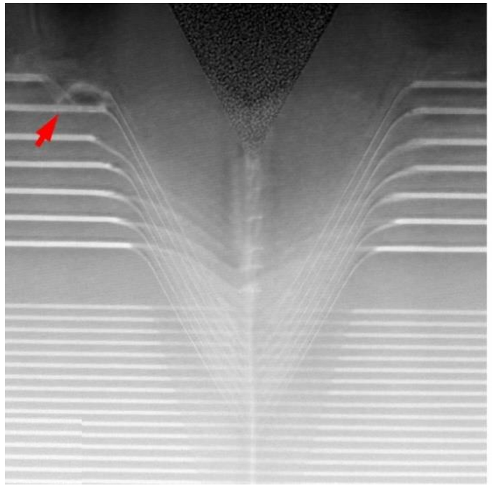
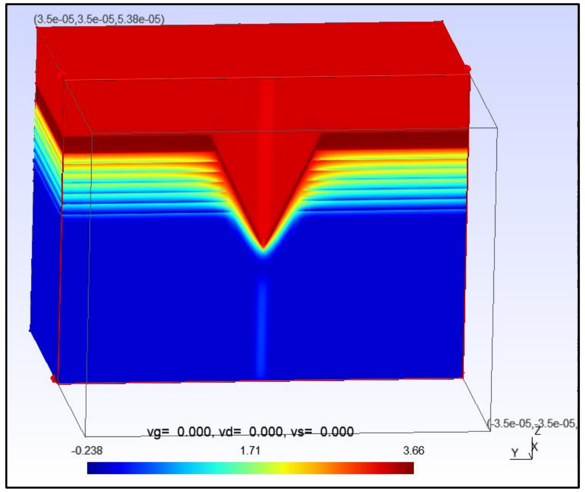
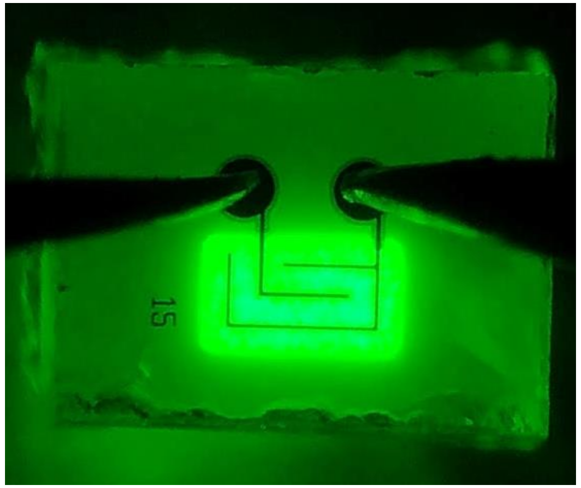
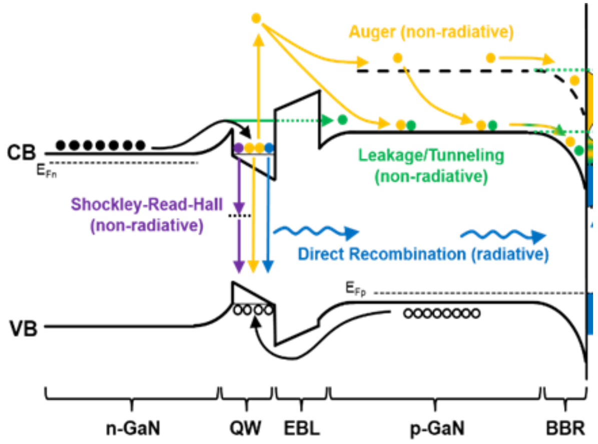
Solutions to Droop and the Green Gap by Novel Carrier Injection









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DOE BENEFIT - EE0009691

Team

Prof. James Speck

Prof. Steven DenBaars

Prof. Shuji Nakamura

Prof. Claude Weisbuch

Dr. Feng Wu

Jacob Ewing

Dr. Yi Chao Chow

Dr. Wan Ying Ho

Dr. Kai Shek Qwah

Alejandro Quevedo

Tanay Tak

Project Summary

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Objective and Outcome

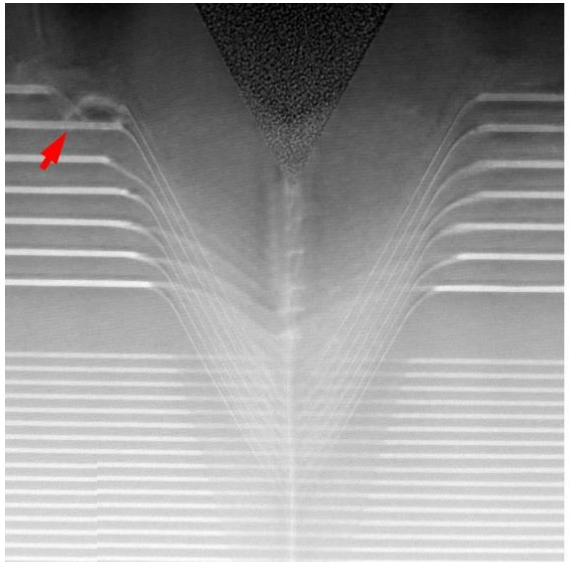
* Low voltage long wavelength III-nitride LEDs via lateral carrier injection

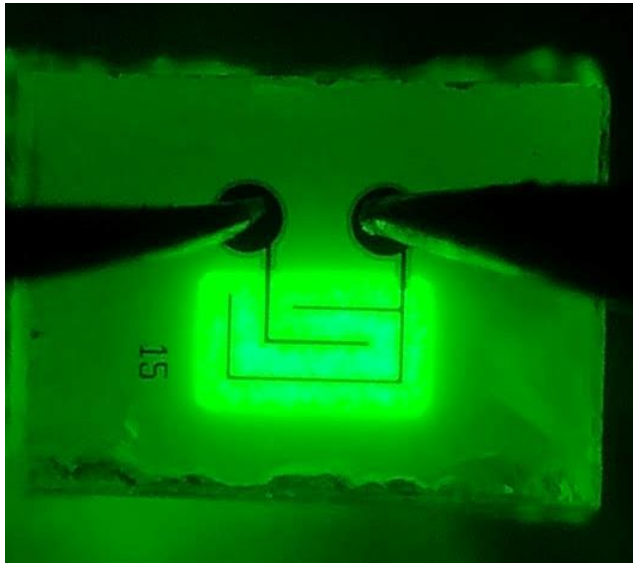
V-defect engineering

Lateral injectors

* Electrical droop improvement via volumetric injection

* Achieve DOE SSL 2025 goals for Blue, Green, Yellow LEDs at all current densities





Team and Partners

Lead-PI: James Speck

Co-PIs: Steve DenBaars, Shuji Nakamura, Claude Weisbuch

UCSB team: Feng Wu, Jake Ewing, Wan Ying Ho, Yi Chao Chow, Kai Shek Qwah, Alejandro Quevedo, Tanay Tak

Stats

Performance Period: 10/01/21-09/30/24

DOE budget: $2,326k, Cost Share: $653k

Milestone 1: Advanced device simulations✓

Milestone 2: Voltage reduction – in progress

Milestone 3: Meet/exceed DOE SSL 2025 goals

Alignment and Impact of Solid-State Lighting

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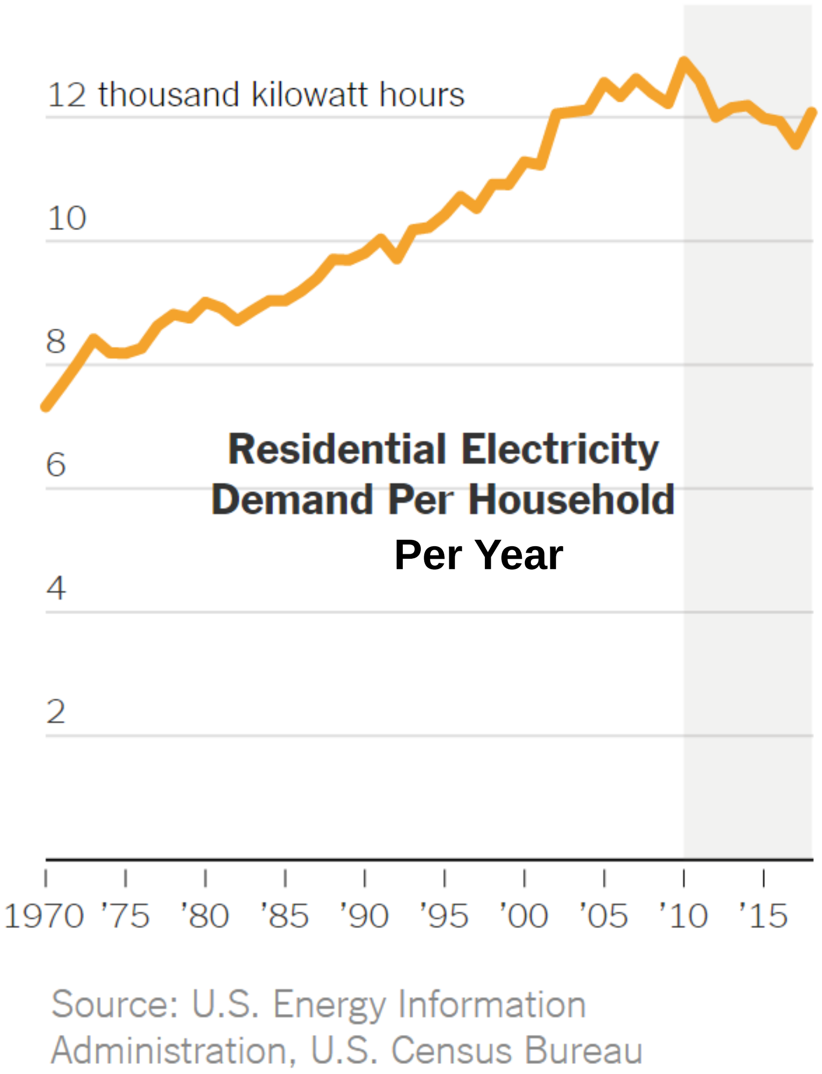

