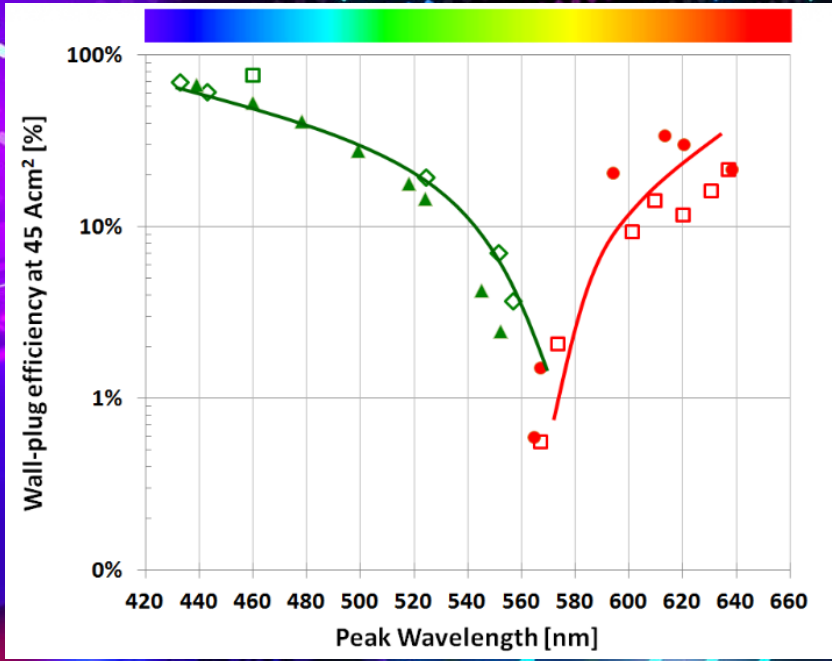

Closing the Green Efficiency Gap... Status and recent approaches

B. Hahn | 03.2.2016 | DOE workshop Raleigh

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