High Performance Green LEDs for Solid State Lighting

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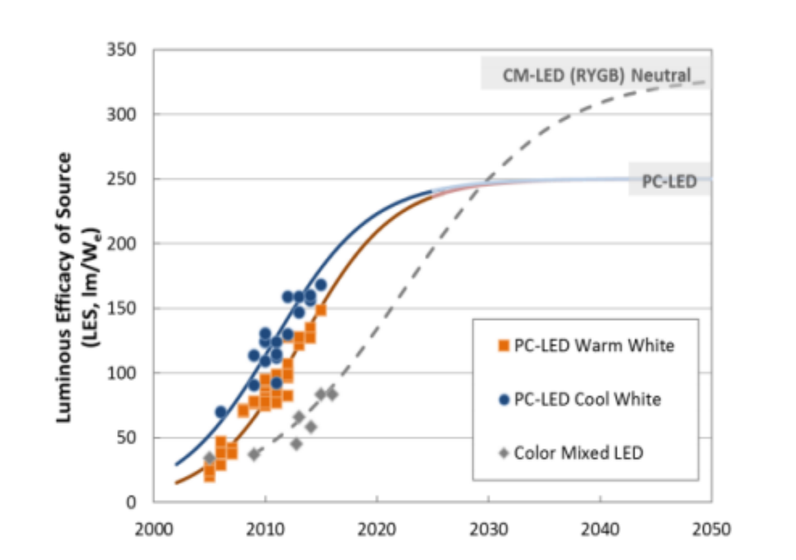
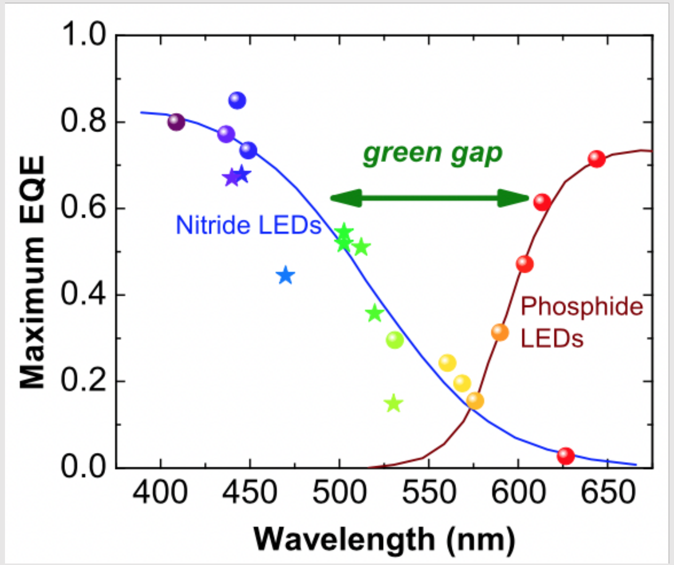
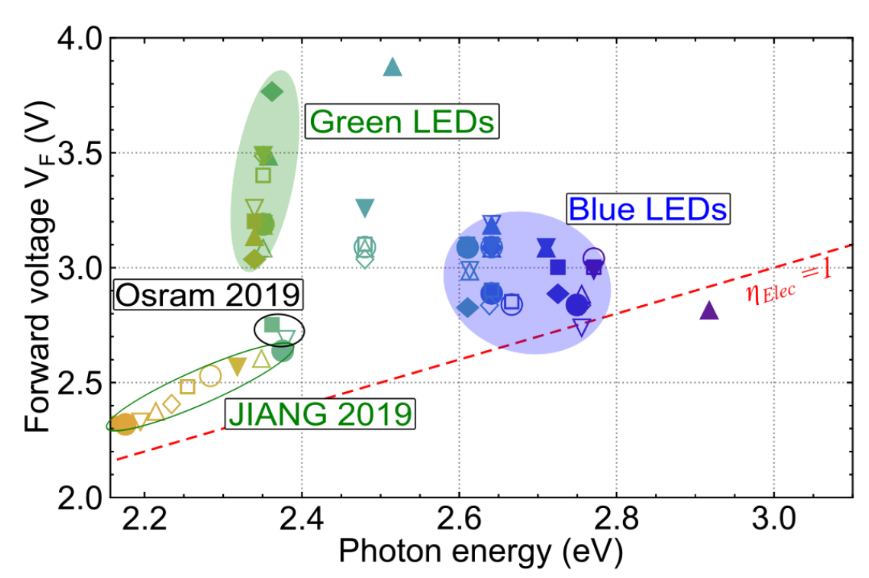
Project motivation and objectives







Color mixed LEDs using red, yellow, green, and blue LEDs, have a higher fundamental limit for luminous efficacy and better color tunability

Solid-State Lighting 2017 Suggested Research Topics Supplement. DOE Office of Energy Efficiency & Renewable Energy September 2017.

