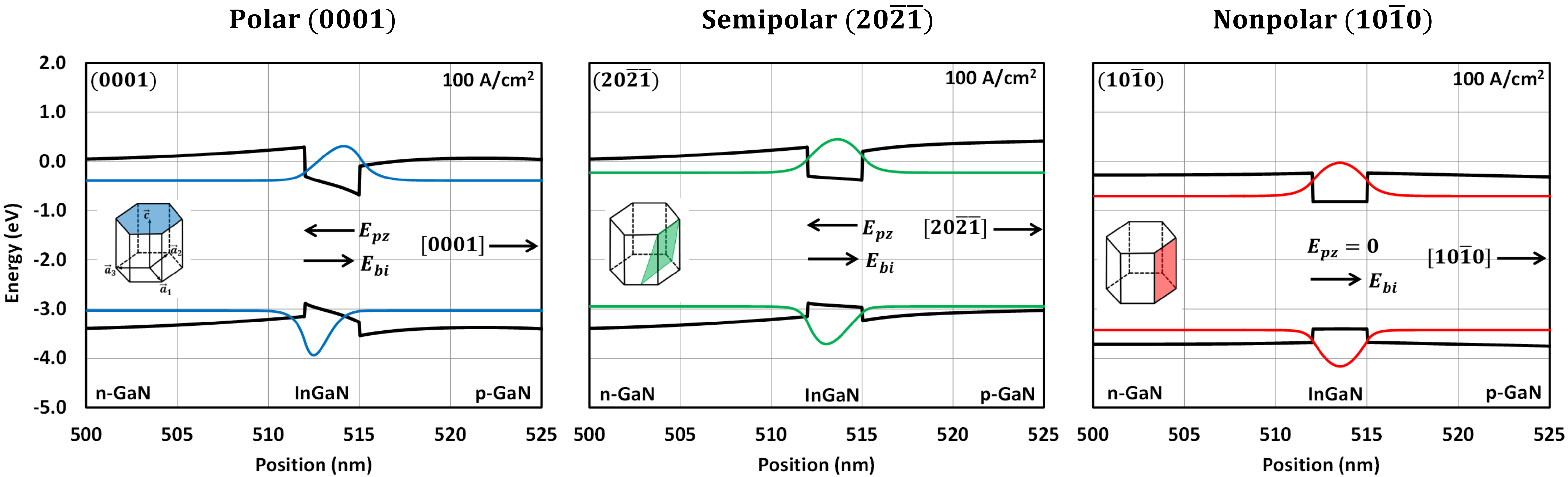




- $C(n)/B(n)$ approaches a similar value at high n for all wavelengths ⇒ effects of material degradation are small
- Differences in $C(n)/B(n)$ between blue, cyan, and green consistent with differences in $C_{bulk}(n)$ from DFT
- ***Decrease of η_r for longer wavelength is mostly from the increase of corresponding n at a given J***
- ***Radiative efficiency is similar for a given n for all wavelengths***
- Target green LED designs that reduce n (multiple QWs) and increase overlap (thin QWs, semipolar, stepped profiles)

Orientation Series: Blue LEDs

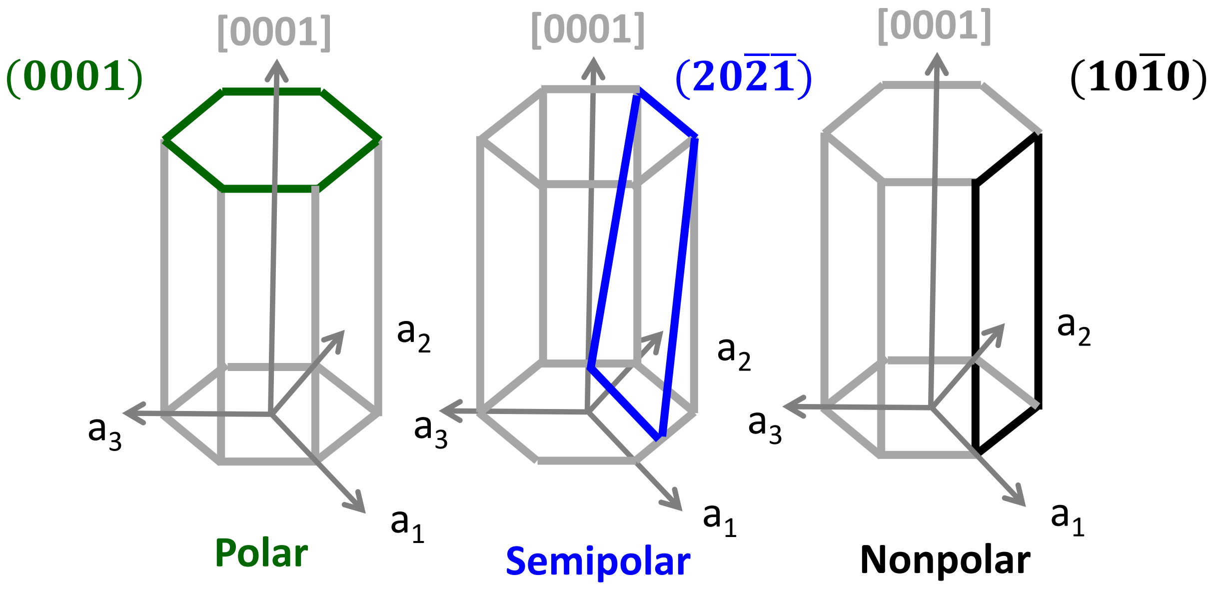
Carrier recombination lifetime (rate) influenced by orientation ($f_{3dB} \propto 1/\tau$):