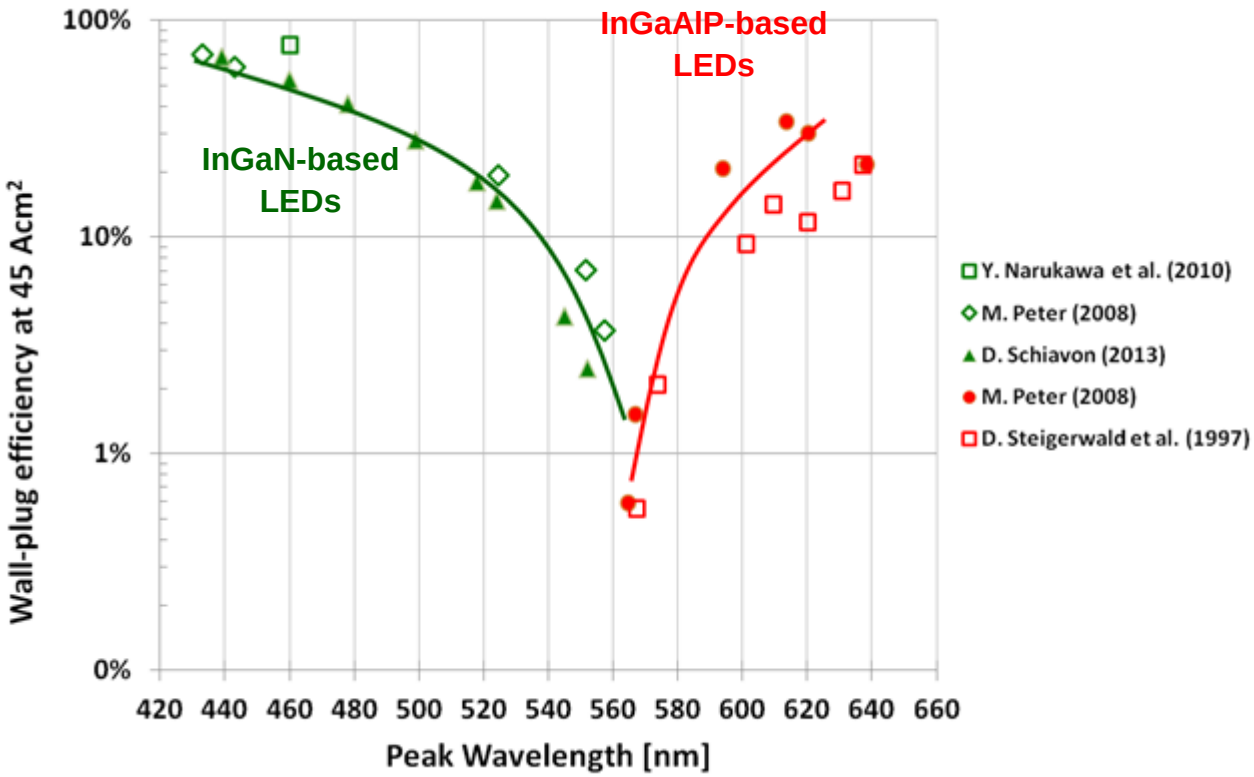
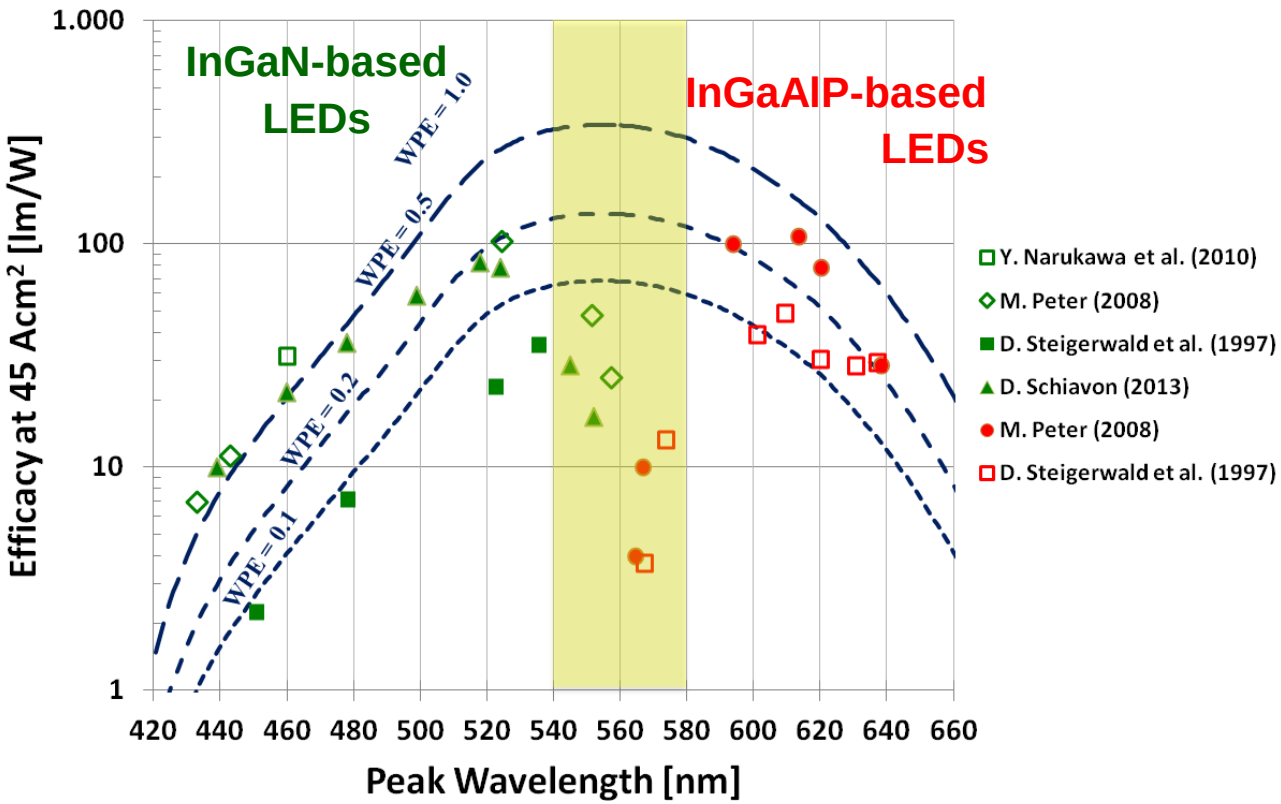
Motivation: The Green Gap
Wall-Plug Efficiency



no efficient light source in the green spectral range
Phosphides are material limited