Limitation of nitride and phosphide LEDs in green-yellow region of spectrum → "Green Gap"

M. Auf der Maur, *et al.*, Phys. Rev. Lett. 116, 027401 (2016).

$$WPE = EE \times IQE \times LEE$$

$$EE = {V_{ph}}/{V_F} \qquad \Delta V_F = V_F - V_{ph}$$

Large excess forward voltage ΔV_F leads to low wall plug efficiency

G. Lheureux, *et al.*, J. Appl. Phys. **128**, 235703 (2020).

R&D approach

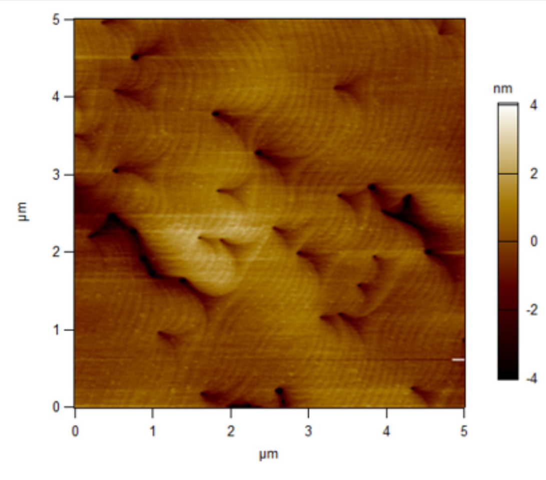
Engineering against Shockley-Read-Hall

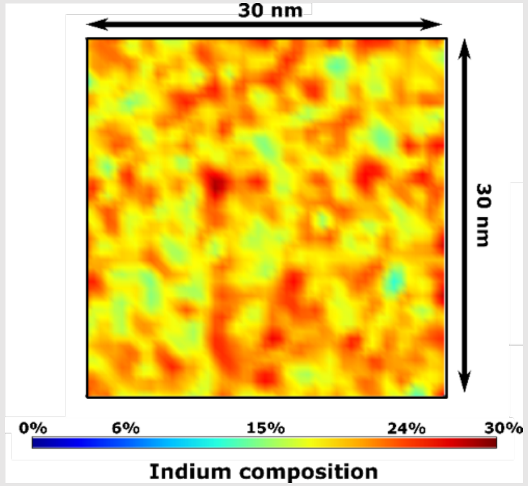
Advanced design

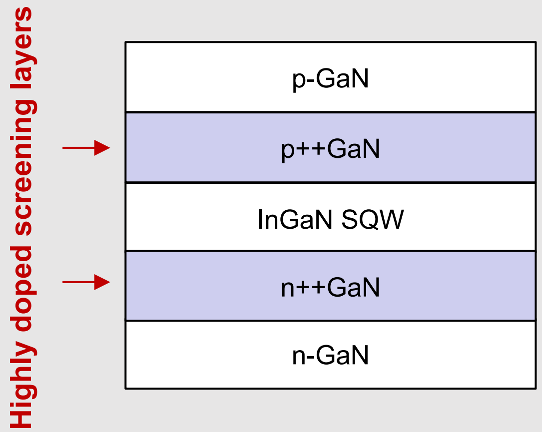
Polarization engineering

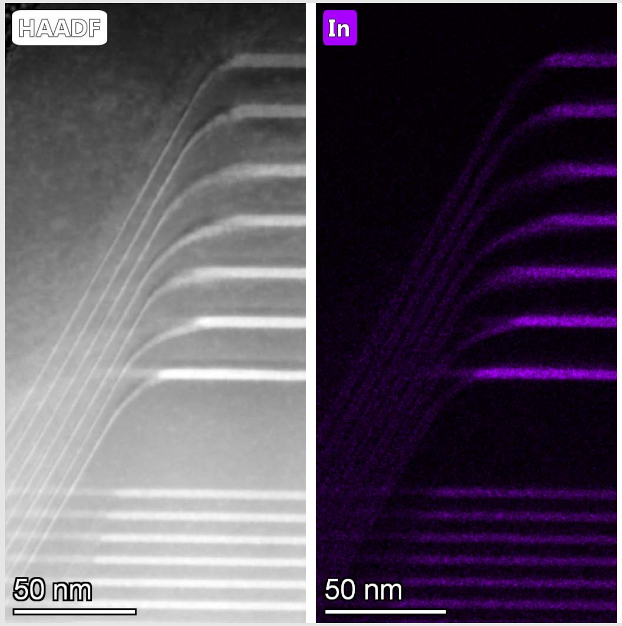
Voltage reduction

Advanced characterization









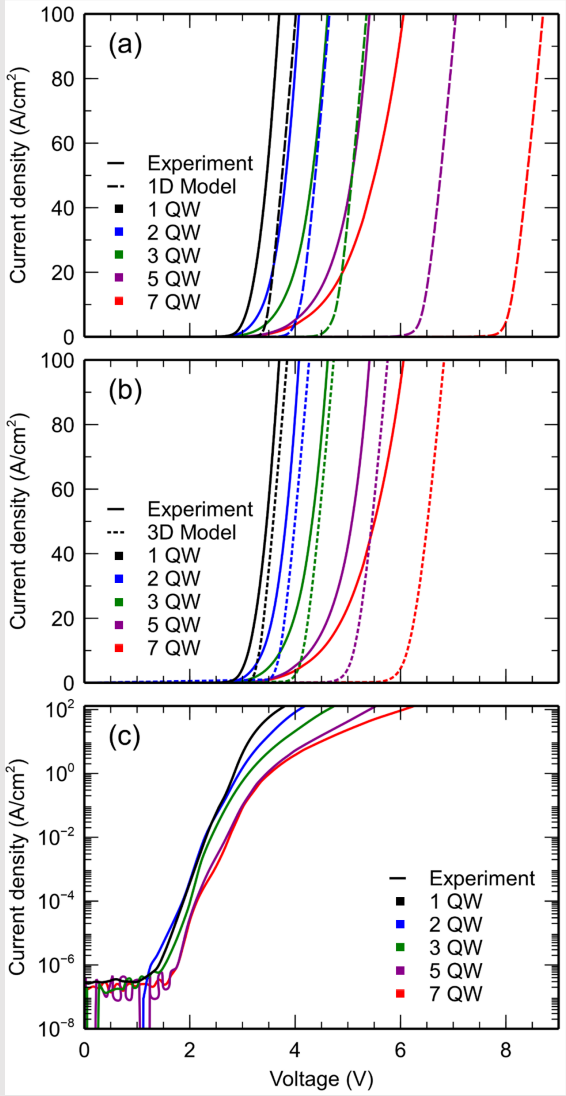
Project outcomes: origin of excess voltage in green LEDs

