Impacts of Carrier Transport and Deep Level Defects on Delayed Cathodoluminescence in Droop-Mitigating InGaN/GaN LEDs

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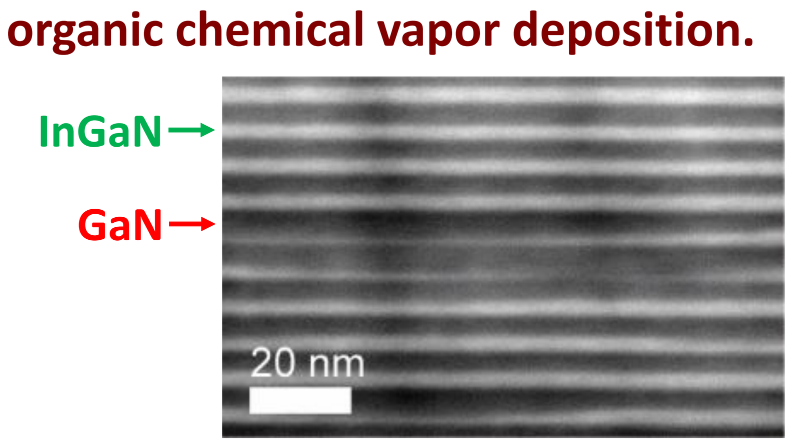
Introduction

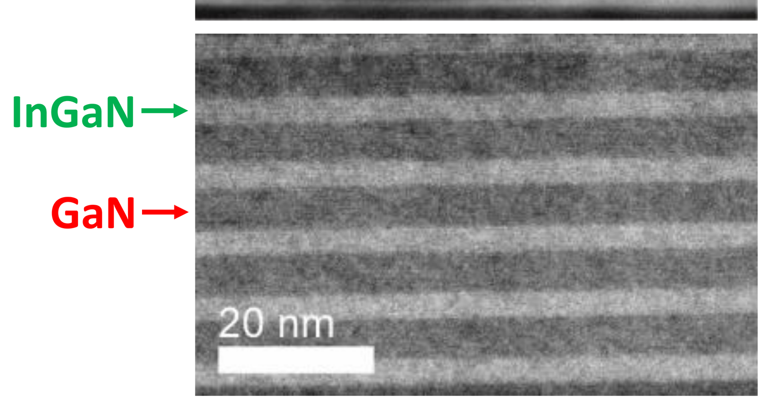
- InGaN/GaN quantum well (QW) heterostructures enable light emitting diodes (LEDs) with external quantum efficiencies (EQE) >70% but suffer from efficiency droop
  - **Efficiency droop:** monotonic reduction in LED EQE at high current densities (>10 A/cm^2)
- Low-droop LED designs require structural and/or compositional modifications in QW region
  - Leads to detrimental reduction in low-current EQE negating high-current droop improvement
- No correlation observed between EQE and intentionally introduced well-width fluctuations
- Delayed cathodoluminescence spectra correlated with carrier transport, deep level defects, and open circuit carrier populations in or near multi-QW active region

Droop-Mitigating InGaN/GaN QW Heterostructures

Two series of droop-mitigating InGaN/GaN QW heterostructure LEDs were grown via metal-organic chemical vapor deposition.