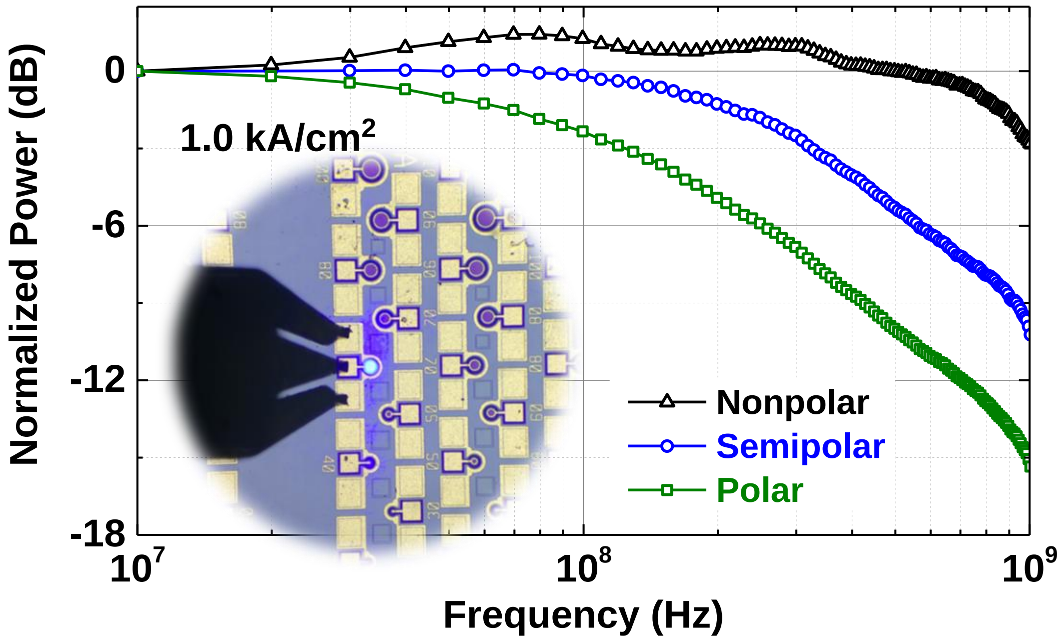


Goal: Investigate the effects of orientation on modulation bandwidth

D. Feezell, *J. Disp. Technol.* **9**, 190-198 (2013)

Orientation Dependence of Bandwidth

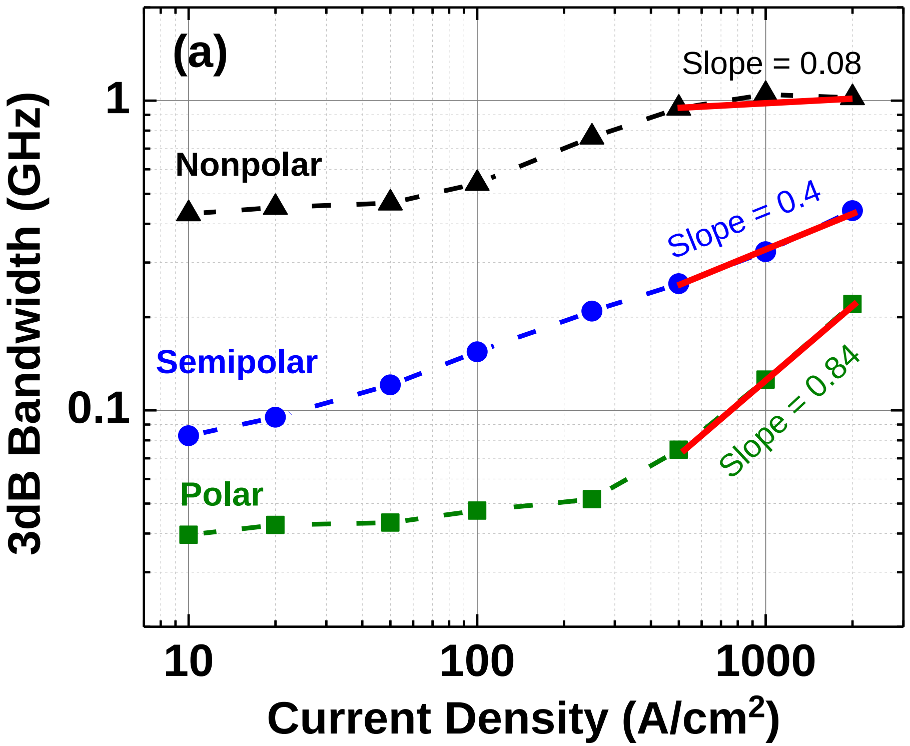


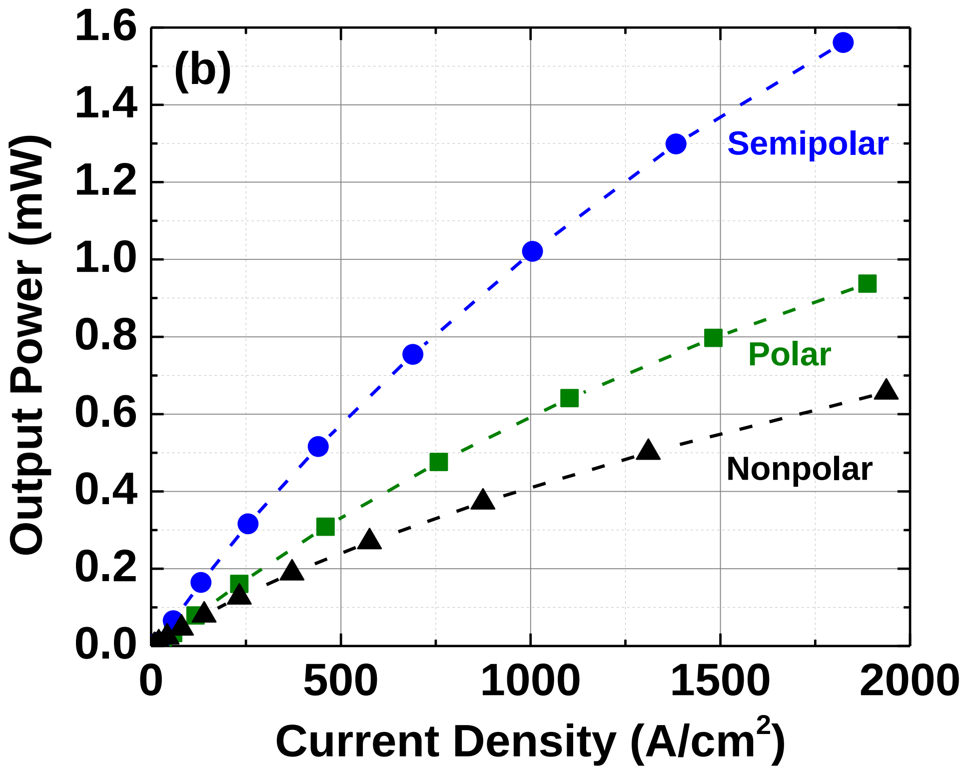


- Compared 450 nm LEDs on polar, semipolar $(20\bar{2}\bar{1})$, and nonpolar orientations
- Bandwidth trends follow wavefunction overlap trends
- $f_{3dB-nonpolar} > f_{3dB-semipolar} > f_{3dB-polar}$