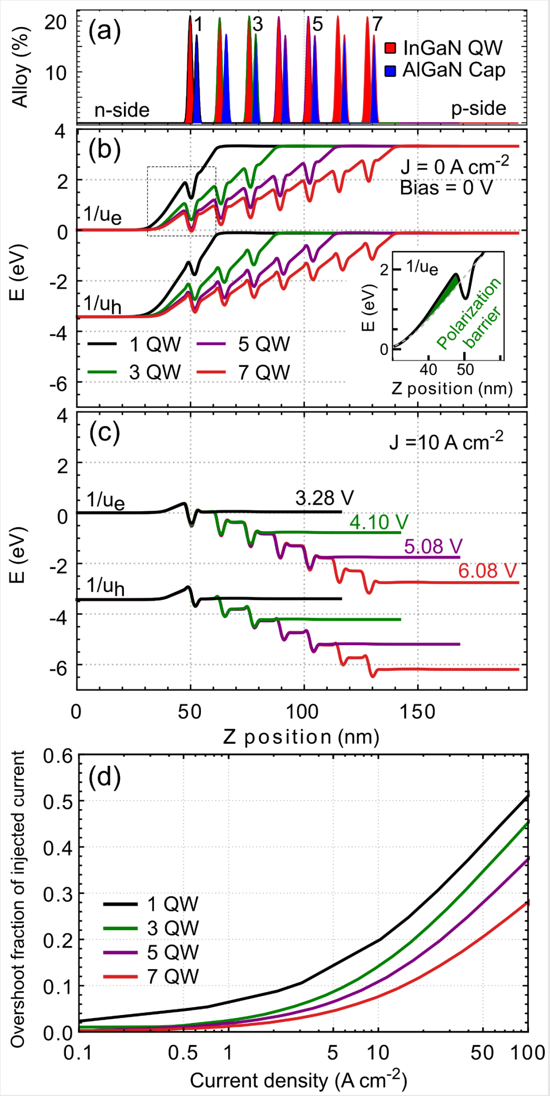
Green LEDs with varying QW number → increase in V_F with each additional QW

Simulations based on landscape theory to account for alloy disorder

Agreement between experiment and 3D simulations without adjusting polarization parameters

Polarization induced barriers at the GaN/InGaN (lower barrier/QW) interfaces contribute to large ΔV_F in MQW green LEDs





C. Lynsky, *et al.*, Phys. Rev. Materials **4**, 054604 (2020).

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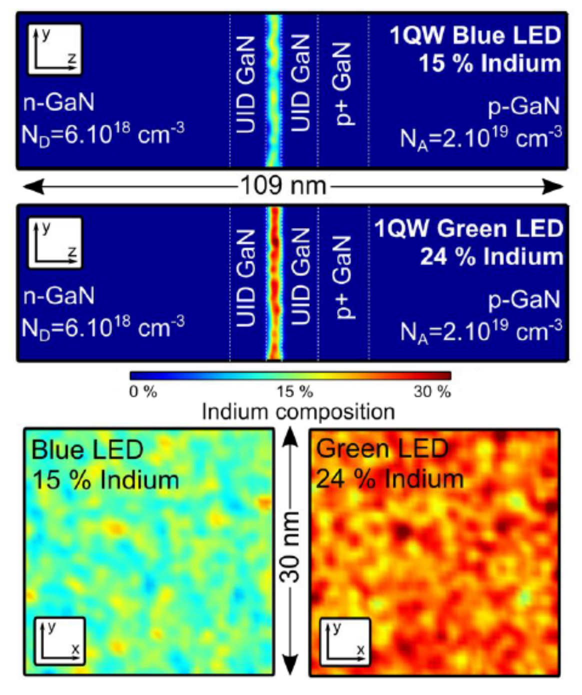
Project outcomes: origin of excess voltage in green LEDs

3D simulations based on landscape theory to account for alloy disorder

Compared blue and green LEDs with either 1 or 5 QWs

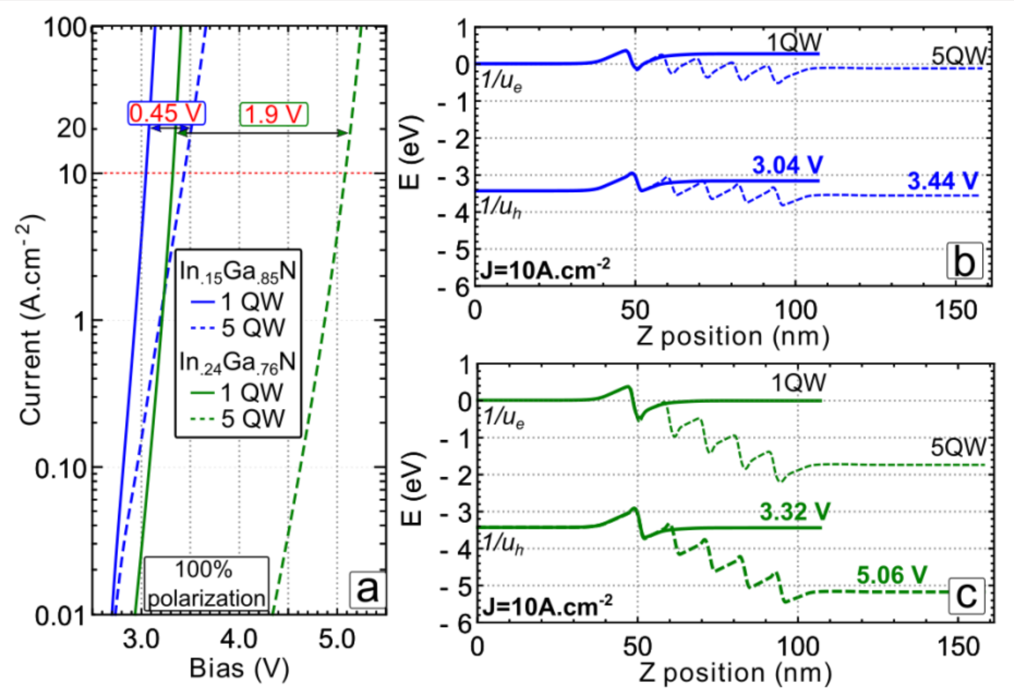
Simulated 1.9 V penalty at 10 A cm^{-2} going from 1 QW to 5 QW for green LEDs