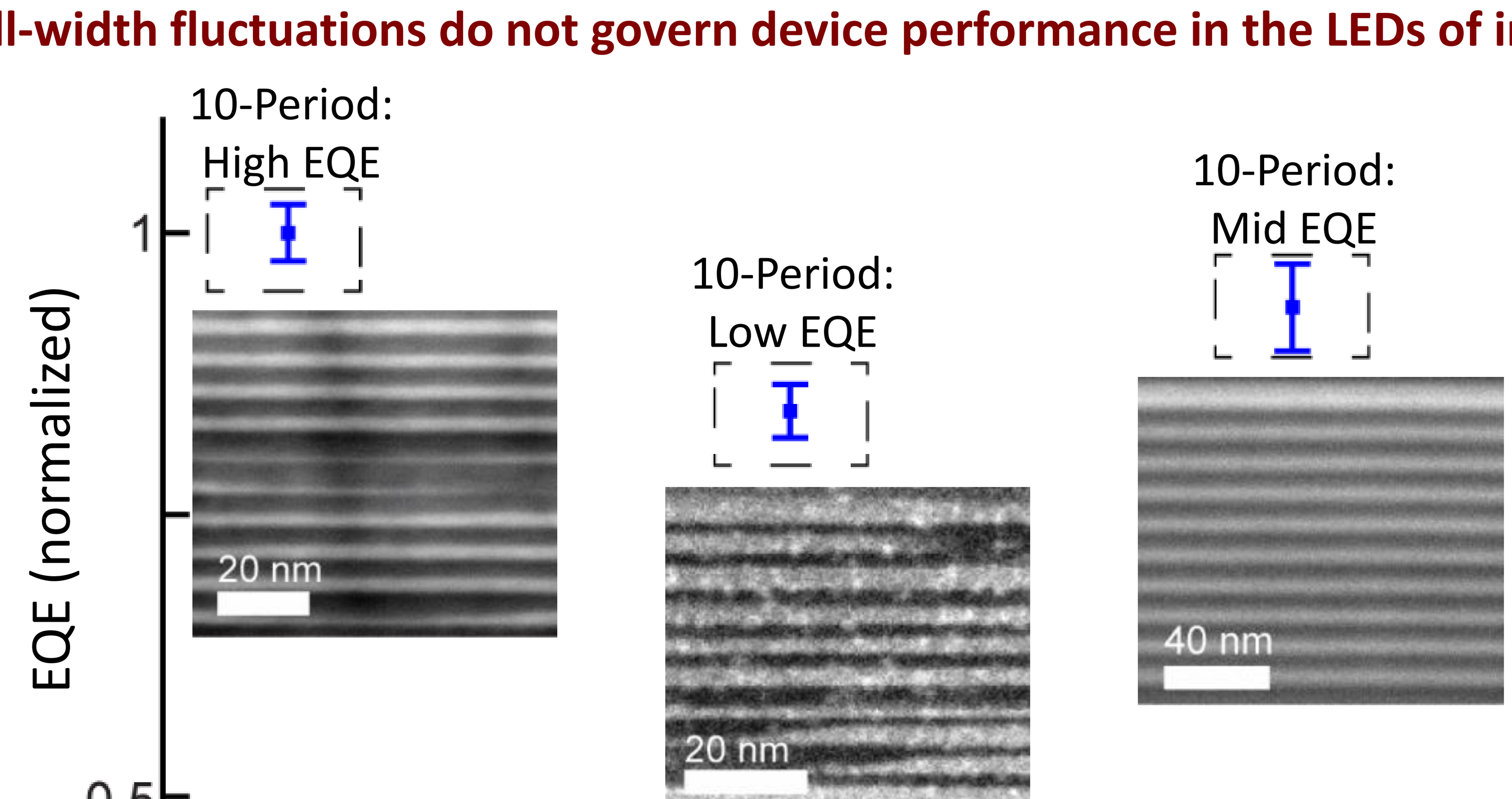
Series 1:
- 10-period multi-QW active region
- 3 samples with 3 different EQEs
  - Denoted *10-Period: High/Mid/Low EQE*
- Well-width fluctuations intentionally introduced in 2 out of 3 samples



Series 2:
- 6-period multi-QW active region
- 2 samples with significantly different EQEs
  - Denoted *6-Period: High/Low EQE*
- Well-width fluctuations absent in both samples