M. Monavarian, et al., *Appl. Phys. Lett.* ***112***, *041104* (2018)

Orientation Dependence of Bandwidth

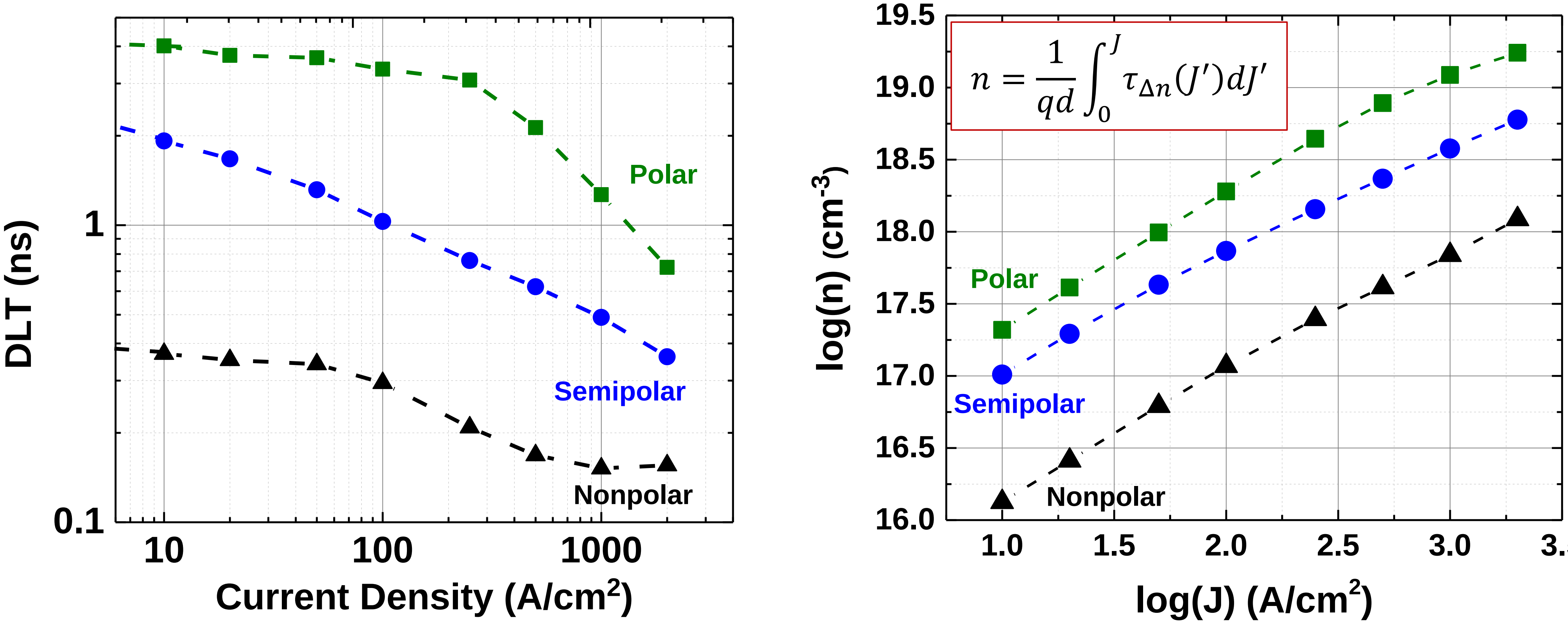




- Nonpolar and semipolar bandwidth is significantly higher at low current densities
- Polar LED experiences screening of the internal electric fields above 500 A/cm^2
- Large bandwidth at low current density important to maximize efficiency

M. Monavarian, et al., *Appl. Phys. Lett.* ***112****, 041104* (2018)

Differential Carrier Lifetime and Carrier Density



- Differential carrier lifetime (DLT) follows inverse trend to bandwidth
- Carrier density for a given current density always lower on nonpolar and semipolar

M. Monavarian, et al., *Appl. Phys. Lett.* ***112***, *041104* (2018)

Effect of Wave Function Overlap

- Recombination rate ($An + Bn^2 + Cn^3$) is roughly proportional to the square of the wave function overlap for a given carrier density (n)
- Overlap is higher in nonpolar/semipolar, increasing the recombination rate and bandwidth
- With higher recombination coefficients (A, B, C), n is lower for a given J
- Lower n at a given J reduces the impact of the Cn^3 term

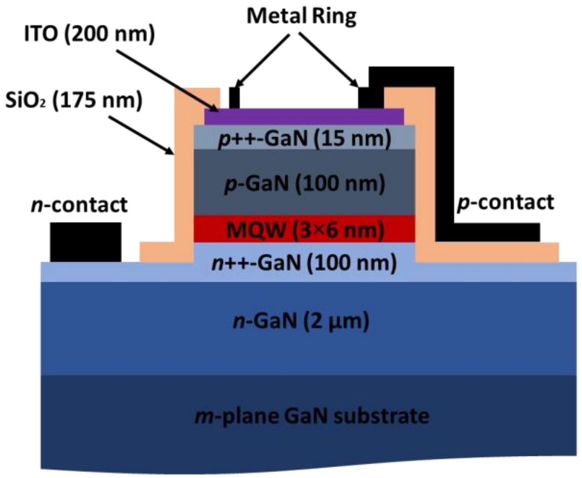
$$A, B, C \propto |\langle F_1 | F_2 \rangle|^2$$

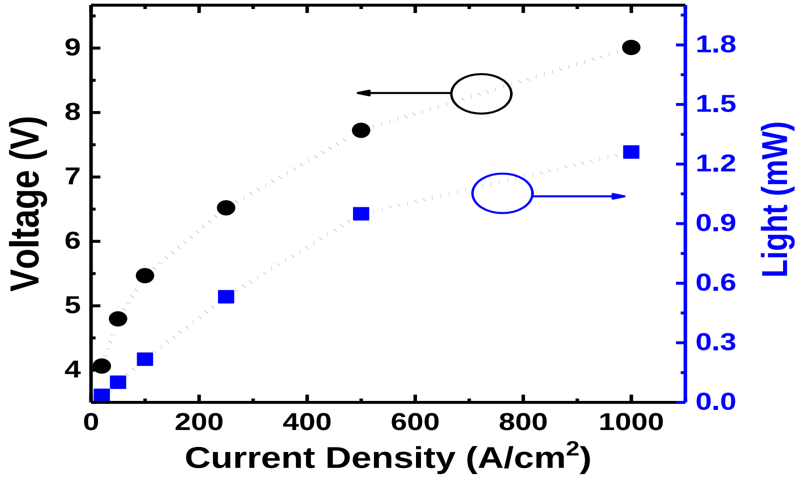
$$J \propto An + Bn^2 + Cn^3$$

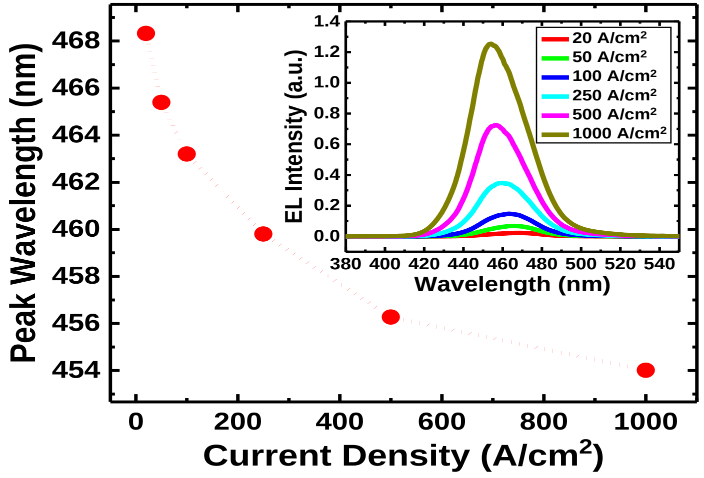
$$\eta_r = \frac{Bn^2}{An + Bn^2 + Cn^3}$$