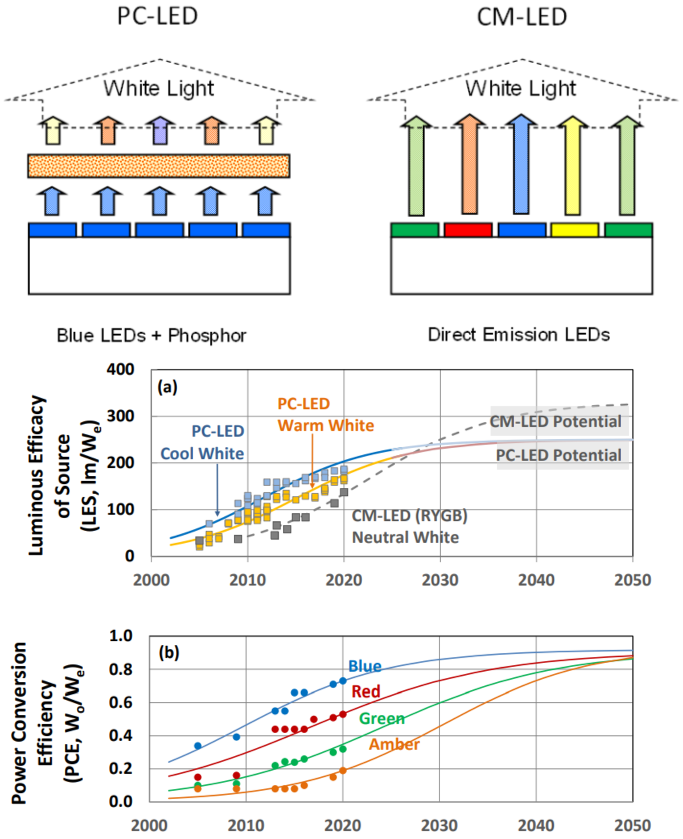

- Color mixed LEDs can exceed the current phosphor-based approaches

- Requires high efficiencies at long-wavelengths

America's Light Bulb Revolution, New York Times, 2019 https://www.nytimes.com/interactive/2019/03/08/climate/light-bulb-efficiency.html
2022 DOE SSL R&D Opportunities https://www.energy.gov/sites/default/files/2022-02/2022-ssl-rd-opportunities.pdf

Wall Plug Efficiency is Everything!

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$$\eta_{WPE} = \eta_{LEE} \cdot \eta_{IQE} \cdot \eta_{EE}$$

Light Extraction Efficiency

$$\text{LEE} = \frac{\text{\# of photons emitted from device}}{\text{\# of photons emitted from QWs}}$$

~85% on Patterned Sapphire Substrates (PSS)

Much less on other substrates

Need to use PSS

Internal Quantum Efficiency

$$\text{IQE} = \frac{\text{\# of carriers that lead to light}}{\text{total carriers injected}}$$

Determined by material quality and epitaxial design

Increasing IQE is a primary topic of our research

Electrical Efficiency

$$\text{EE} = \frac{V_{photon}}{V_{Forward}} = \frac{\left(\frac{hc}{q\lambda}\right)}{V_F}$$

Reducing the forward voltage is a primary topic of our research

Wall Plug Efficiency and V-Defects

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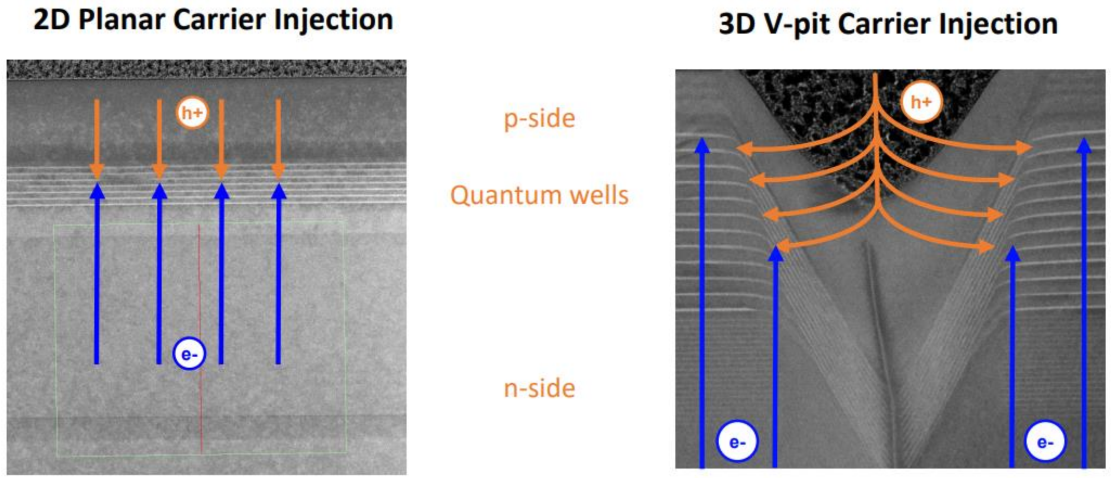
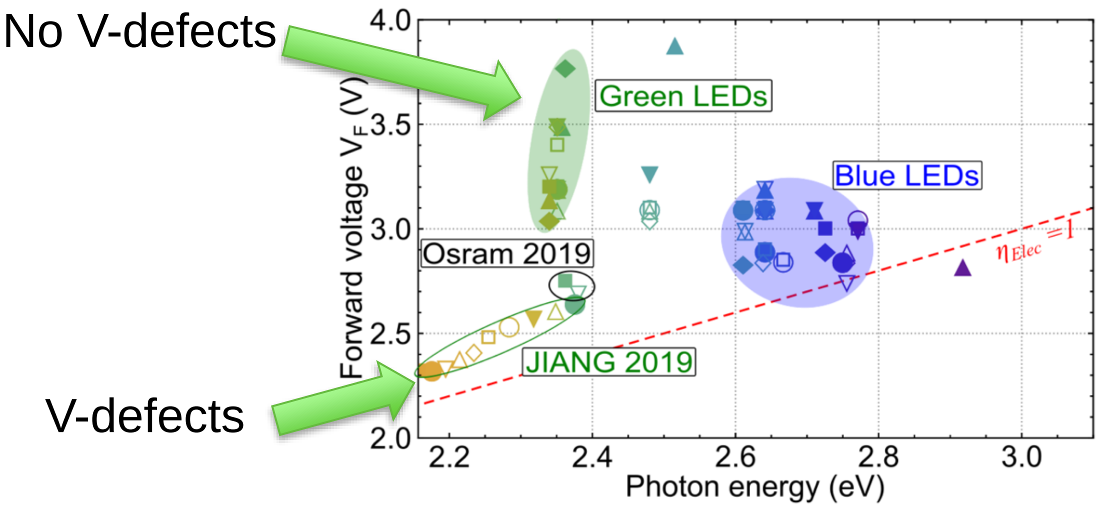
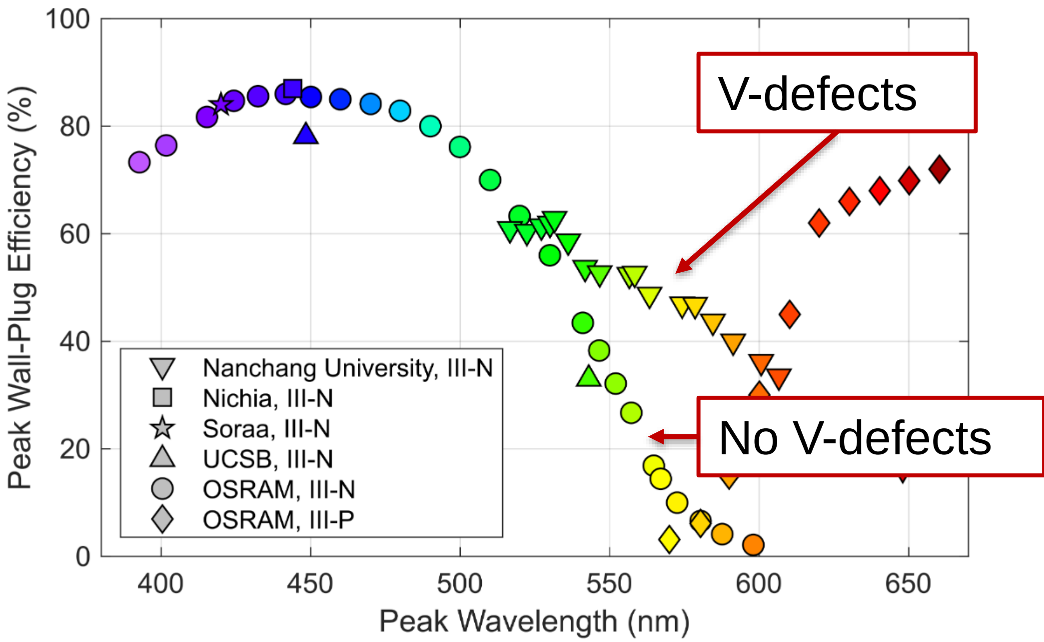
- Large polarization barriers in green and yellow contribute to excess voltage and reduced WPE
- Novel carrier injection with V-defects has shown promise in mitigating these effects