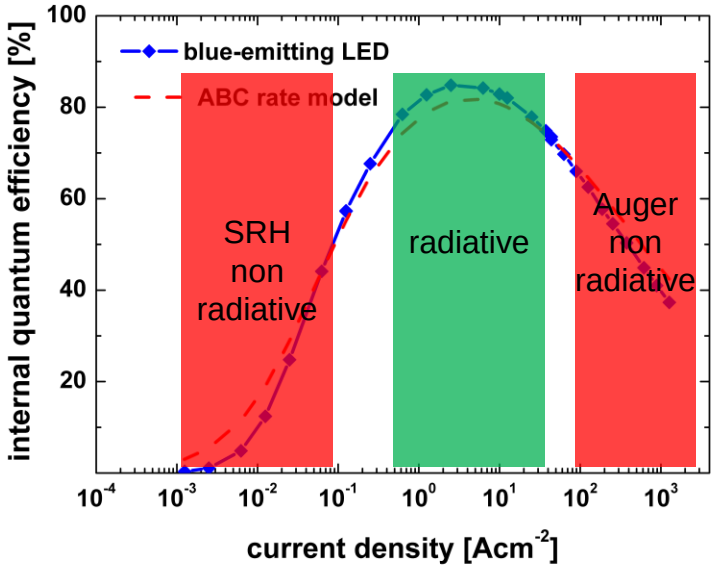
Motivation: The Green Gap
Efficacy



→ LED **Efficacy** Gap despite the fact, that highest human eye sensitivity is in the Gap
The phosphides are limited by material properties (indirect bandgap
→ **Can the nitrides fill the gap?**

ABC Rate Model

Simple explanation for InGaN internal quantum efficiency (IQE): *ABC* rate model



- **injection losses are negligible**

  (shown years ago for commercial grade LEDs by Shen et al., Laubsch et al., David et al., Galler et al.,…)

  → **all carriers recombine in QWs**
- **free carriers are only present due to excitation**

  → ***n=p=:x* in QWs**
- **there are 3 relevant recombination paths**

  - **Shockley-Read-Hall:** $R_{SRH} = Ax$
  - **radiative:** $R_{rad} = Bx^2$
  - **Auger :** $R_{Aug} = Cx^3$

shown in 2013 by Iveland et al., Binder et al.

calculate *x(I,A;B;C)* from continuity equation

current →

$$\frac{I}{eV} = Ax + Bx^2 + Cx^3$$

elementary charge active volume

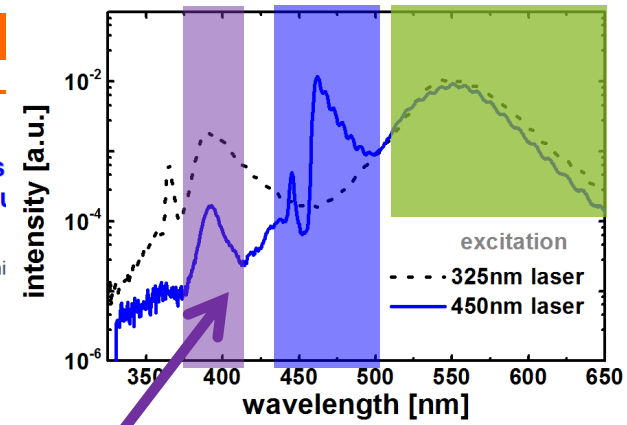
$$IQE = \frac{Bx^2}{Ax + Bx^2 + Cx^3}$$

OSRAM Approach
Detection of UV Photons from Hot El

APPLIED PHYSICS LETTERS **103**, 071108 (2013)

Identification of *nnp* and *npp* Auger recombination as s to the efficiency droop in (GaIn)N quantum wells by visu carriers in photoluminescence

M. Binder,[1,a)] A. Nirschl,[1,2] R. Zeisel,[1] T. Hager,[1] H.-J. Lugauer,[1] M. Sabathi D. Bougeard,[2] J. Wagner,[3] and B. Galler[1]