Simulated 0.45 V penalty at 10 A cm^{-2} going from 1 QW to 5 QW for blue LEDs



G. Lheureux, *et al*., J. Appl. Phys. **128**, 235703 (2020).

100% Polarization



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Project outcomes: origin of excess voltage in green LEDs

Higher avg. carrier density, radiative recombination rate in top QW compared to deeper QWs

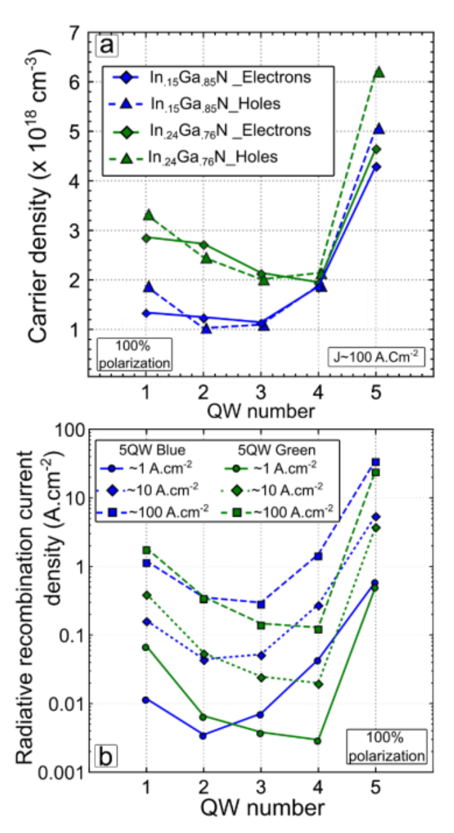
Artificially set piezoelectric and spontaneous polarization values to 0%

At 0% pol. very small penalty for blue LEDs, still large penalty for green LEDs from 1 to 5 QWs

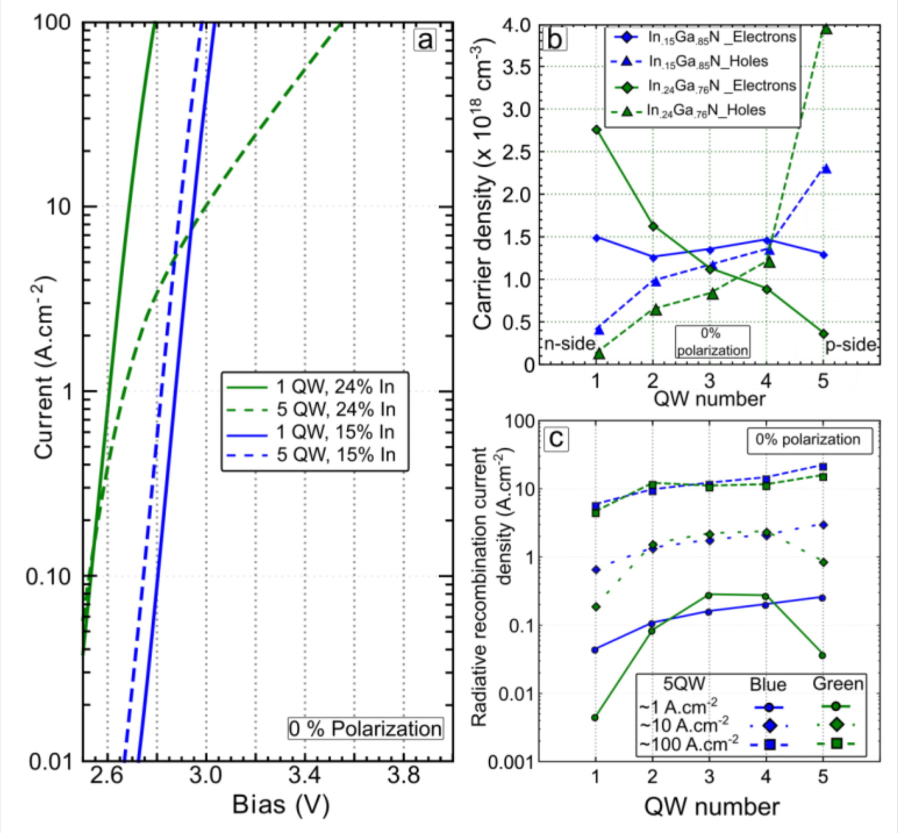
For green LED, extreme QWs have highly unbalanced carrier densities, leads to central QW having highest R_{rad} at low J