Our group has extensively simulated V-defects and understood their impact





C.K. Li, … Y.R. Wu, AIP Adv. **6**, 055208 (2016)
G. Lheureux, C. Lynsky, *et al*., J. Appl. Phys. **128**, 235703 (2020)
C.H. Ho, J.S. Speck, C. Weisbuch, Y.R. Wu, Phy. Rev. Applied. **17**, 014033 (2022)

Project Goals, Technical Challenges and Mitigation Strategies

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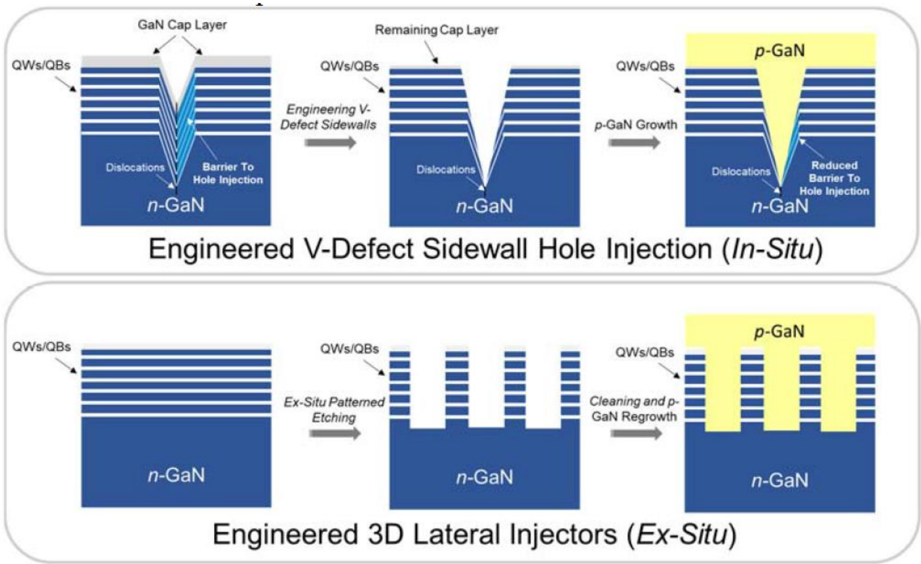
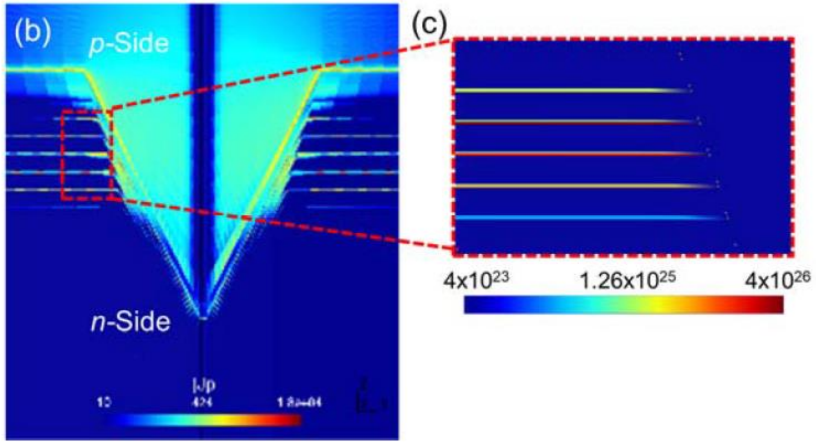
- Project Goal: Improve WPE of green and yellow LEDs through novel carrier injection

- Technical Challenges:
  - Achieving high V-defect density on PSS
    - Nanchang V-defect LED results are on Si
    - PSS offers better light extraction, compressive stress and simpler fabrication
  - Growth optimization with high V-defect density

- Mitigation Strategies
  - Ex-situ etching of trenches or pits for lateral injection
  - Cascaded TJ LEDs
  - Field screened QWs





C.H. Ho, J.S. Speck, C. Weisbuch, Y.R. Wu, Phy. Rev. Applied. **17**, 014033 (2022)
2196-1510 UCSB Technical Volume, DOE BENEFIT Project Proposal

The UCSB Approach to V-Defect Engineered LEDs

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Substrates are very important!

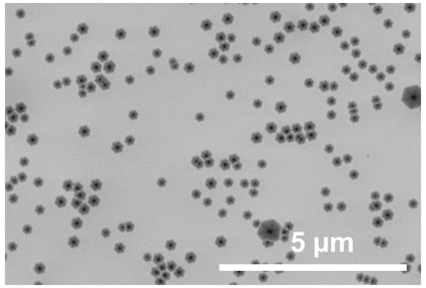
Nanchang V-defect LEDs are on Si

- Expensive for LEDs
- Requires flip-chip processing
- Easier to form V-defects

Patterned Sapphire is primarily used in the LED industry

- Better light extraction
- Cheaper
- Simpler epitaxial growth

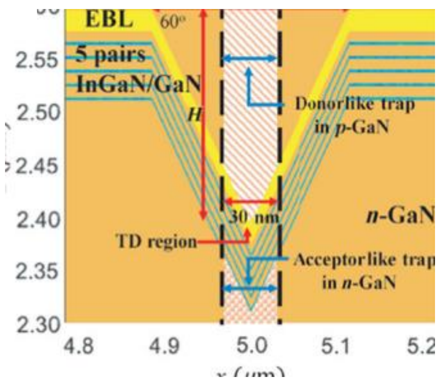
We’ve demonstrated methods for improving V-defect density on PSS

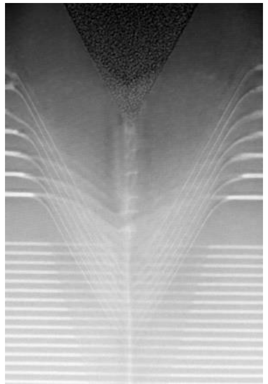


World-class understanding of V-defects through simulations and microscopy

DOE supported simulation work that advances the theoretical understanding of V-defects

DOE supported experimental work on the structure of V-defects and their formation in epitaxial films



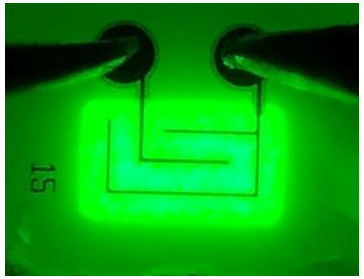


World-class epitaxial capabilities to grow and fabricate LEDs

On-going epitaxial development

- Improving material quality with high In%
- Reducing forward voltage through V-defect engineering
- Managing morphology, excess voltage, non-radiative recombination

We’ve already demonstrated high IQE in green, yellow, and red LEDs



Advanced V-Defect Modeling with Alloy Fluctuations

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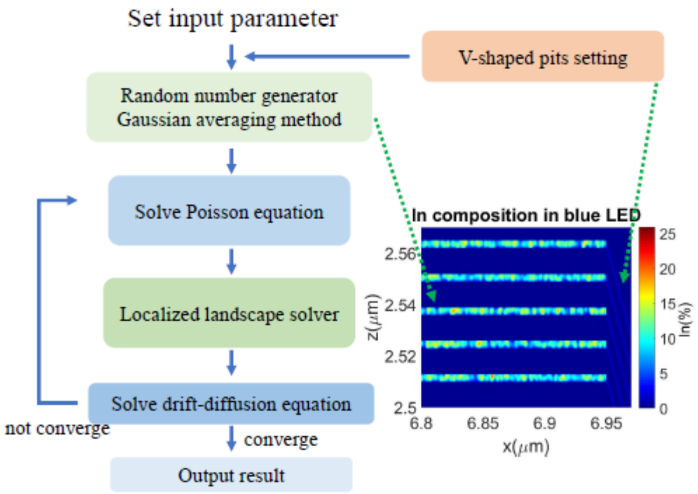