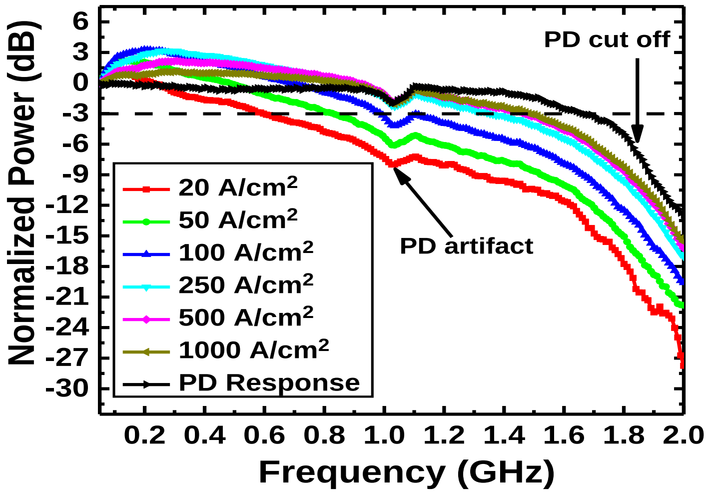
	polar	nonpolar / semipolar
$\|\langle F_1 \| F_2 \rangle\|^2$	↓	↑
A, B, C	↓	↑
n @ given J	↑	↓
J @ given n	↓	↑

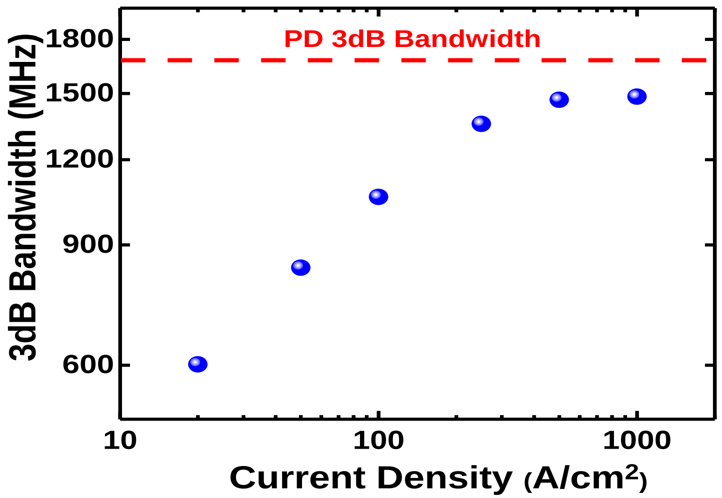
Nonpolar LED with 1.5 GHz Modulation Bandwidth