Evidence of sequential injection of carriers due to large band offsets present in green LEDs, also contributes to large ΔV_F

100% Polarization



0% Polarization

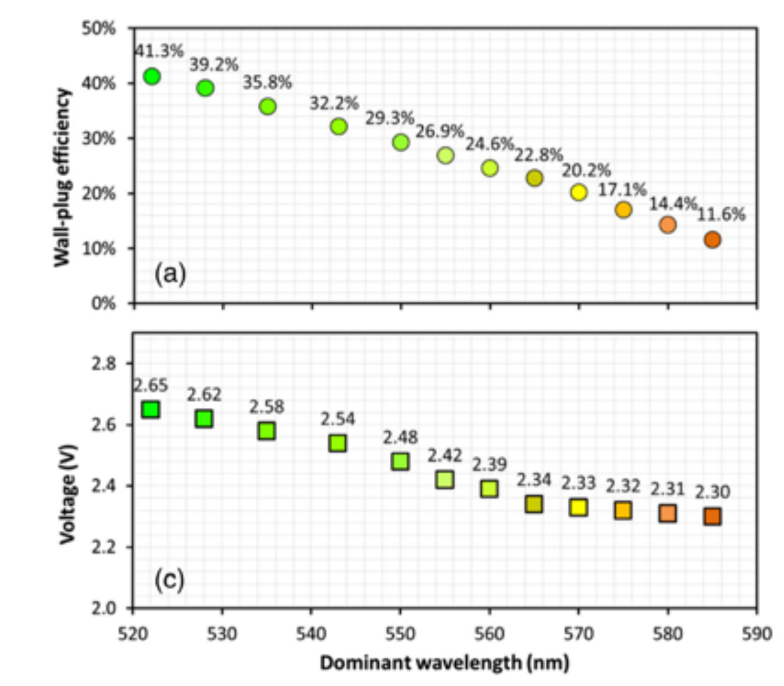


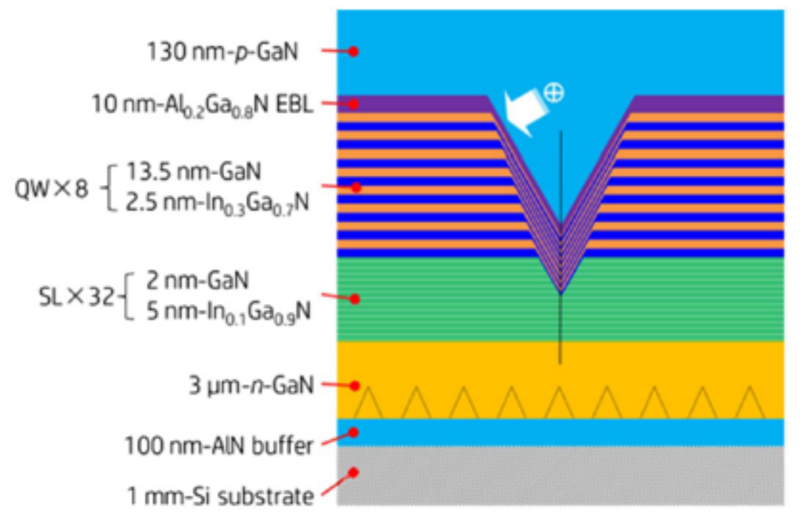
G. Lheureux, *et al*., J. Appl. Phys. **128**, 235703 (2020).

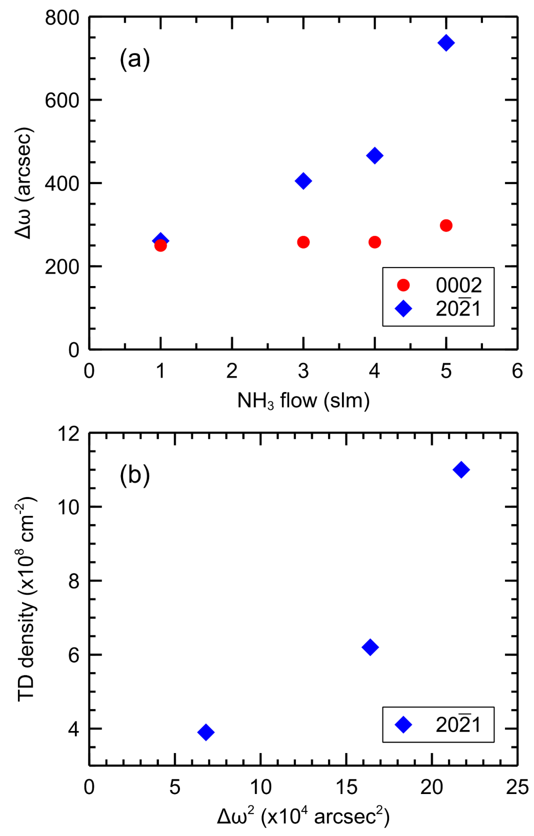
Project outcomes: V-defect engineering

- Demonstrated from 522–621 nm for GaN on Si
- Attribute low V_F to V-defects from superlattice
- Semipolar sidewall QWs → low polarization barrier
- Improved hole injection into deeper QWs

- UCSB approach: V-defect engineering on sapphire
- Difference between GaN on Si and GaN on sapphire is threading dislocation and V-defect density
- *Increase* TD, V-defect density by increasing NH_3 flow