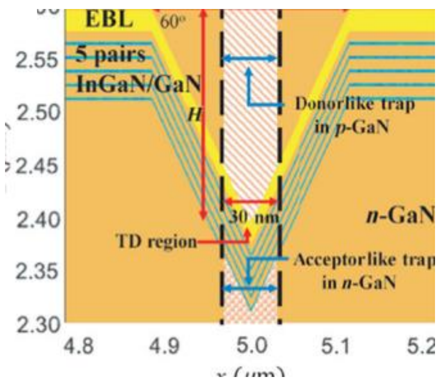

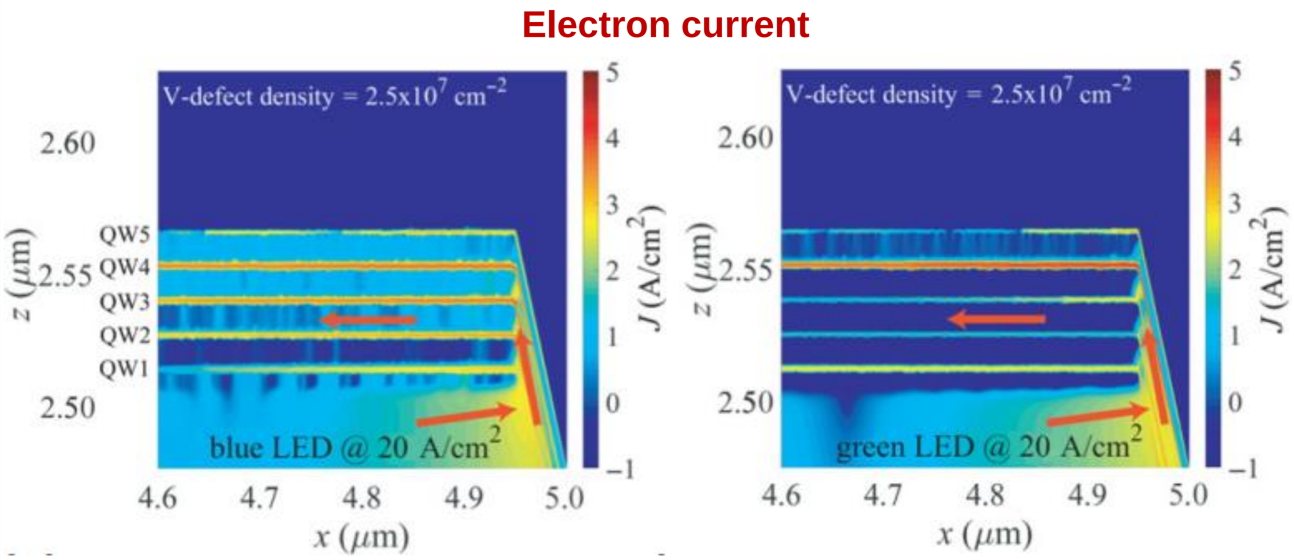

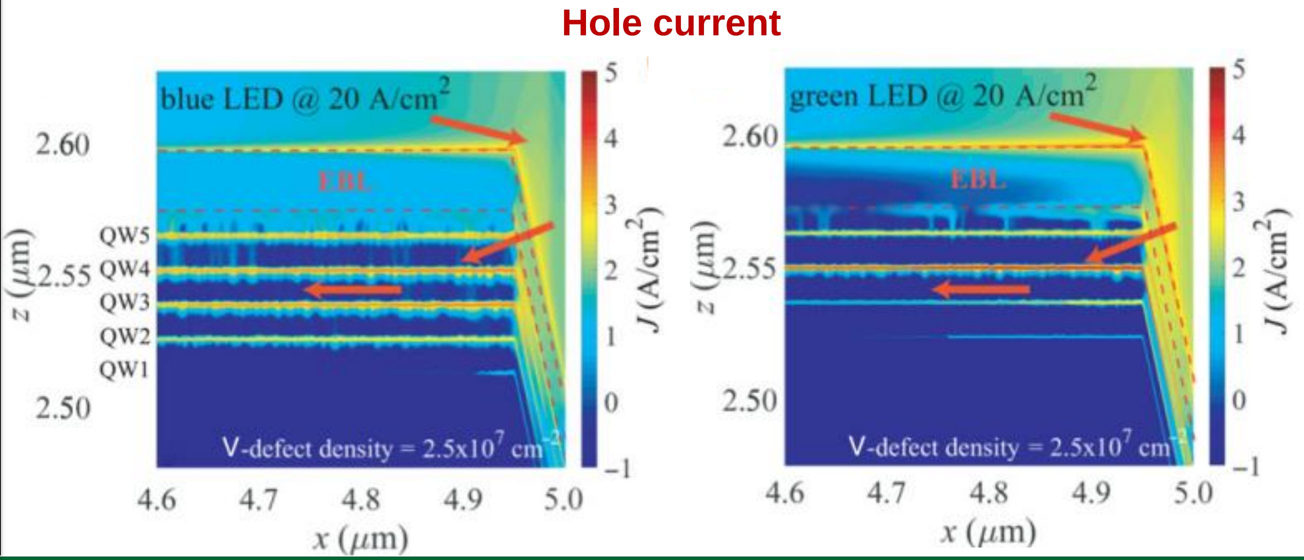

- **2D simulations (with alloy disorder)**
  - Holes are injected through the sidewall of LED into QW
  - Electrons flow up sidewall into QW

C.H. Ho, J.S. Speck, C. Weisbuch, Y.R. Wu, Phy. Rev. Applied. **17**, 014033 (2022)

V-Defect Optimization via Advanced Simulations

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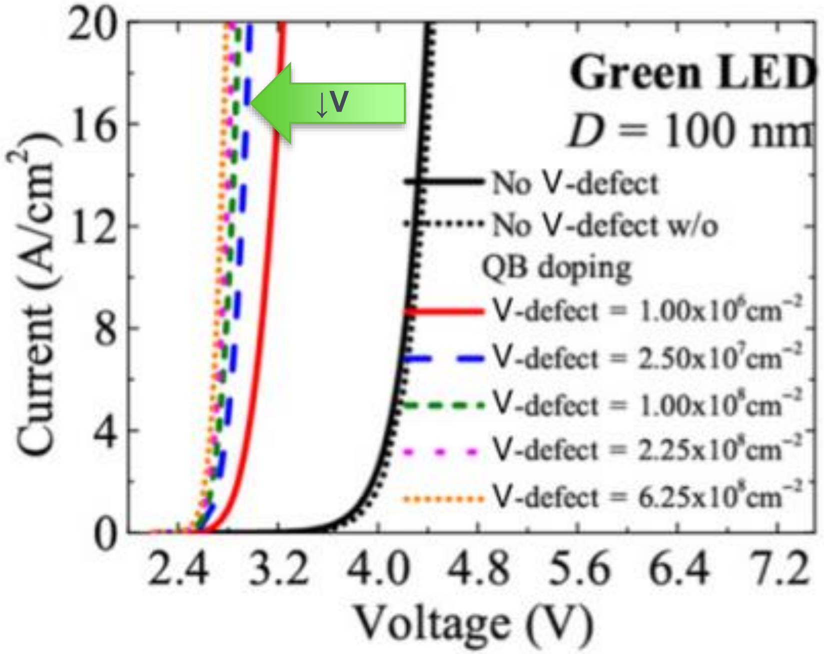


Higher V-defect densities lead to lower voltage

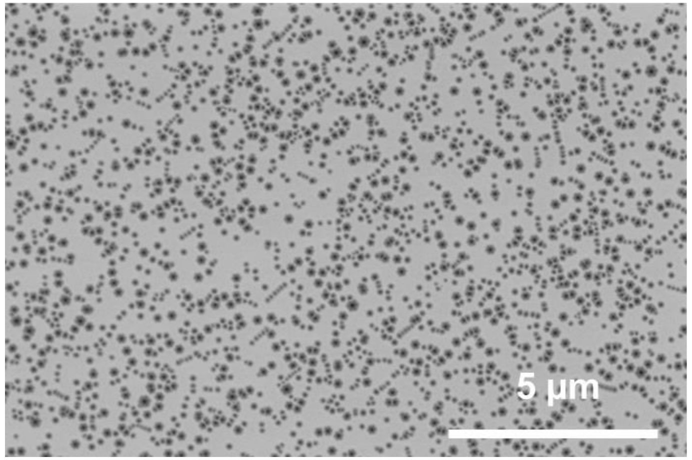
V-defect density has a significant effect on voltage

No V-defects → 1 × 10^6 cm^{-2}: **1.2 V decrease**

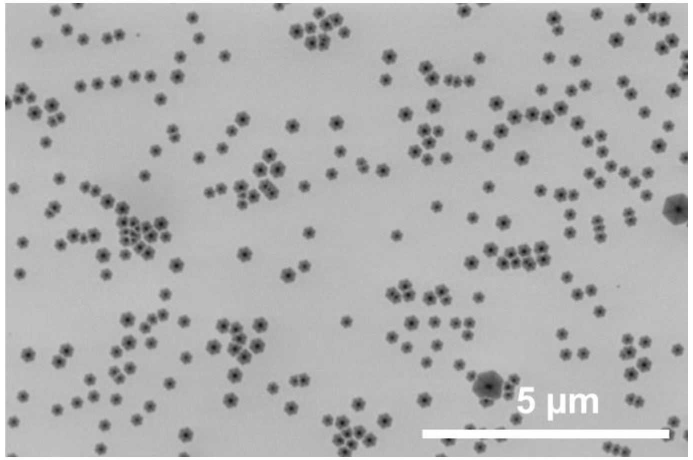
1 × 10^6 cm^{-2} → 6.25 × 10^8 cm^{-2}: **0.4 V decrease**

Simulations show a significant relationship between V-defect density and voltage

FSS: 1.5 × 10^9 cm^{-2}



PSS: 2 × 10^8 cm^{-2}



Experimental V-defect densities on FSS and PSS

V-Defects: Good and Bad!