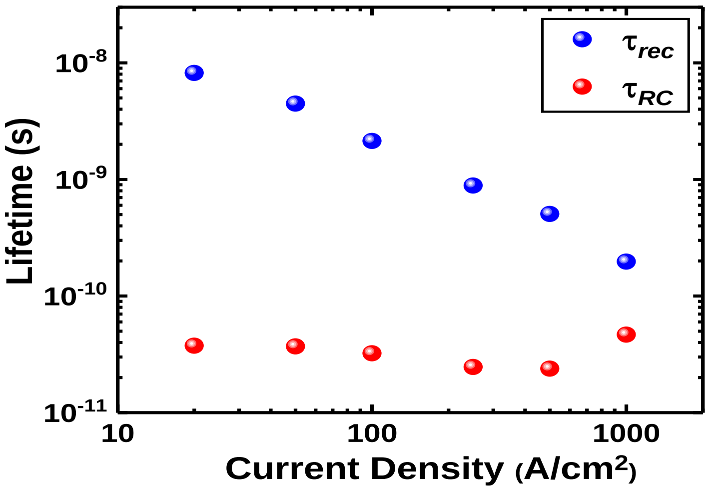








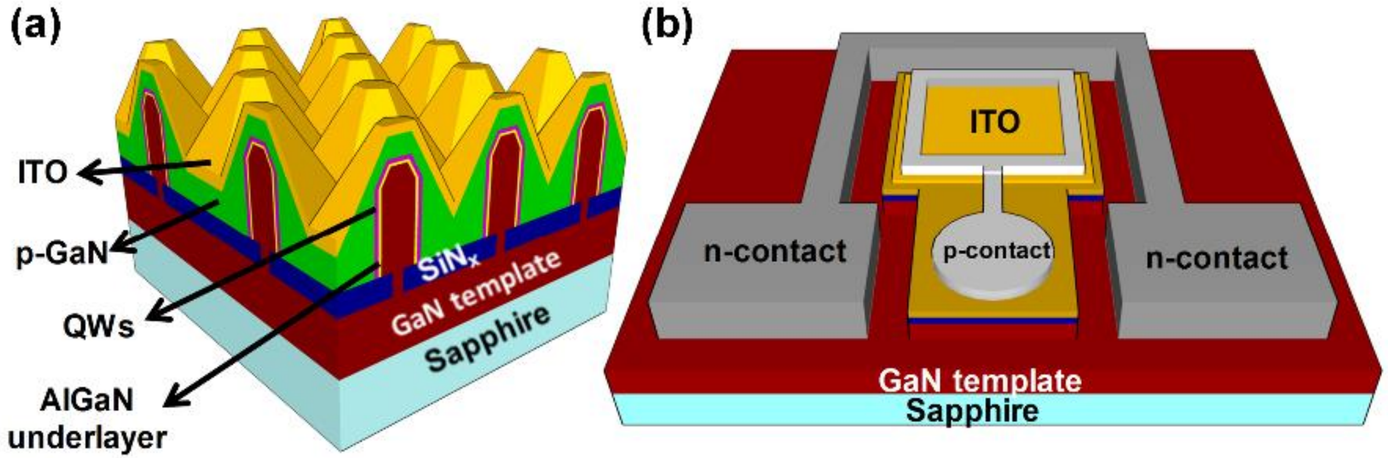


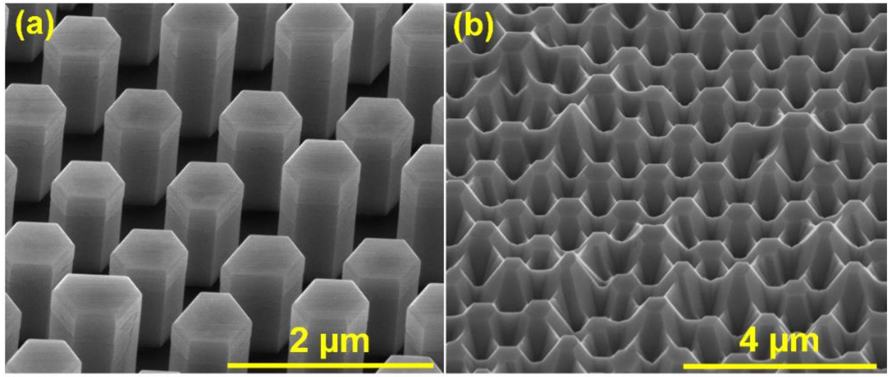


Similar modulation bandwidth to highest reported GaAs-based LED

A. Rashidi, et al., *Elect. Dev. Lett.* (2018)

Nonpolar Core-Shell Nanowire-Based LEDs





Potential Advantages:

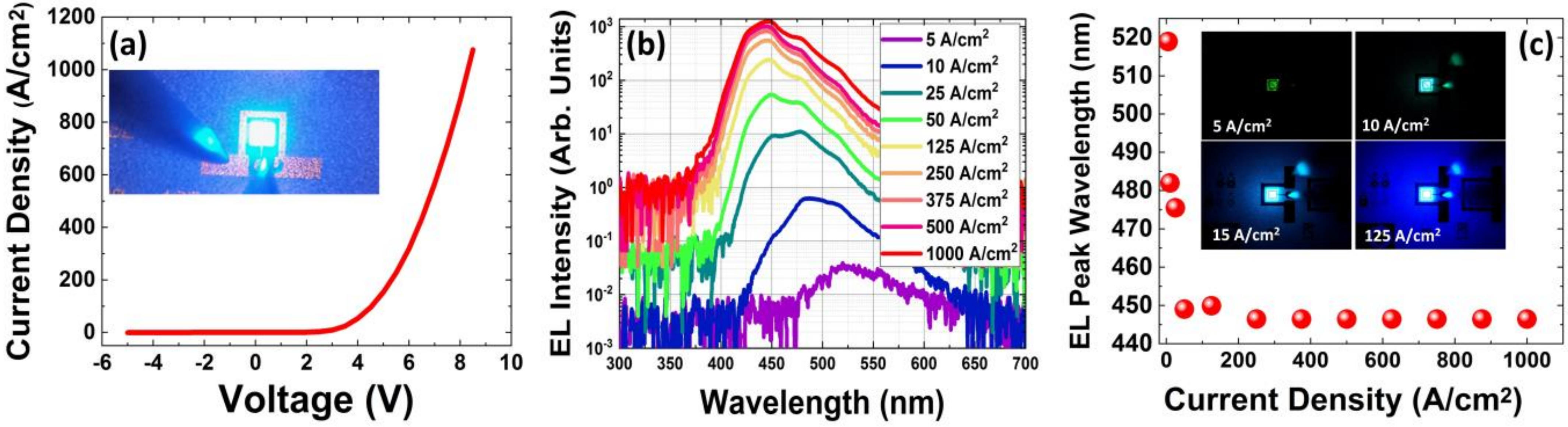
- **Polarization-free active regions**
- **Large effective active region area**
- **Elimination of threading dislocations**
- **Strain relaxed structures possible**
- **Monolithic integration of multi-color LEDs**

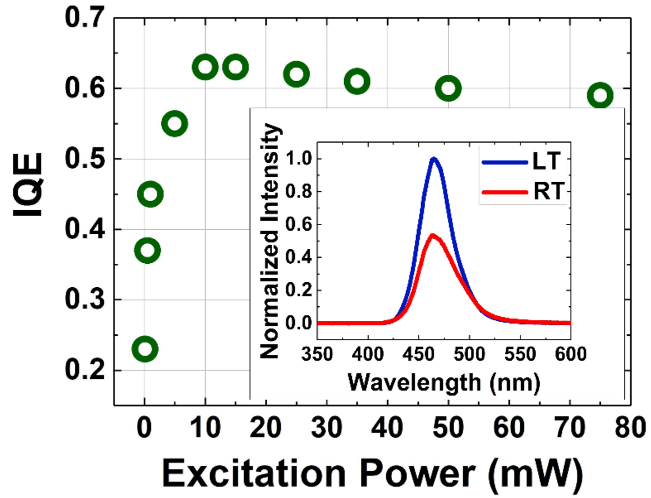
- Bottom-up selective-area growth
- 4 X 2.5-nm-thick QWs
- AlGaN underlayer and electron blocking layer
- Peak IQE ~ 62%
- 60 µm x 60 µm area of NWs

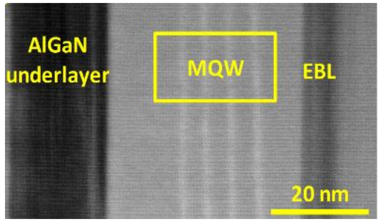
M. Nami, et al., *Sci. Reports* **8** , 501 (2018)