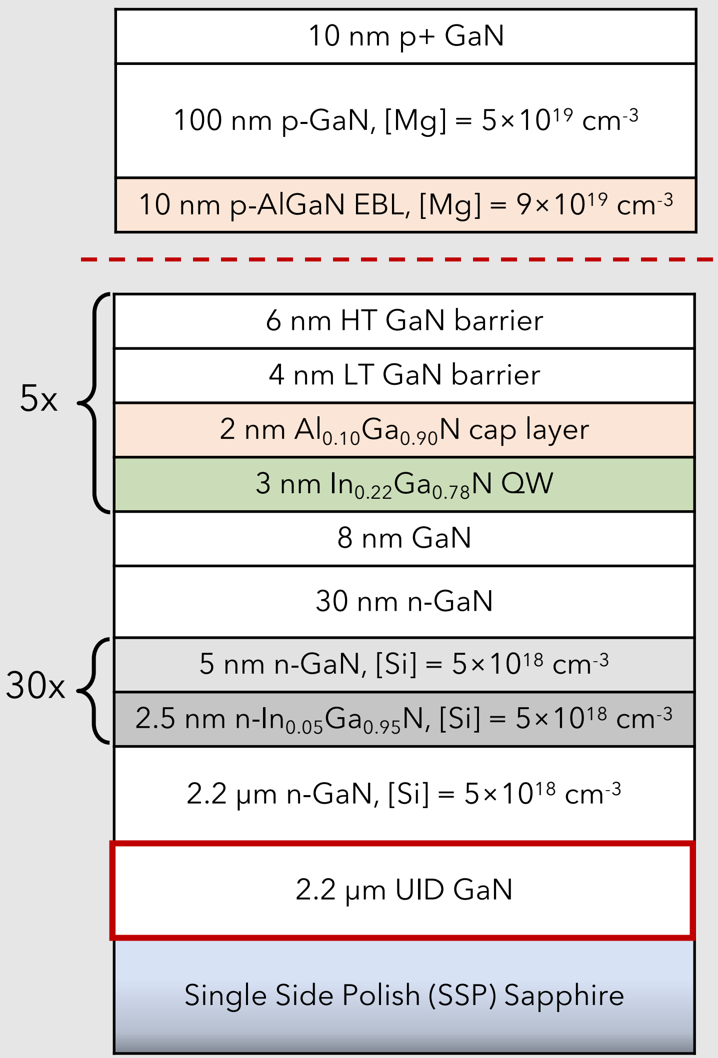




F. Jiang, *et al.*, Photonics Res. **7**, 144 (2019).

C. Lynsky, *et al.*, J. Cryst. Growth, *Accepted* (2020).

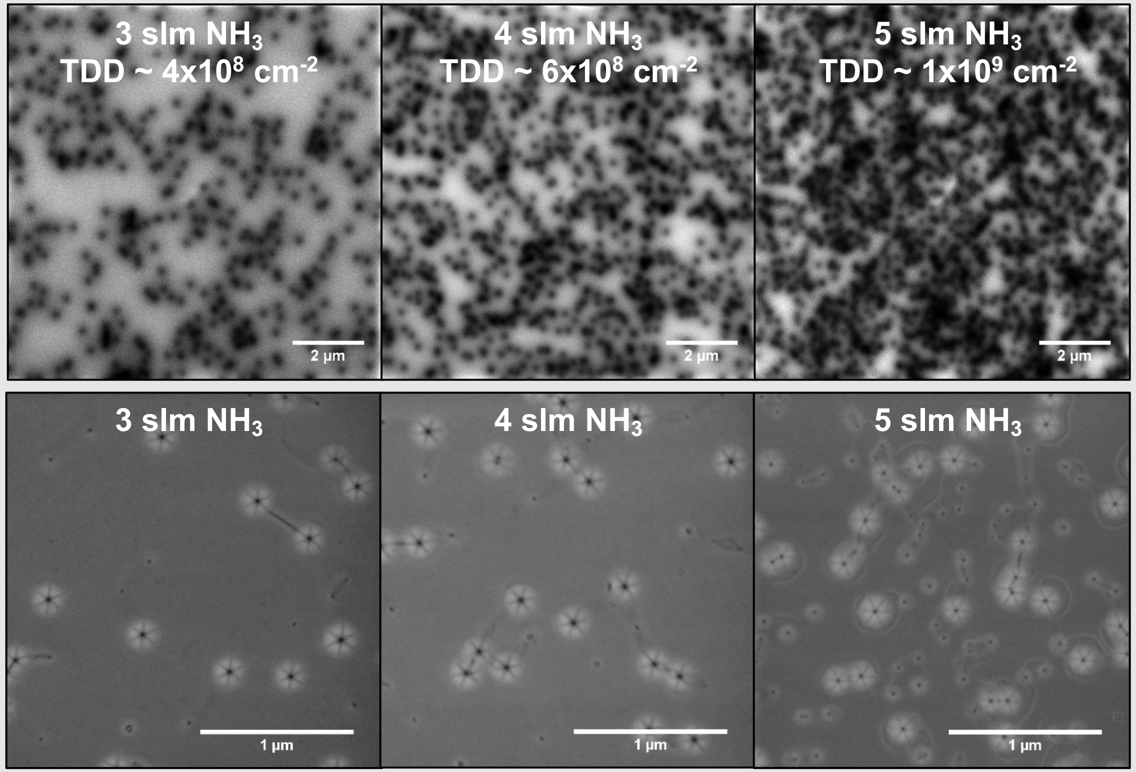
Project outcomes: V-defect engineering



Panchromatic cathodoluminescence shows increase in TDD from ~4x10^8 to ~1x10^9 cm^{-2}