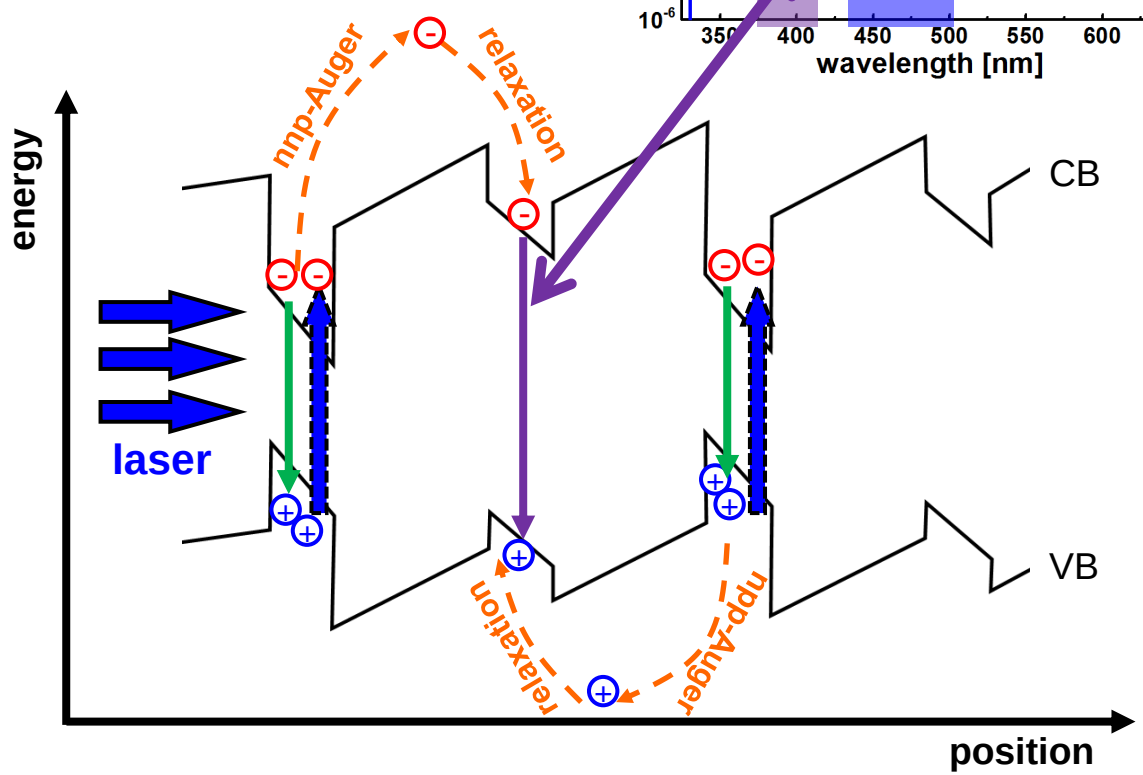
- **sample:**
  InGaN-MQW, alternating **UV/green** QWs

- resonant pumping of **green** QWs with high-power laser (**450 nm**)

- droop regime
  →detection of **UV** photons?
  ☺

- after excluding other possible origins…
  Auger recombination (*nnpleeh* and *npplehh*!) only reasonable explanation