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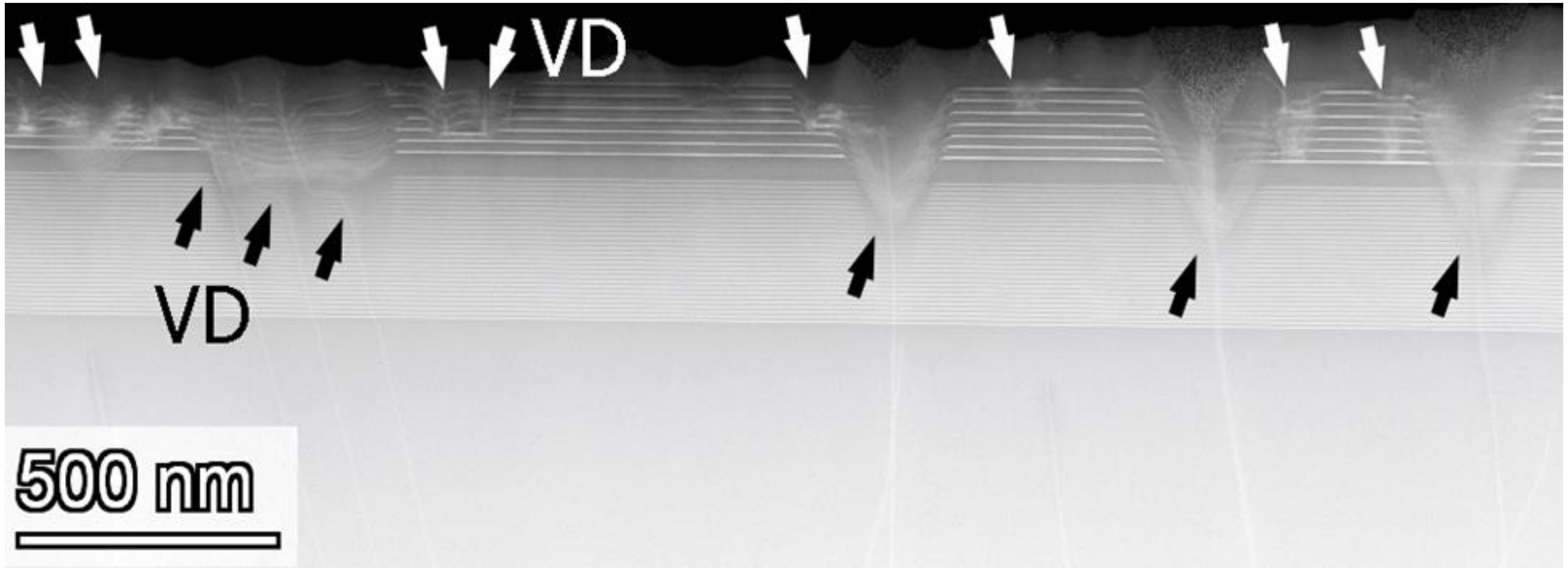
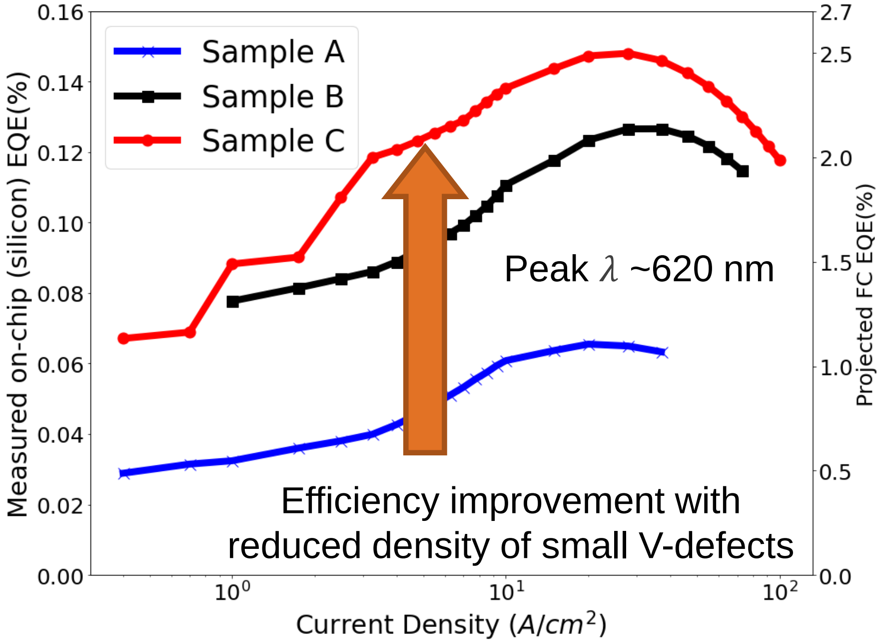
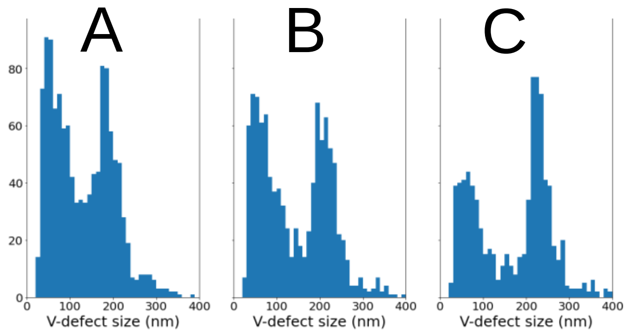




TEM studies identified two distinct types of V-defects

- **Large V-defects (black arrows)**
  - Enable semipolar-sidewall-assisted hole injection
  - Increase LED efficiency and reduce voltage
- **Small V-defects (white arrows)**
  - Shockley-Read Hall (SRH) and Trap-Assisted Auger Recombination (TAAR) centers
  - Deleterious to device performance



F. Wu, et al., J Appl Phys **035703**, (2023)
J. Ewing et al., Crystals (Basel) **12**, (2022)

Compositional Analysis of V-defects

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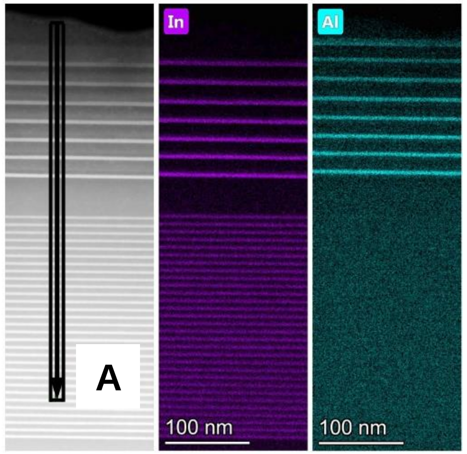
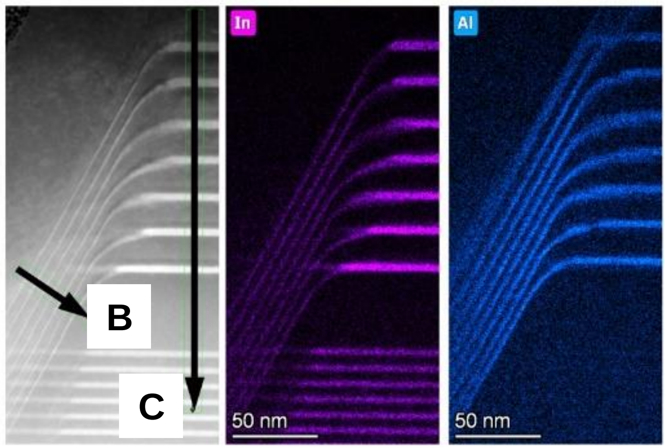
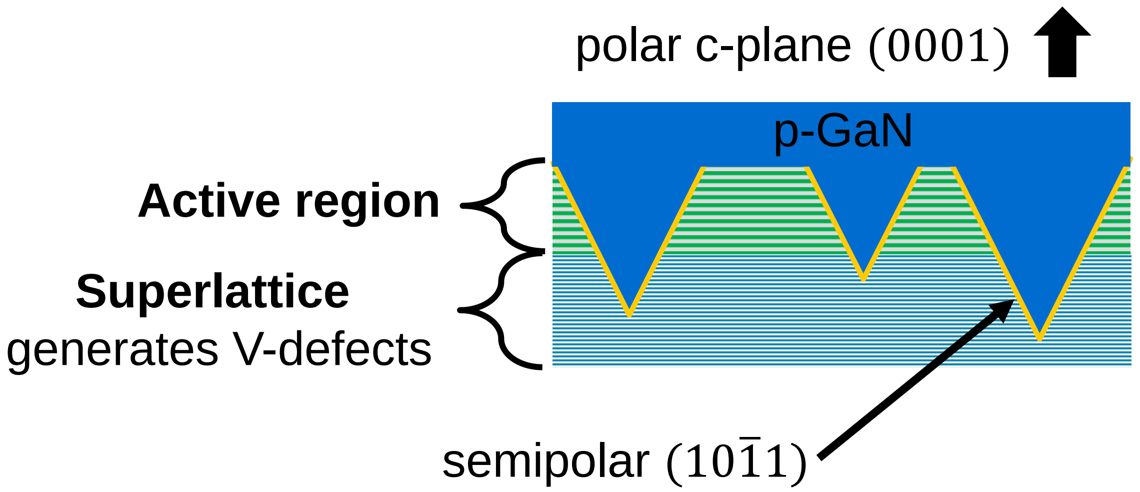
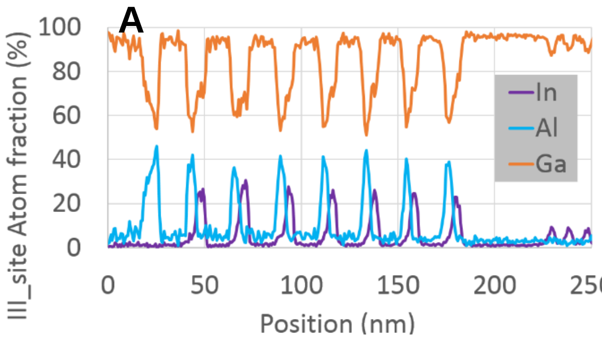
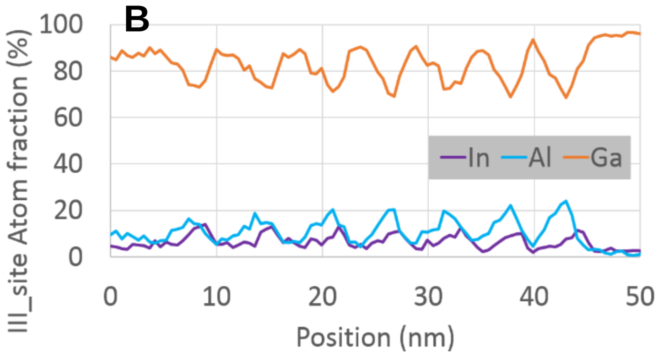
- Growth rate is significantly different on c-plane compared to semipolar
  - This allows us to open V-defects under appropriate growth conditions