M. Nami, et al., *Nanotechnology* **28** , 025202 (2017)

Electrical and Optical Characteristics

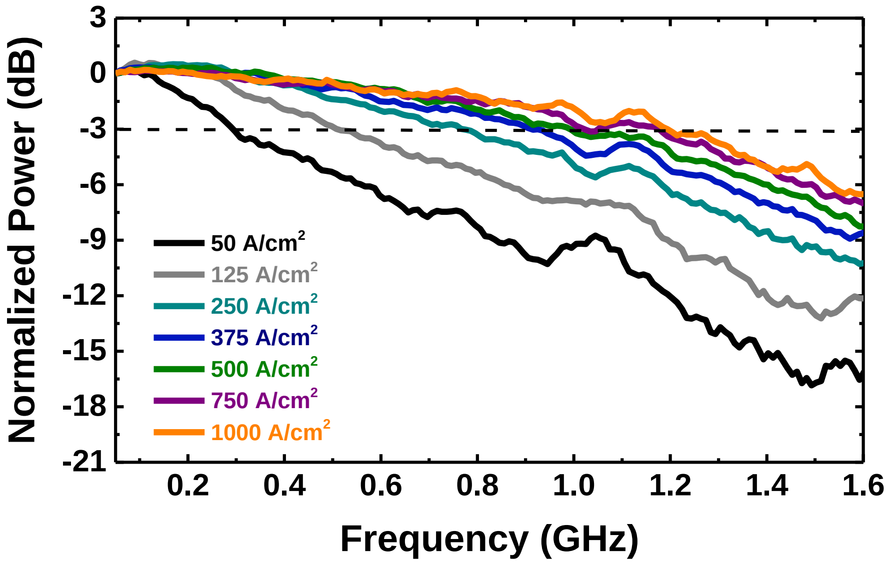


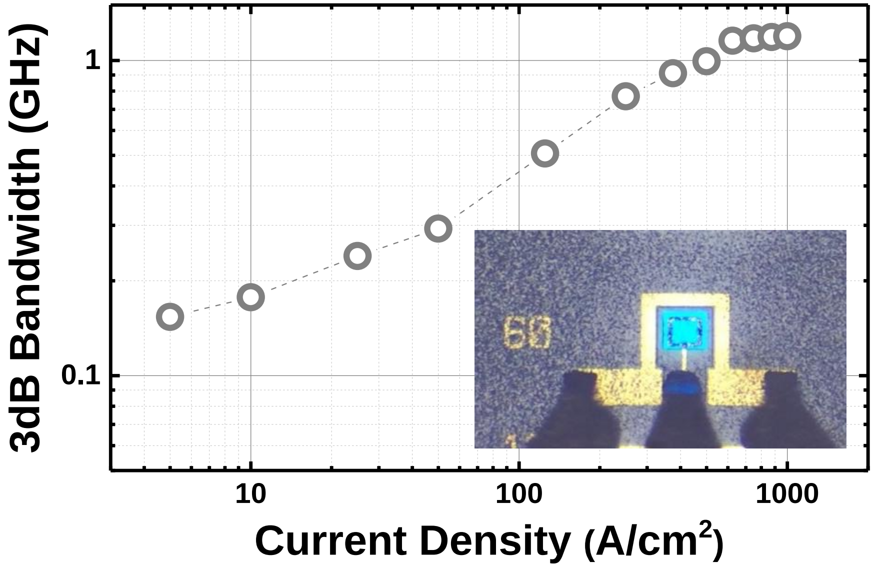




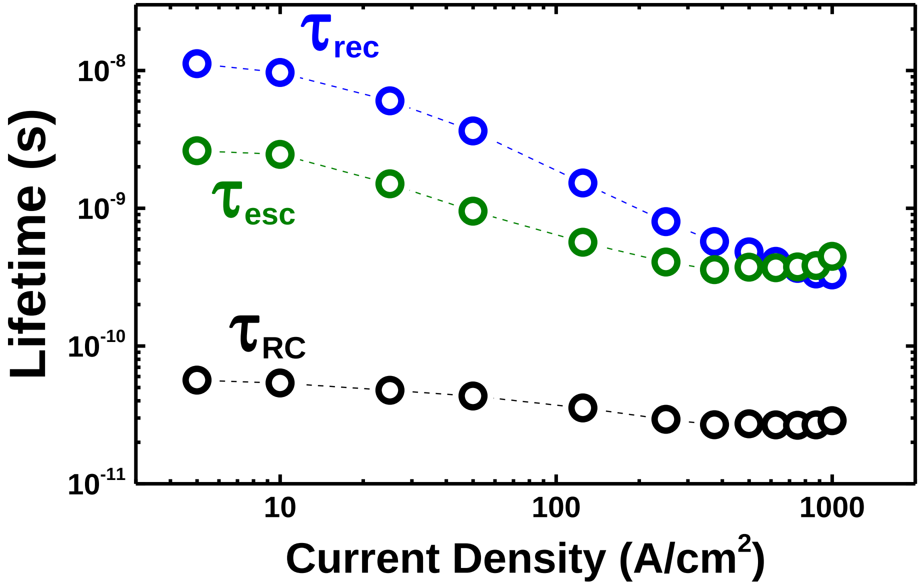
- *Excellent diode behavior was obtained for the nanowire LED using AlGaN underlayer*
- *Nanowire LEDs show an IQE of 0.62*