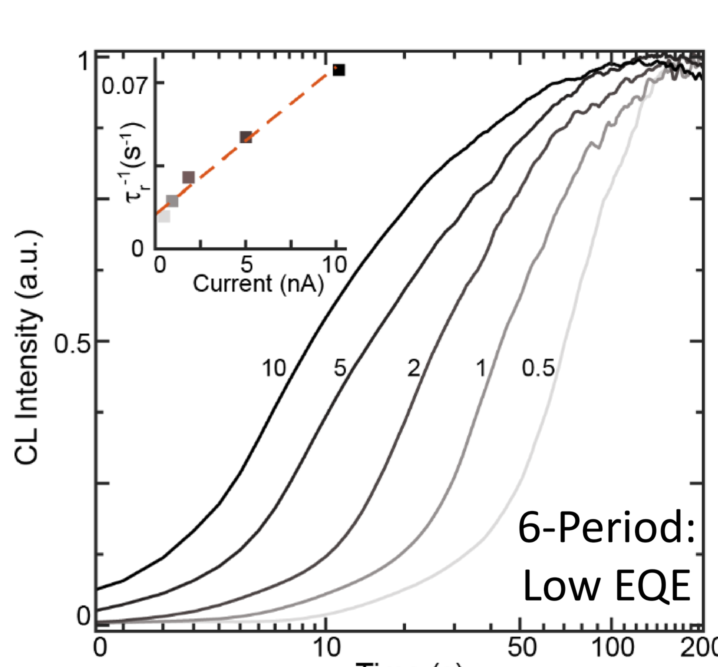
Well Width Fluctuations vs. EQE

No correlation was observed between EQE and the presence of well-width fluctuations. Hence, well-width fluctuations do not govern device performance in the LEDs of interest.



Delayed Cathodoluminescence: Current Dependence

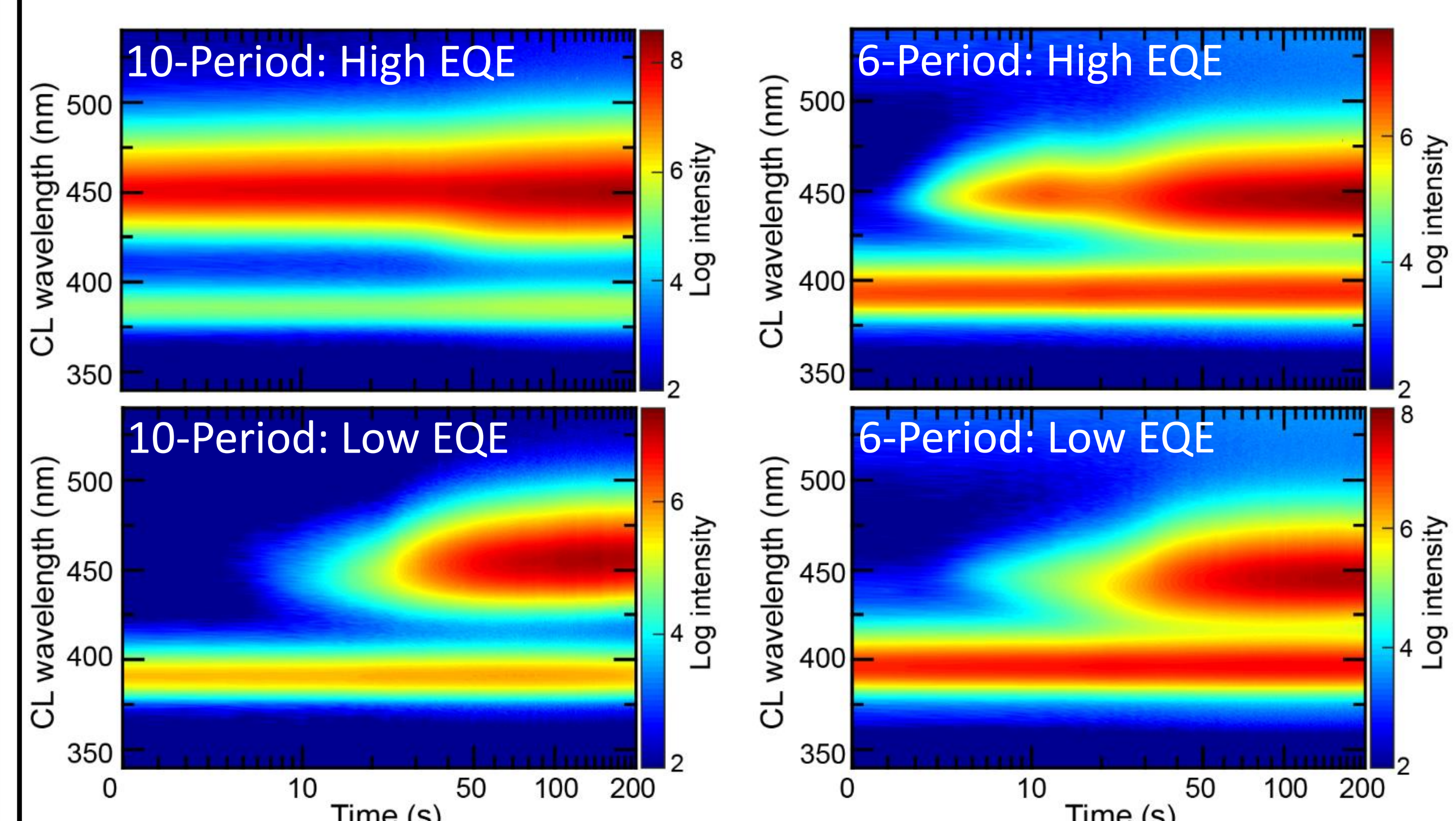
Delayed cathodoluminescence (CL) kinetics observed in certain LEDs are strongly dependent on electron beam current.