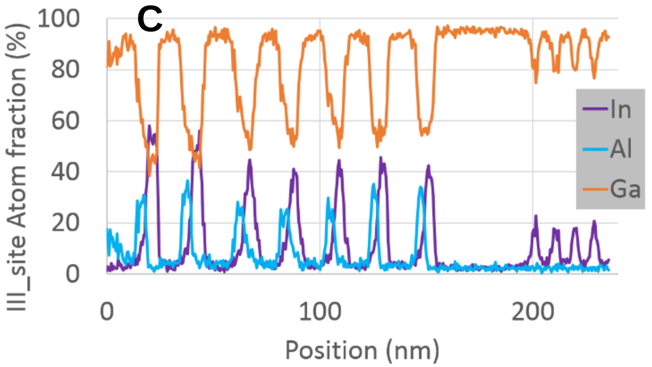










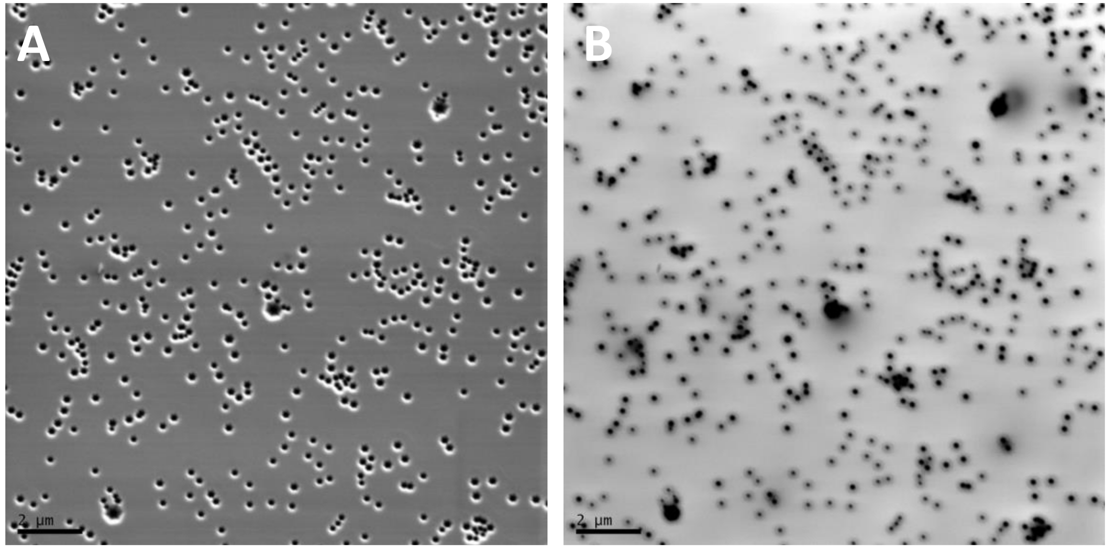


F. Wu, et al., J Appl Phys **035703**, (2023)

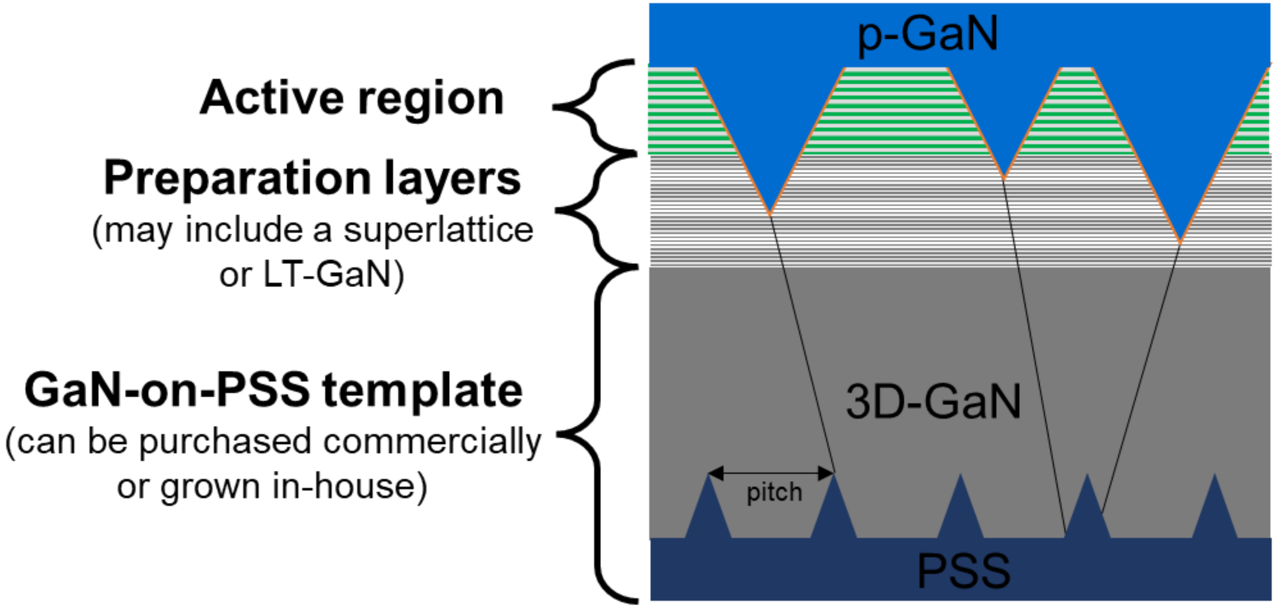
V-Defect Nucleation

- We’ve developed a growth process for nucleating V-defects on existing threading dislocations using low temperature GaN

- We demonstrated ~100% of TDs nucleate V-defects



(a) SEM image showing V-defects (b) Cathodoluminescence image showing threading dislocations