Frequency Response and Lifetimes



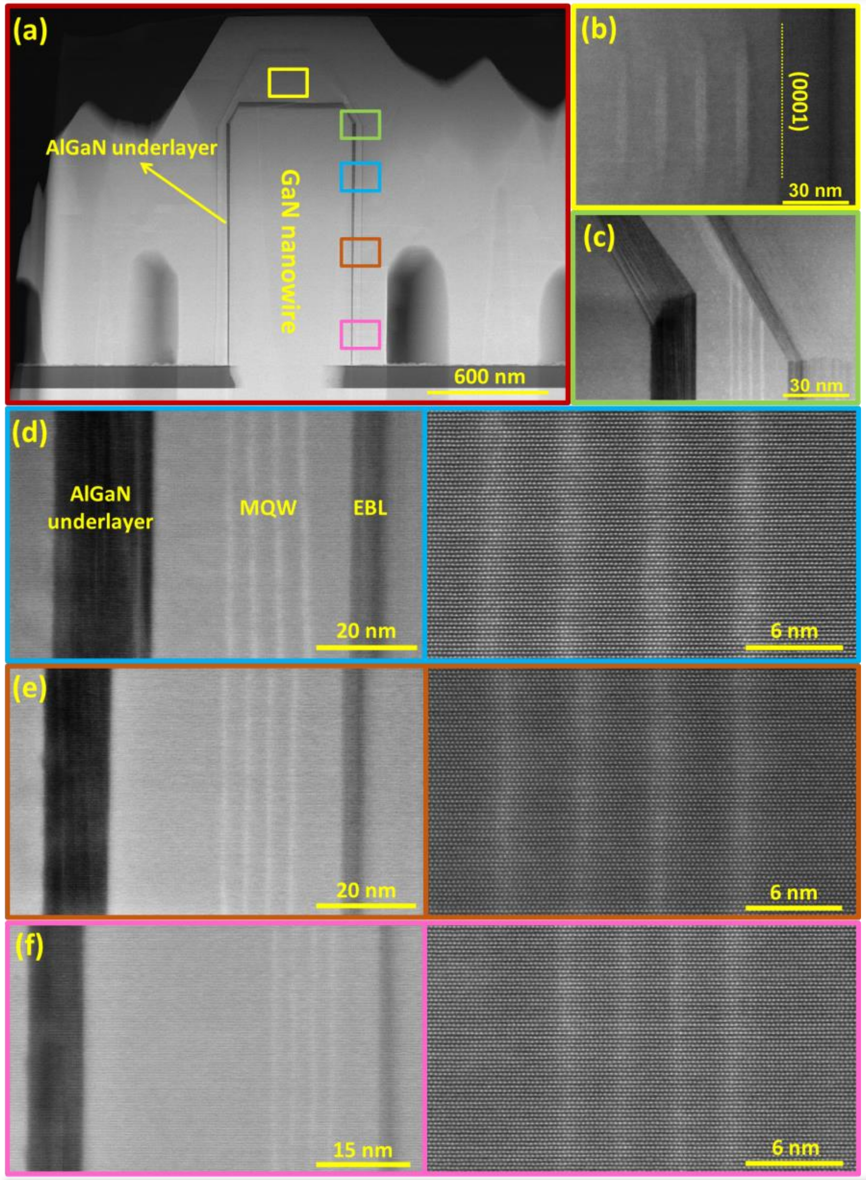


- 1.2 GHz bandwidth at 1 kA/cm^2
- Non-uniform injection affects spectrum and BW vs. J trend
- ***Similar maximum bandwidth to planar m-plane LED***