- efficiency droop (Cn^3) caused by Auger recombination



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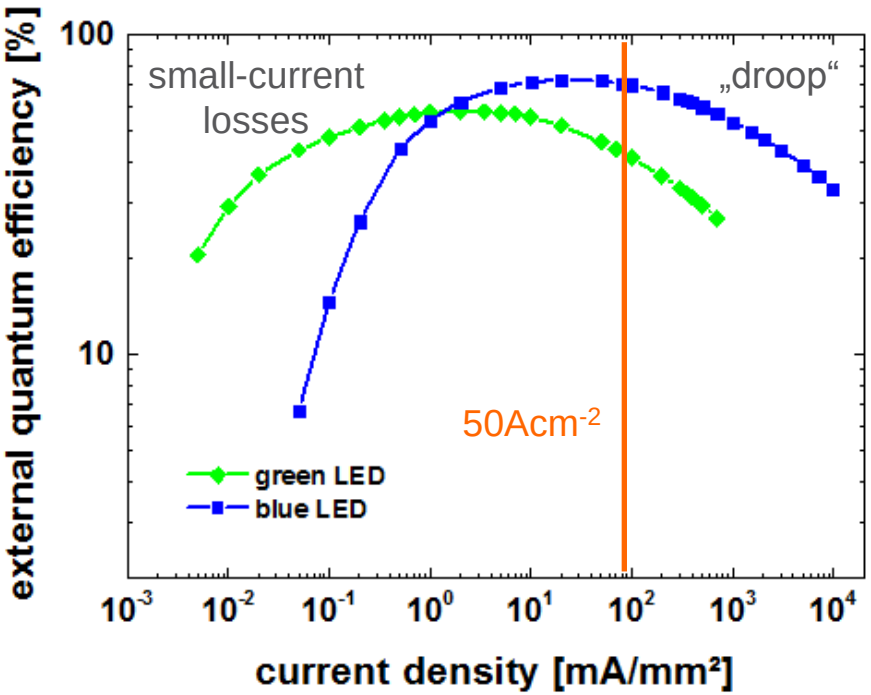
InGaN External Quantum Efficiency Introduction

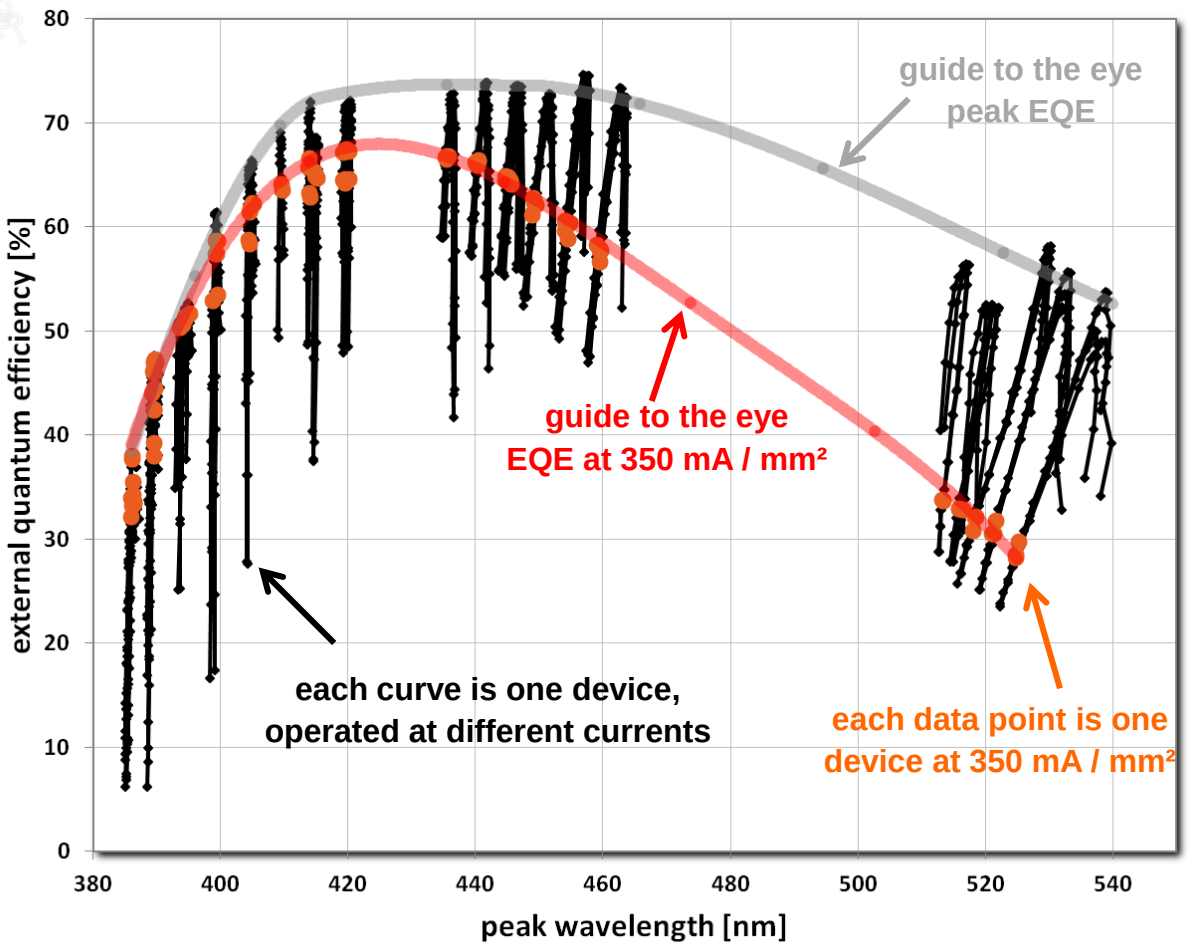
$$EQE := \frac{\text{emitted photons per second}}{\text{injected electrons per second}}$$