Controlling Internal Field in Thick QW LEDs with Doped Barriers

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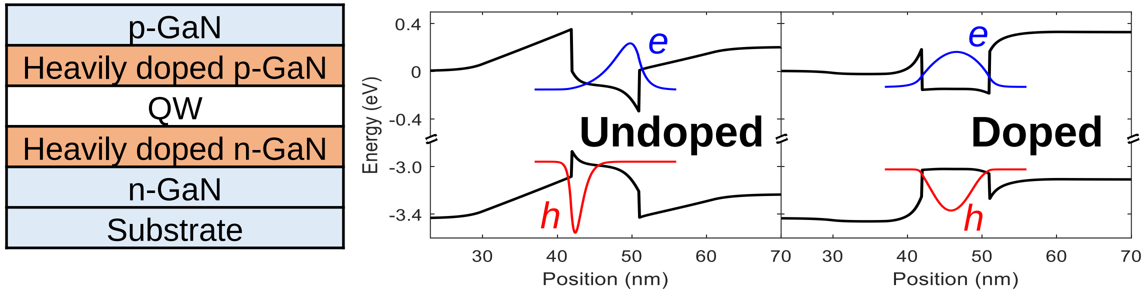
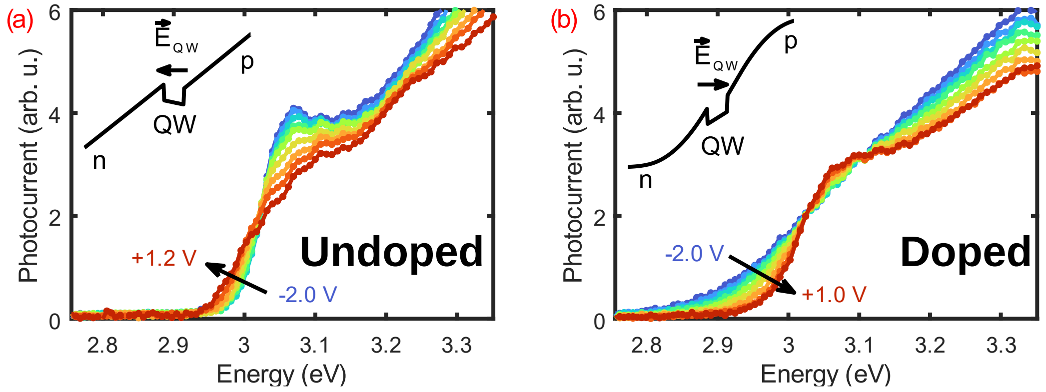
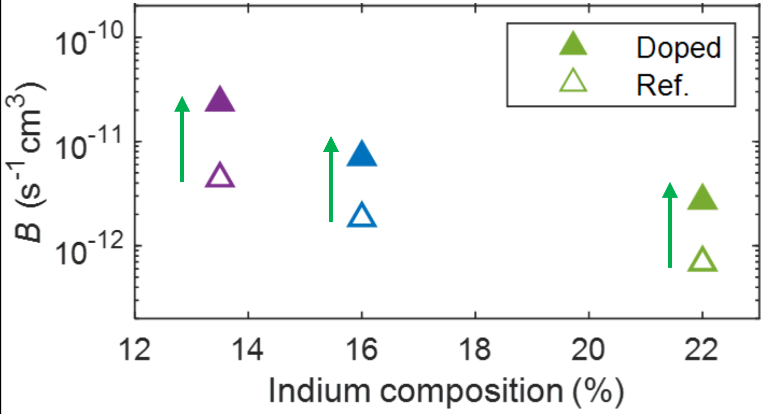
Objective: Improve efficiency droop performance by reducing internal electric fields in *c*-plane **thick quantum well** LEDs by using **doped barriers**

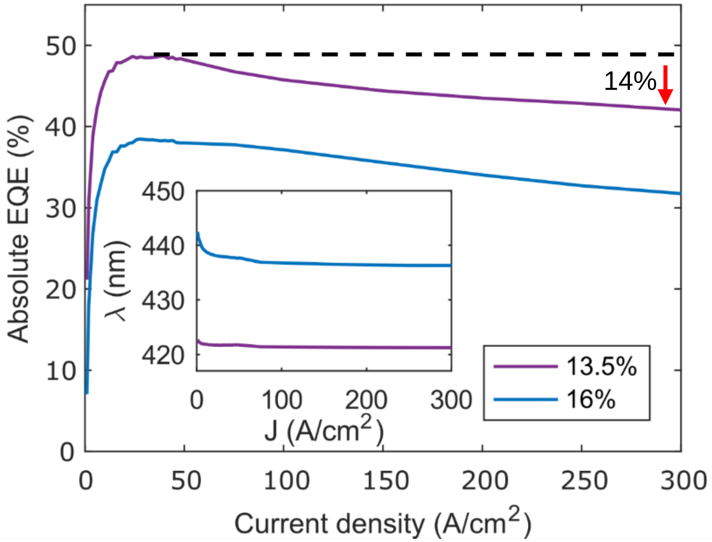


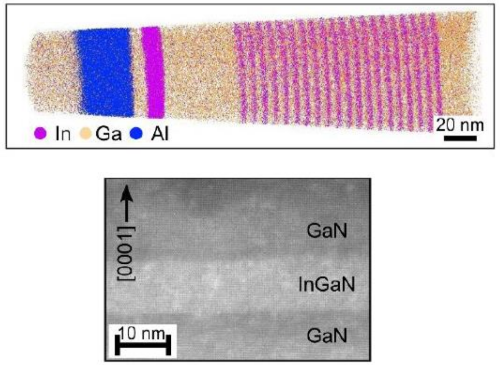


Biased photocurrent spectroscopy showed Doped barriers → Reduction in internal electric field



Differential carrier lifetime measurements showed Doped barriers → Enhanced recombination coefficients (improvement of e-h overlap)

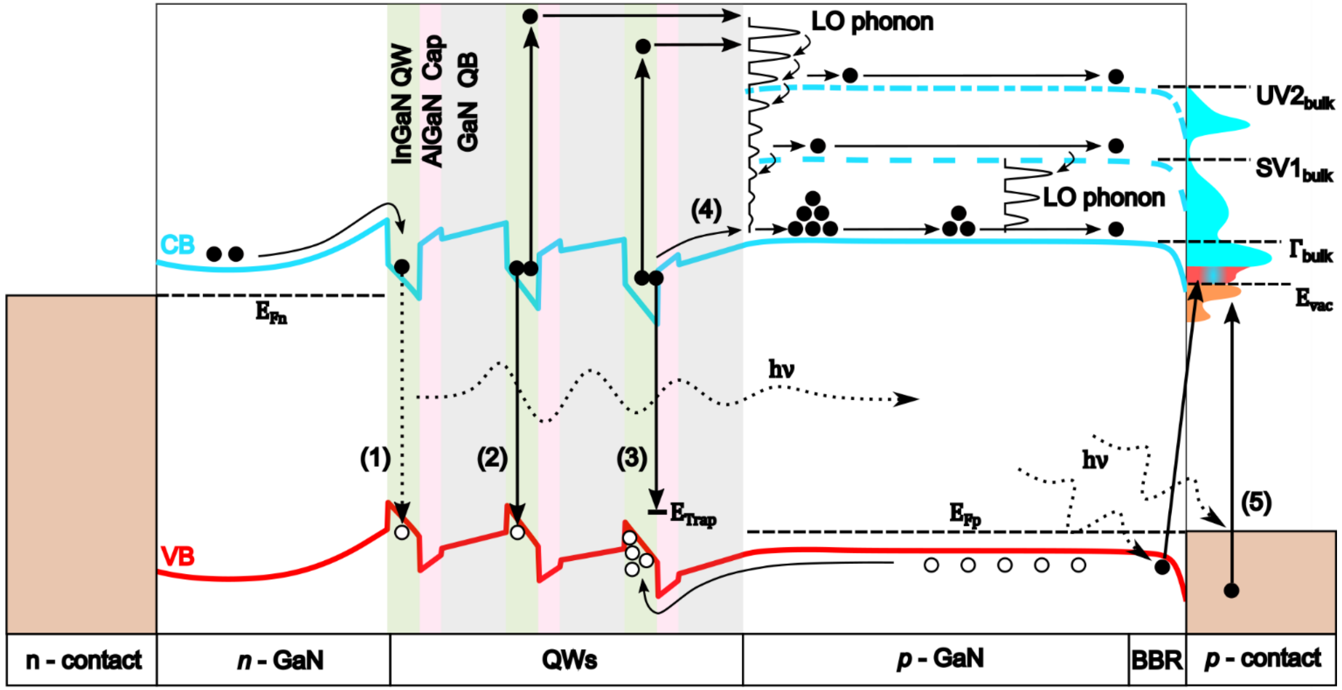




Achieved low-efficiency-droop thick QW LEDs with optimized doped barriers

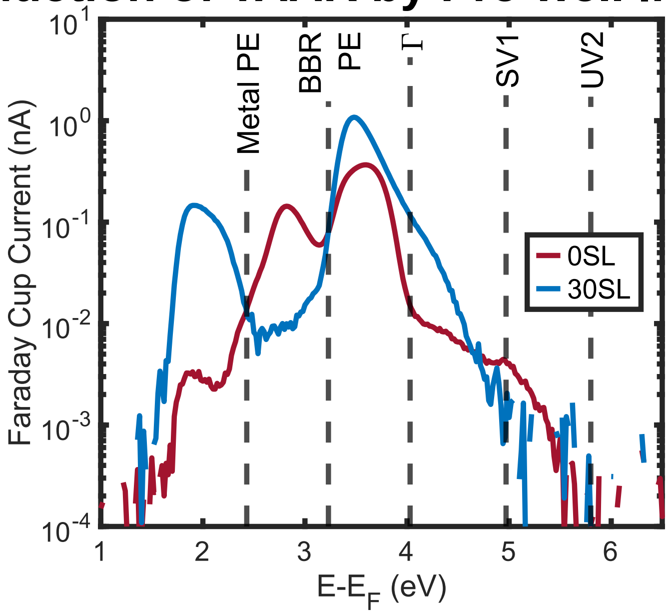
1. Y.C. Chow, et al., Appl. Phys. Lett. **119**, 221102 (2021).
2. Y.C. Chow, et al., Appl. Phys. Lett. **121**, 181102 (2022).
3. Y.C. Chow, et al., J. Appl. Phys. **133**, 143101 (2023).