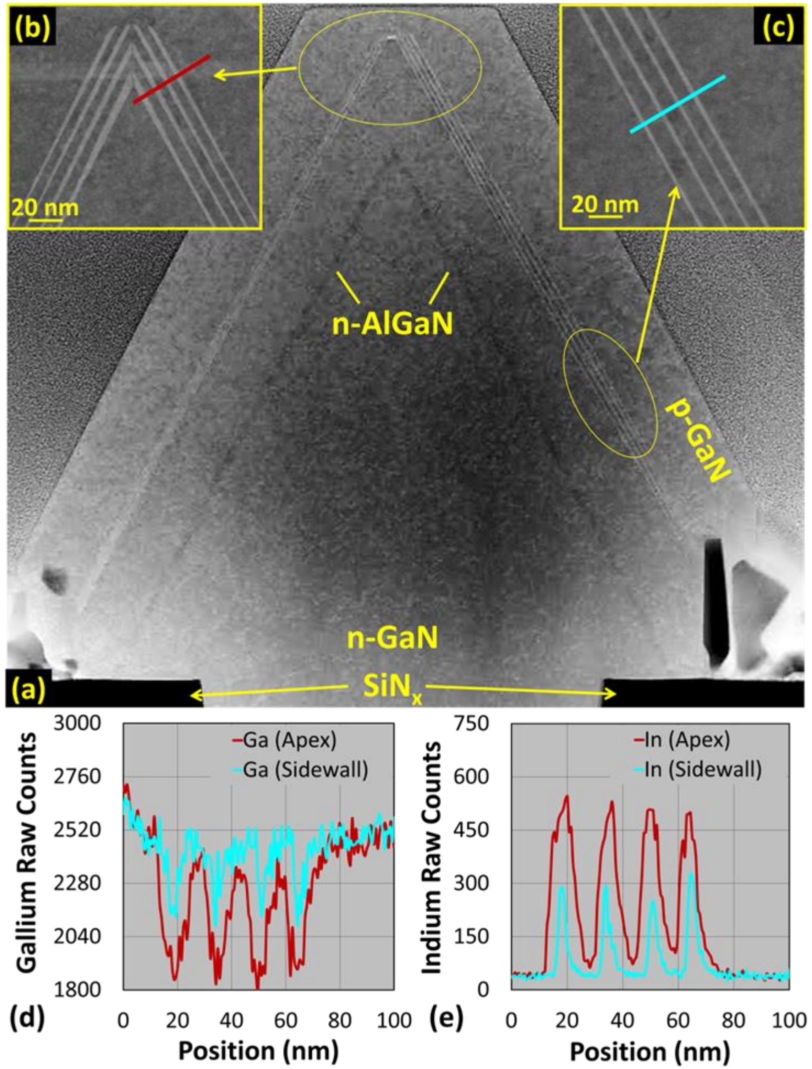


M. Nami, et al., *ACS Photonics* **6**, 1618 (2019)

QW Non-uniformity Across The Nanowires

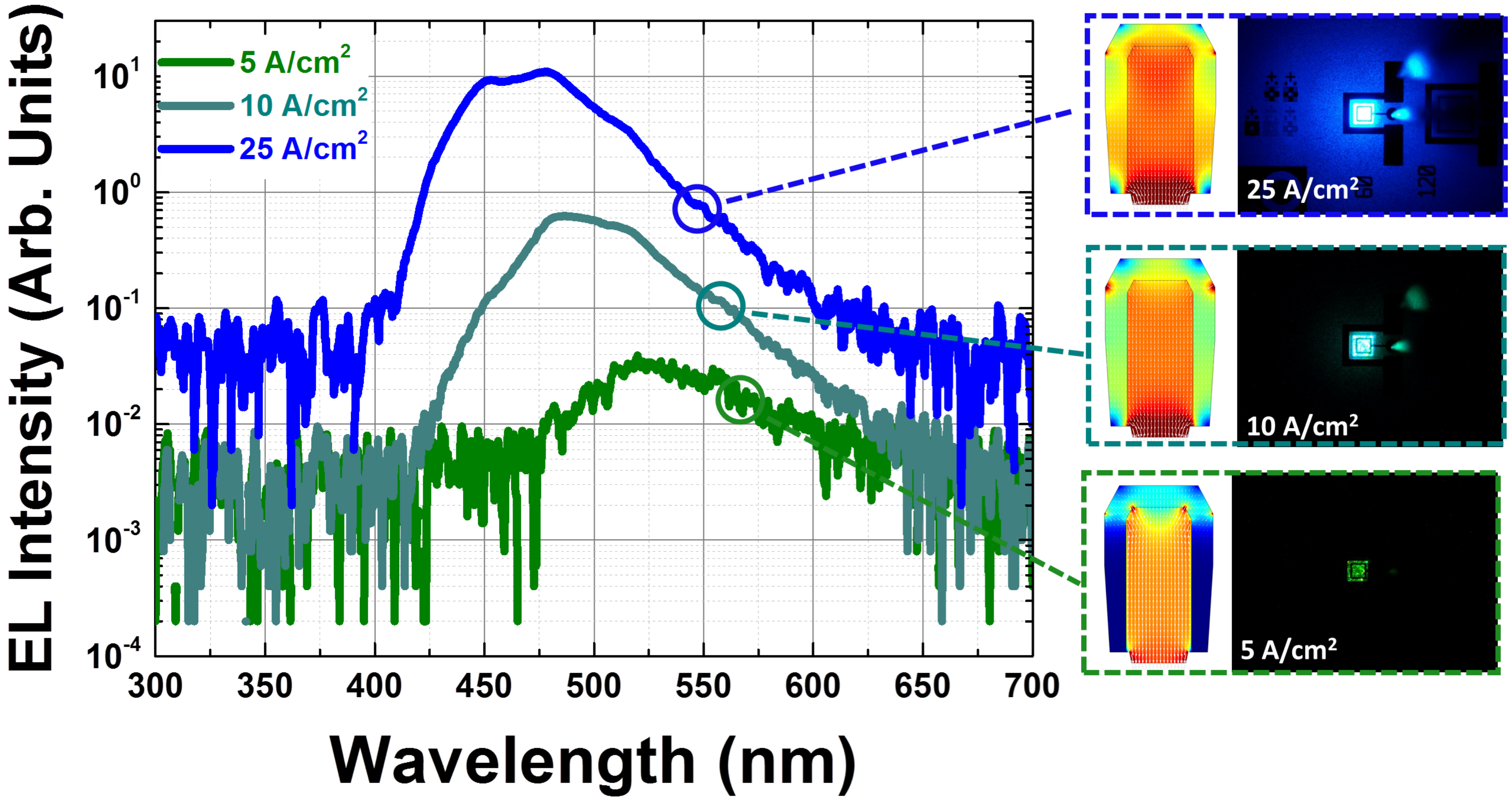


- Non-uniformity in InGaN growth rate and QW thickness
- Non-uniformity in indium content
- Both result in variation in QW emission



A. Rishinaramangalam, et al., Appl. Phys. Express **9**, 032101 (2016)
S. Okur, et al., Nanotechnology 2**9**, 235206 (2018)

Nanowire Emission From Blue to Green

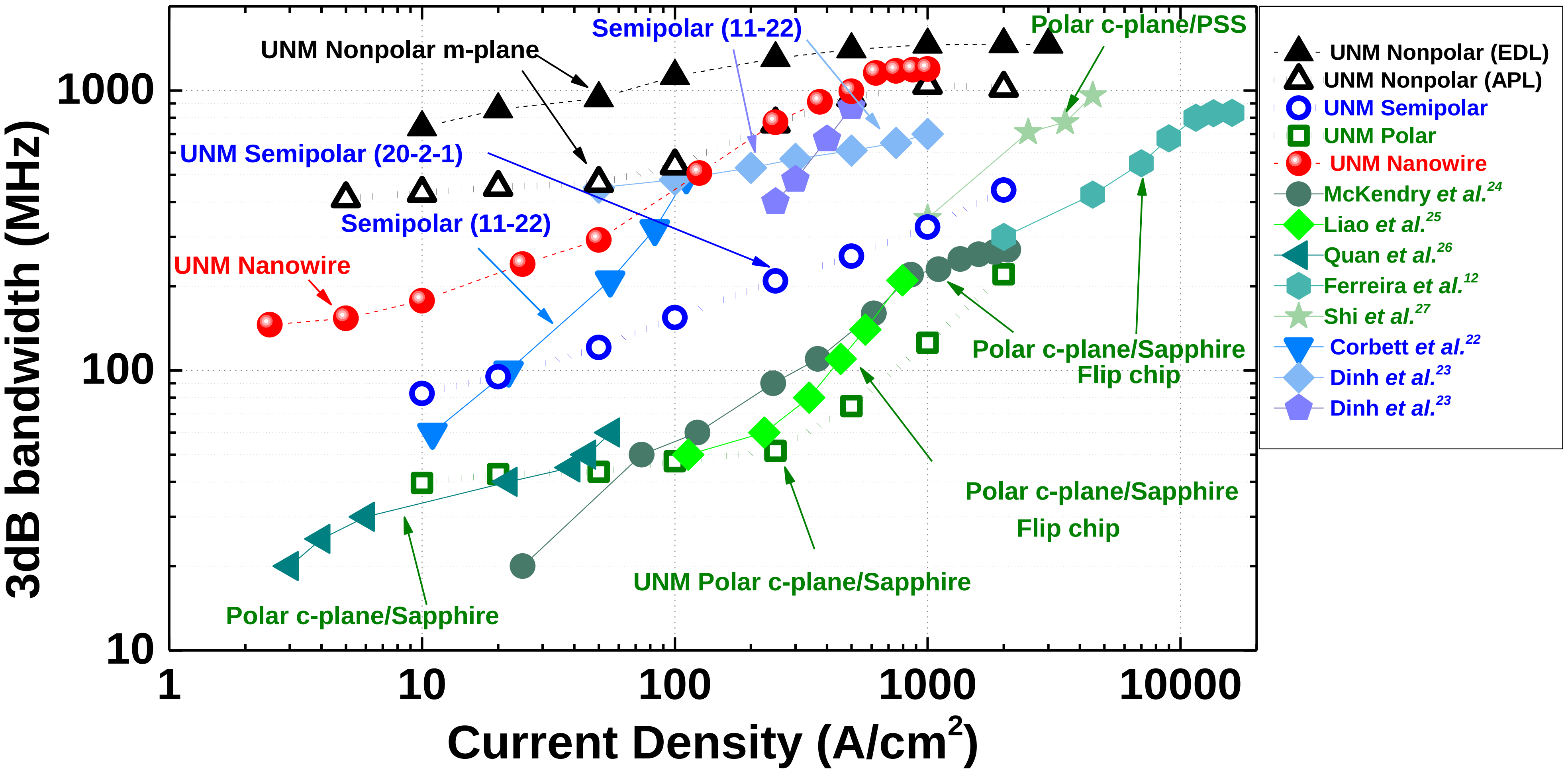


- Carrier injection non-uniformity in EL suggested by the simulation results
- Due to non-uniformity of QW emission, EL spectra is strongly dependent on the current density

Emission color changes from green to blue by changing current density

M. Nami, et al., *ACS Photonics* **6**, 1618 (2019)

Comparison of Bandwidth for Various Orientations



c-plane bandwidth is fundamentally lower due to internal electric fields (QCSE)

M. Monavarian, et al., *Appl. Phys. Lett.* ***112****, 041104* (2018)

Conclusions

- Small-signal electroluminescence measurements used to study carrier dynamics in polar, semipolar, and nonpolar LEDs under real operating conditions

- Analysis of an LED wavelength series on commercial epitaxy shows decrease in IQE for longer wavelength is mostly from the increase of corresponding n at a given J

- Nonpolar and semipolar orientations are fundamentally faster than *c*-plane, as expected from increased wave function overlap

- Core-shell nanowire LEDs showed >1 GHz 3dB bandwidth, but suffered from non-uniform carrier injection


Thank You!