Efficiency droop is …

- green LED is actually much more efficient at small current densities
- “green gap” at typical operating is mainly due to earlier onset of efficiency droop

Green Gap
A Closer Look…



green gap is hardly existent on "nitride side" if *peak* quantum efficiency is considered

even more striking when keeping in mind that, owing to extremely narrow market under today's conditions, industrial
R&D effort for green
<<
R&D effort for blue

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InGaN: Efficiency vs. Current Density and Wavelength SQW Active Regions

D.Schiavon, PhD thesis

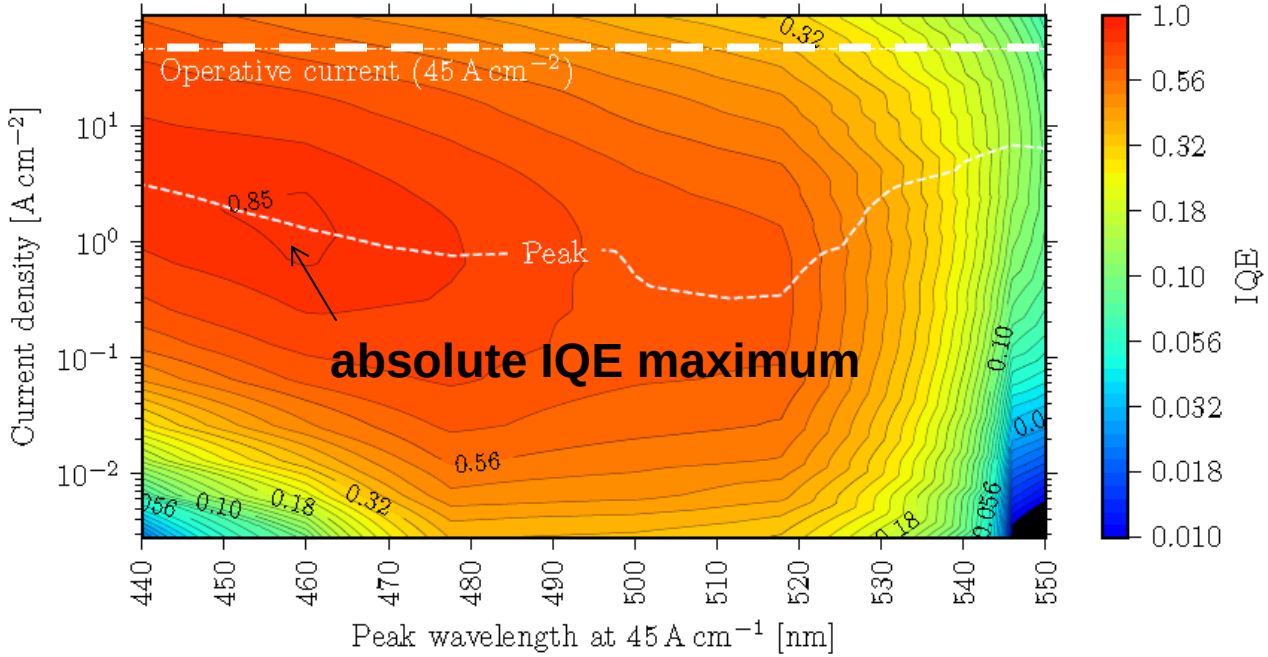

Figure 4.8: IQE as a function of both wavelength and current density. The dashed line shows the wavelength dependence of the peak current.