Current-dependent CL Rise:
- CL rise described by rise time constant τ_r ~ tens of seconds
- Rise rate (τ_r^{-1}) linearly correlated with current
- Similar current dependence observed in *6-Period: High EQE* and *10-Period: Low EQE* LEDs

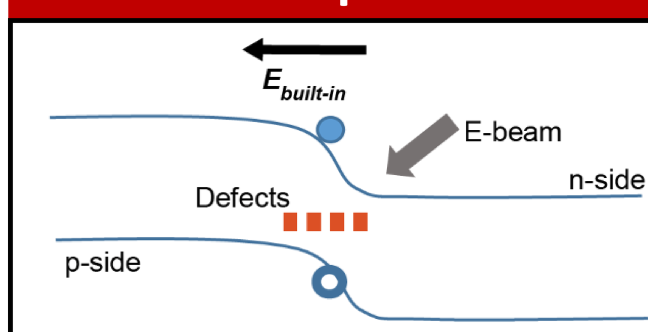
Delayed Cathodoluminescence: Rise Dynamics

Delayed CL observed in samples whose calculated band profiles suggest facile carrier escape in reverse bias from individual QWs (*6-Period: High/Low EQE* and *10-Period: Low EQE* LEDs).

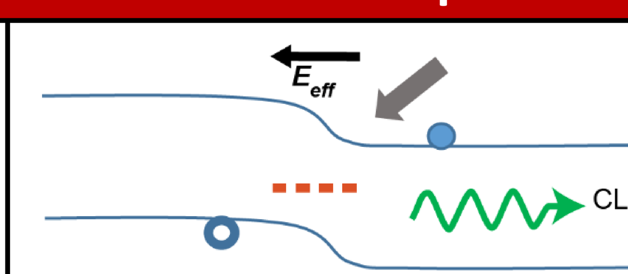


Time-dependent QW CL:
- CL signal saturates over the course of 120 s
- CL enhancement persists for >30 mins
- NOT observed in samples lacking a p-n junction (not shown)

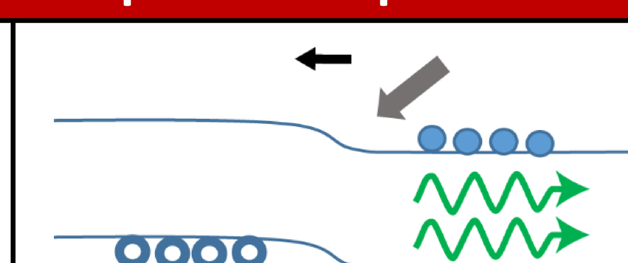
Proposed Mechanism: Carrier Sweep-Out and Deep Level Traps



Initial time:
- Carriers generated by the electron beam within the multi-QW p-i-n junction
- Carriers are separated by the built-in field and/or captured by deep level traps
- <u>No CL is generated</u>