Interrupt growth after last QB to characterize surface

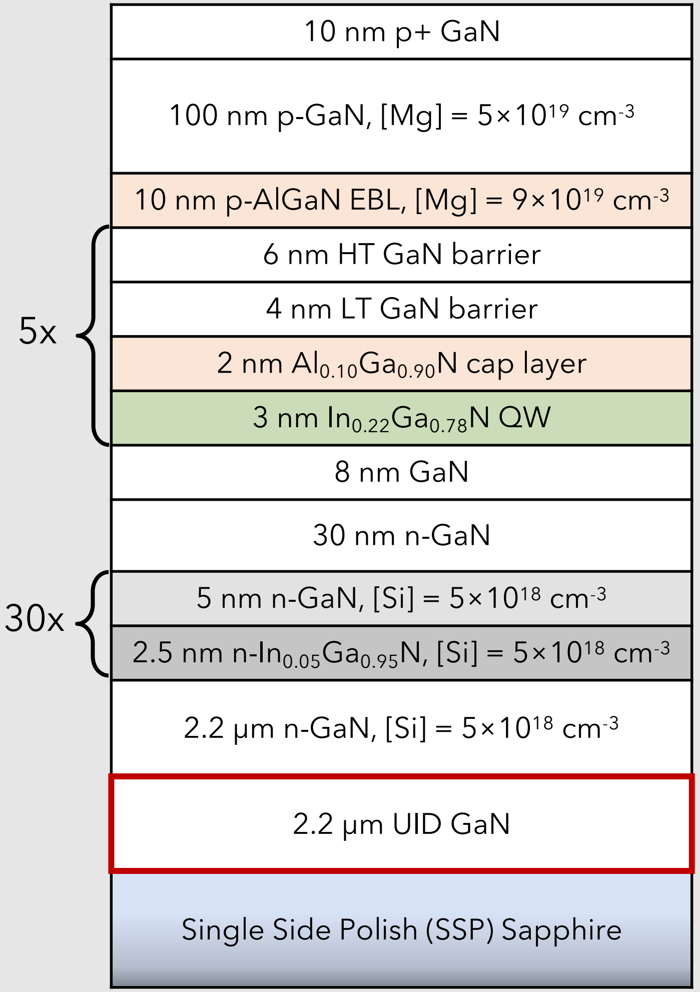
3 samples grown with either 3, 4, or 5 slm NH_3 flow during the temperature ramp and HT UID GaN



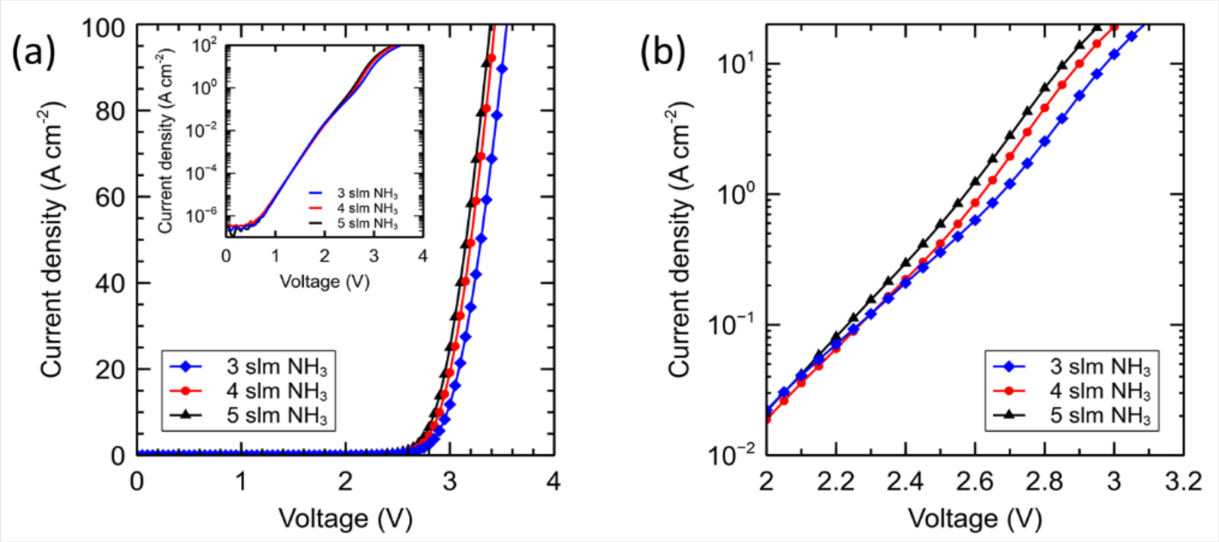
NH_3 flow (slm)	Avg size large defects (nm)	Density large defects (cm^{-2})	Density small defects (cm^{-2})	Total defect density (cm^{-2})
3	184 ± 15	1.95×10^8	2.18×10^8	4.13×10^8
4	206 ± 17	2.64×10^8	3.56×10^8	6.19×10^8
5	174 ± 27	5.05×10^8	1.16×10^9	1.66×10^9
		2.6x increase	5.3x increase	4x increase