- **absolute efficiency maximum (state-of-the-art growth): ~460nm , ~2A/cm²**
- **current density where maximum efficiency is reached decreases by factor ~10 from green to blue**

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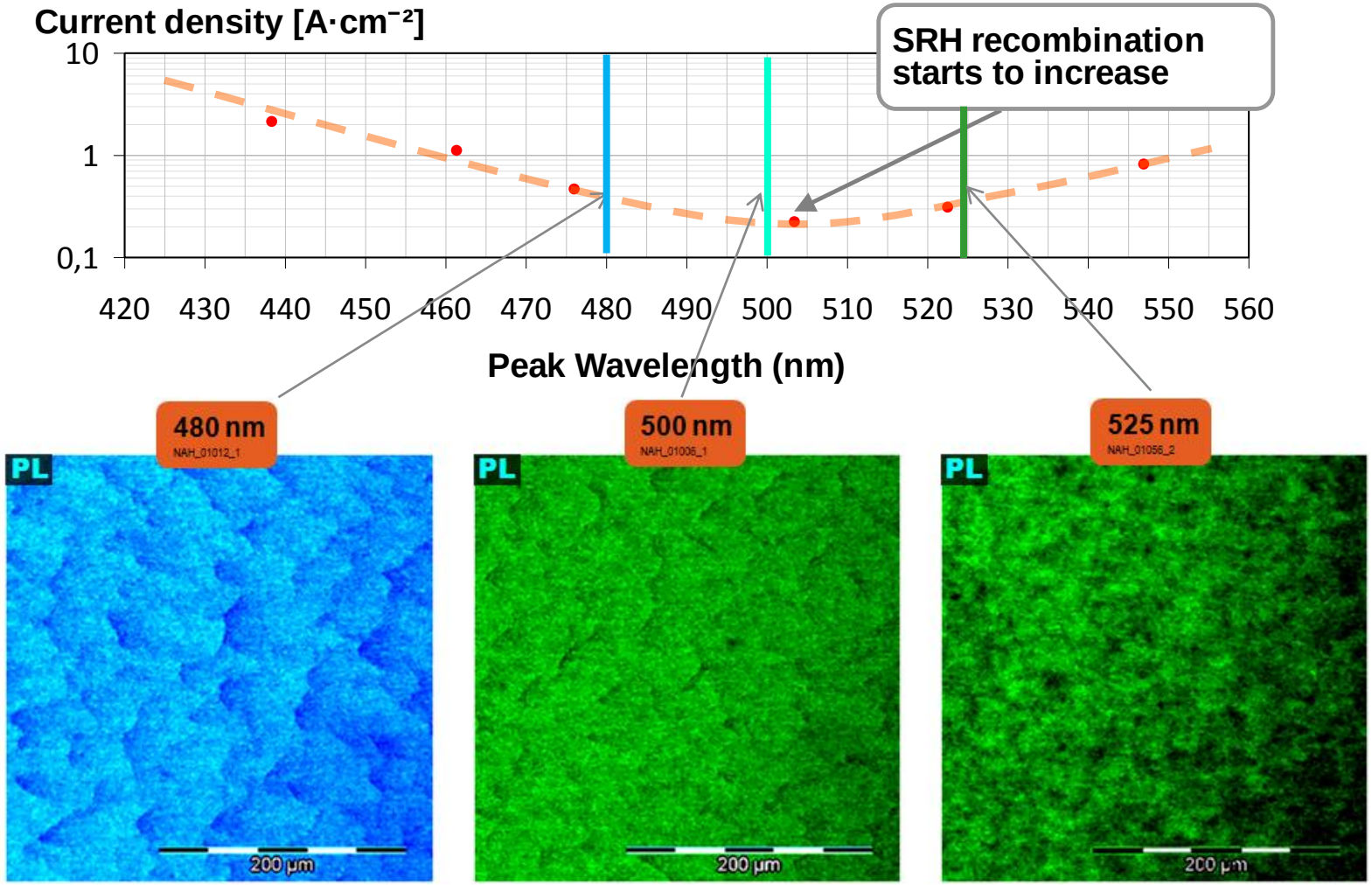
InGaN: Efficiency vs. Current Density and Wavelength SQW Active Regions