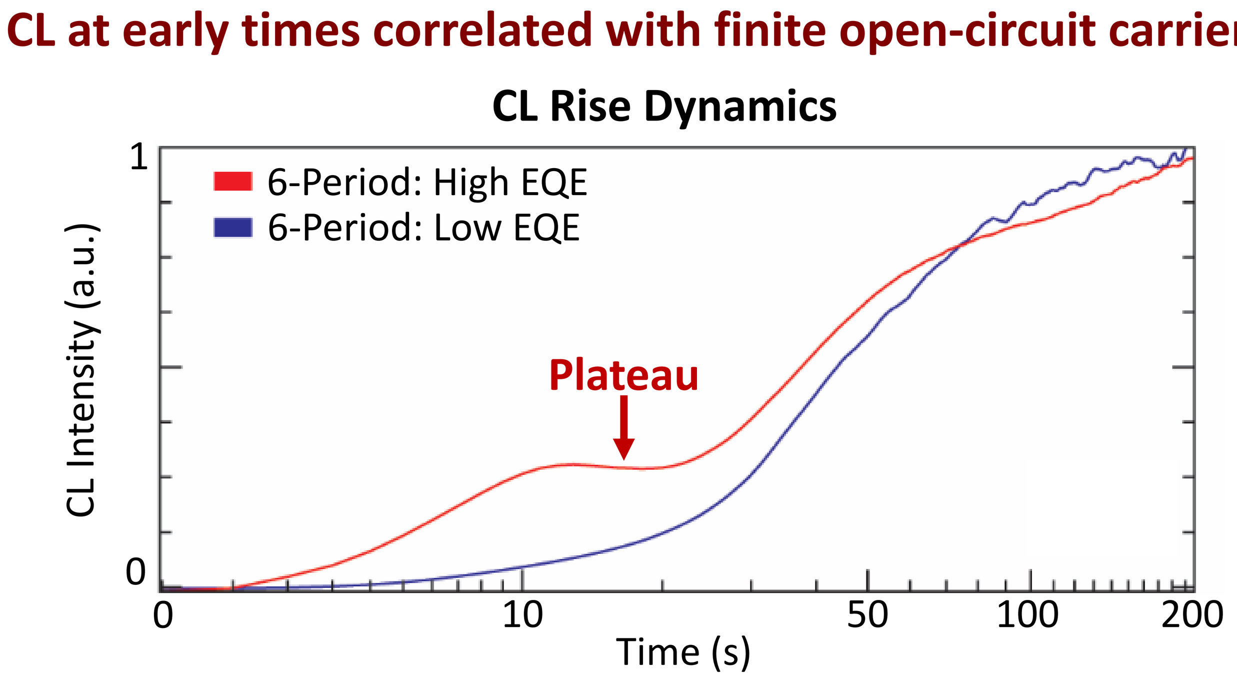
Intermediate times:
- Carriers accumulate on either side of the junction
- Time-dependent counter-voltage reduces strength of built-in field
- <u>Some CL is emitted</u>

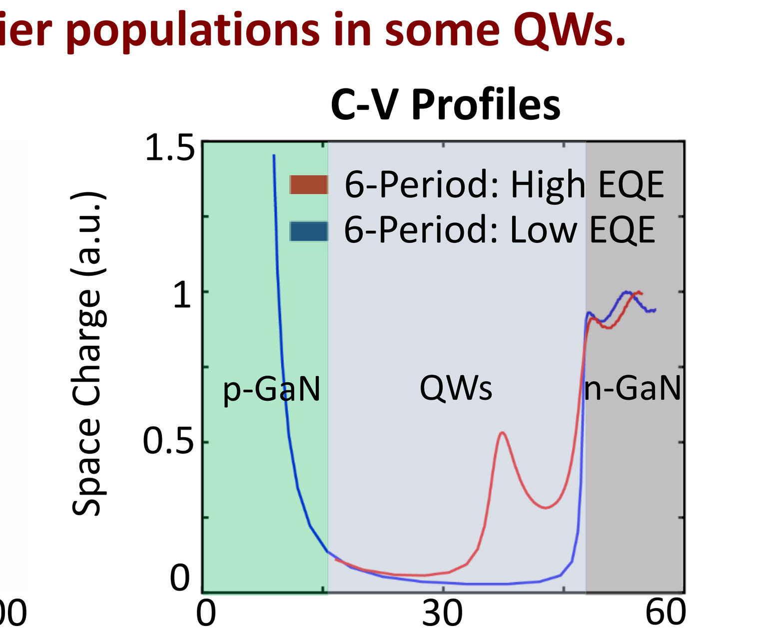


Steady state:
- Carriers accumulate until new steady-state open circuit voltage is reached
- Defect levels are filled
- <u>CL intensity saturates</u>

Capacitance-Voltage (C-V) Profiles

C-V profiles allow depth-resolved measurements of charge density. Samples with plateau in CL at early times correlated with finite open-circuit carrier populations in some QWs.





Conclusions and Outlook

- EQE and electronic carrier properties are not directly governed by microscopic structural defects
- Dynamical features of SEM-CL spectra yield device-relevant insights into:
  - Carrier escape and confinement within individual QWs
  - Deep level trap states in or near QW active region
  - QW open circuit carrier populations
- SEM-CL can help identify efficiency-limiting mechanisms and guide future LED development

Acknowledgements

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