C. Lynsky, *et al.*, J. Cryst. Growth, *Accepted* (2020).

Project outcomes: V-defect engineering



3 LEDs grown with either 3, 4, or 5 slm NH_3 flow during the temperature ramp and HT UID GaN



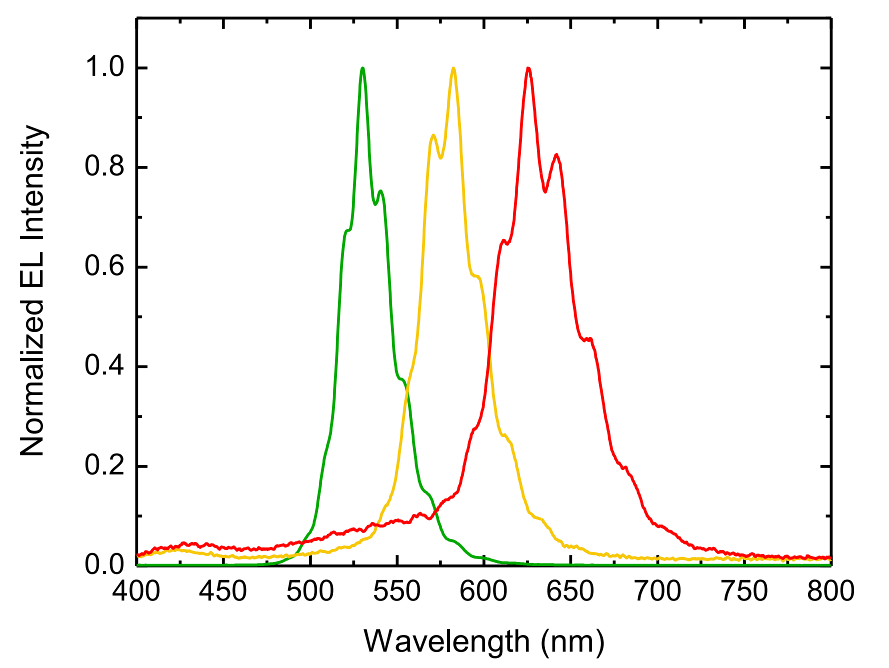
NH_3 flow (slm)	Voltage (V)	Power (mW)	Peak wavelength (nm)	FWHM (nm)
3	3.07	0.53	516.3	25.9
4	3.02	0.50	521.1	28.2
5	2.94	0.43	522.6	31.8

C. Lynsky, *et al.*, J. Cryst. Growth, *Accepted* (2020).

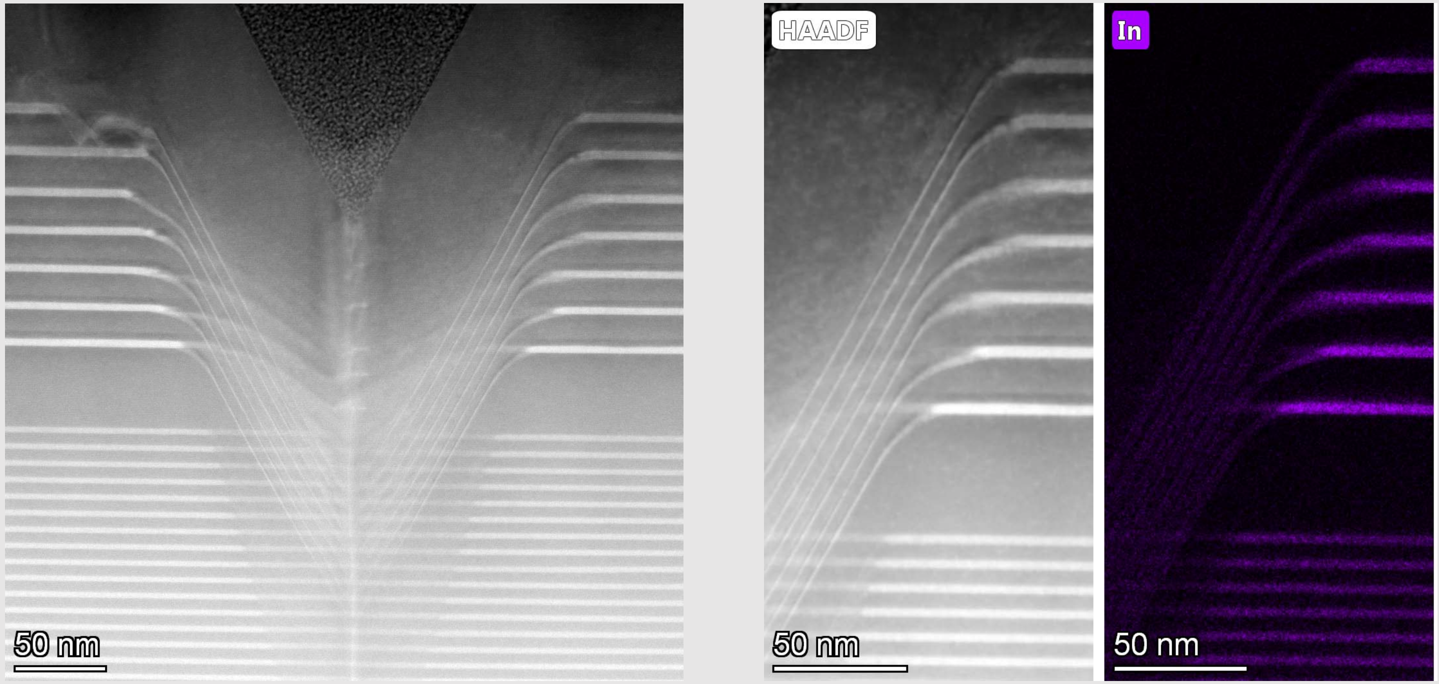
Recent and future work

Exploring V-defect engineering for long wavelength LEDs (λ = 525 – 625 nm) on sapphire and silicon substrates

Combining experimental, advanced characterization, and 3D simulations methods to realize high WPE long wavelength LEDs with reduced current droop



Electroluminescence spectra at 5 mA of green to red LEDs grown at UCSB



TEM and EDX of 7 QW red LED with engineered V-defect

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Thank you