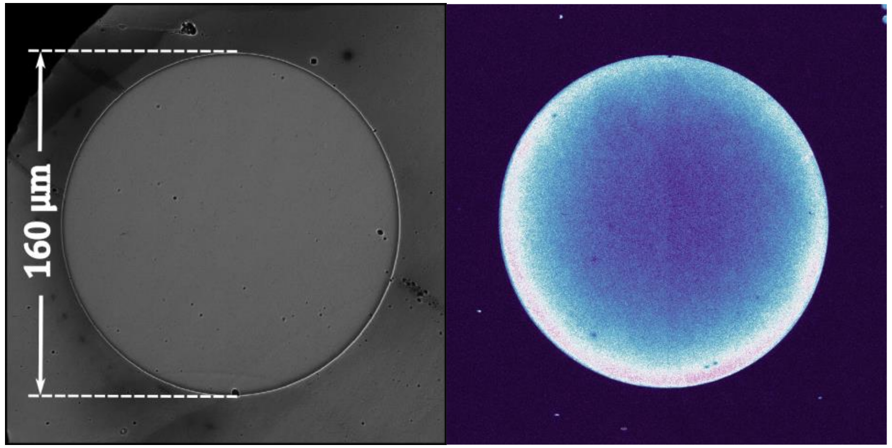
Electron Emission Spectroscopy and Microscopy



(1) Radiative recombination
(2) eeh 3-body Auger recombination
(3) Trap-assisted Auger recombination (TAAR)
(4) Overflow electrons (overshoot/escape)
(5) Photoemission from contact metal

Reduction of TAAR by Pre-well InGaN





Imaging Hot Electron Emission in EEM

W.Y. Ho, et al., Phys. Rev. B **107**, 035303 (2023)

Recent LED Results

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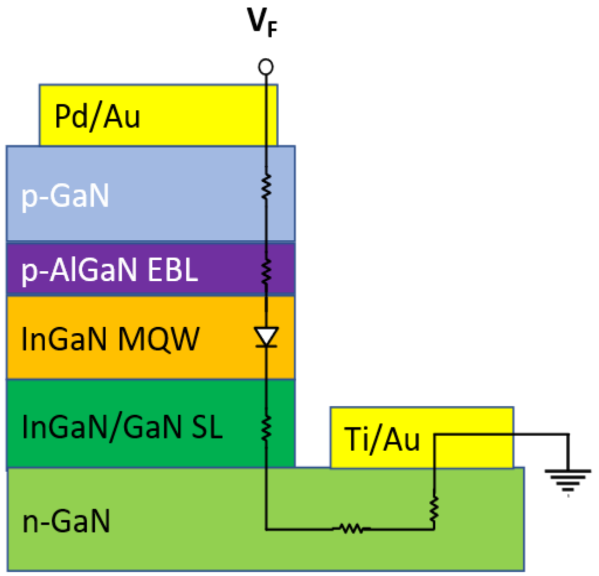
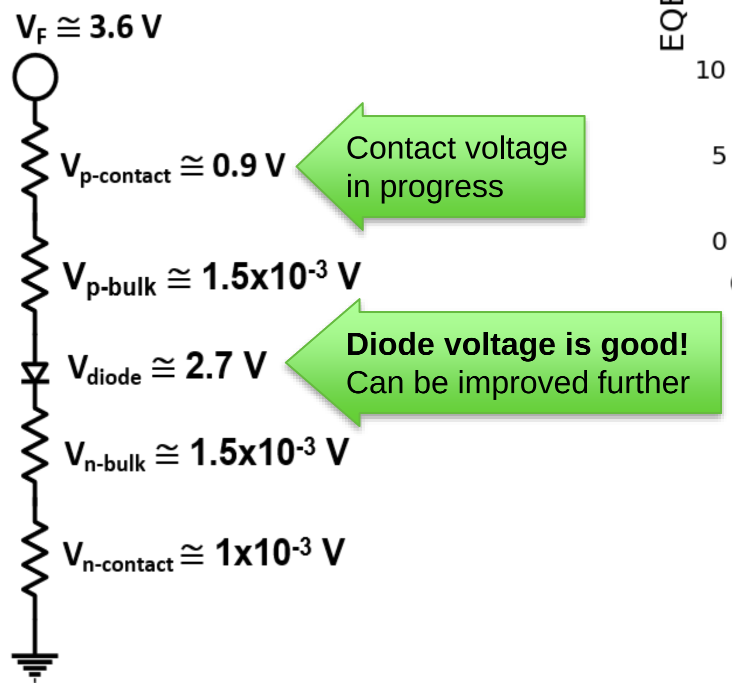
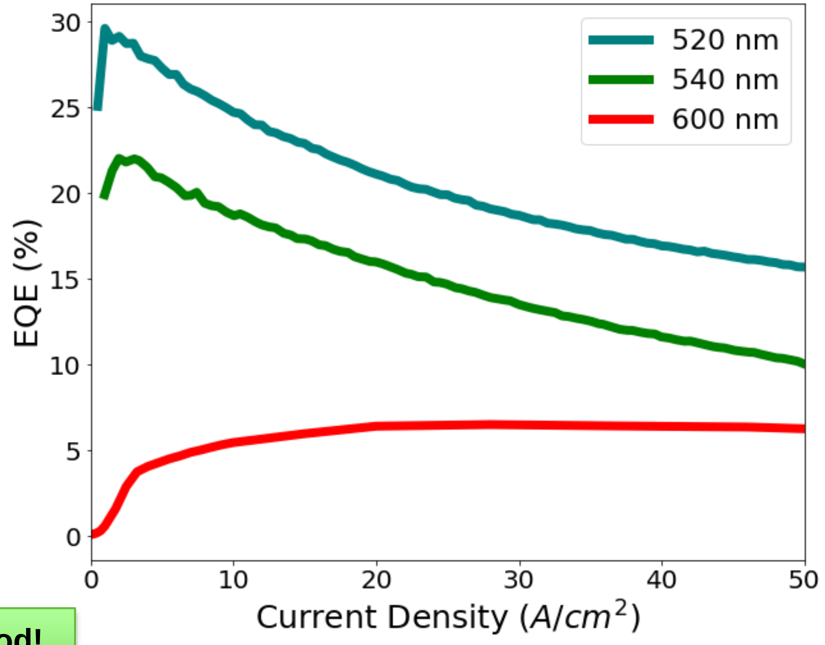
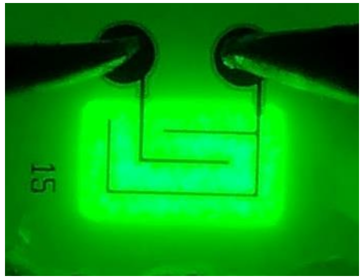
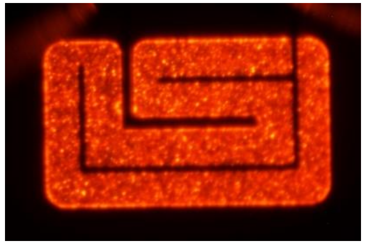
- We've demonstrated high IQEs from 520-600 nm
- Still need to improve V-defect density and eliminate any excess voltage to improve WPE











Peak EQEs:

29.6% EQE at 521 nm, 1 A/cm^2, 2.88 V

22% EQE at 544 nm, 2 A/cm^2, 2.74 V

6.5% EQE at 600 nm, 20 A/cm^2, 3.67 V

Thank You

University of California, Santa Barbara
Jim Speck
speck@ucsb.edu
DOE BENEFIT - EE0009691

Project Execution

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	FY2022				FY2023				FY2024			
Planned budget												
Spent budget												
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Subtask 1.0: Blue and green ref LEDs												
Subtask 2.1, 2.2: V-defect Simulations (Go/No-Go)												
Subtask 3.4: Advanced Characterization of V-defects												
Subtask 6.1, 6.2, 6.3, 6.4: Internal Field Screening Experiments												
Subtask 7.1: Role of superlattice in impurity capture												
Current/Future Work												
Subtask 2.3: 3D V-defect simulations												
Subtasks 3.1, 3.2, 3.3, 3.5, 3.6: MOCVD growth												
Subtasks 4.4, 4.5, 4.6: Lateral Injectors												
Subtasks 7.2 – 7.6: Understanding non-radiative recombination												

- Y1 Go/no-go: 2D V-defect simulations → Completed on schedule
- Y2 Go/no-go: 0.8 V reduction compared to reference → On-going work

- Subtask 6 (field screening) was completed ahead of schedule
- Subtask 5 (mitigation strategy (tunnel junctions)) – significant progress

EERE/BTO goals

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The nation's ambitious climate mitigation goals

Greenhouse gas emissions reductions

50-52% reduction by 2030 vs. 2005 levels

Net-zero emissions economy by 2050

Power system decarbonization

100% carbon pollution-free electricity by 2035

Energy justice

40% of benefits from federal climate and clean energy investments flow to disadvantaged communities

EERE/BTO's vision for a net-zero U.S. building sector by 2050

Support rapid decarbonization of the U.S. building stock in line with economywide net-zero emissions by 2050 while centering equity and benefits to communities

Increase building energy efficiency

Reduce onsite energy use intensity in buildings 30% by 2035 and 45% by 2050, compared to 2005

Accelerate building electrification

Reduce onsite fossil -based CO_2 emissions in buildings 25% by 2035 and 75% by 2050, compared to 2005

Transform the grid edge at buildings

Increase building demand flexibility potential 3X by 2050, compared to 2020, to enable a net-zero grid, reduce grid edge infrastructure costs, and improve resilience.

Prioritize equity, affordability, and resilience

Ensure that 40% of the benefits of federal building decarbonization investments flow to disadvantaged communities

Reduce the cost of decarbonizing key building segments 50% by 2035 while also reducing consumer energy burdens

Increase the ability of communities to withstand stress from climate change, extreme weather, and grid disruptions