D.Schiavon, PhD thesis



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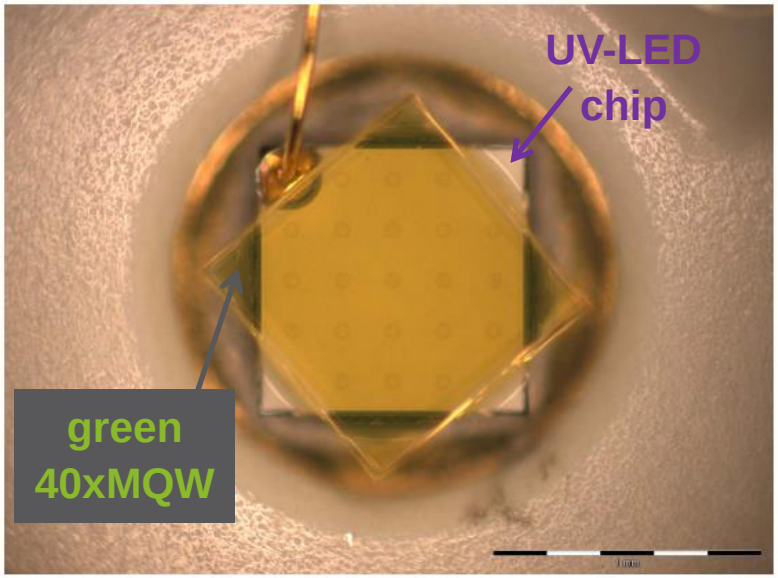
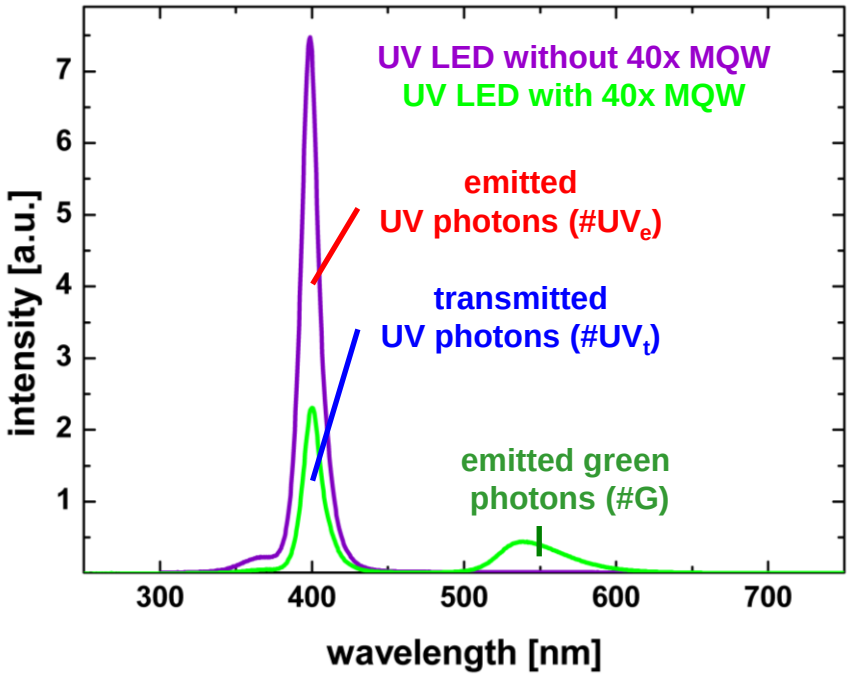
Shift IQE maximum of green MQW to High Power: Proof of Principle Using Optical Pumping





- green 40xMQW as converter on pre-characterized UV-LED
  →enables rather homogeneous operation of large number of QWs
- high chip reflectivity, strong MQW absorption → negligible optical losses

$$\text{EQE of 40xMQW} = \#G / (\#UV_e - \#UV_t)$$

Phys. Status Solidi C 8, No. 7–8, 2369–2371 (2011) / DOI 10.1002/pssc.201001065

Green high-power light sources using InGaN multi-quantum-well structures for full conversion

B. Galler*, M. Sabathil, A. Laubsch, T. Meyer, L. Hoeppel, G. Kraeuter, H. Lugauer, M. Strassburg, M. Peter, A. Biebersdorf, U. Steegmueller, and B. Hahn

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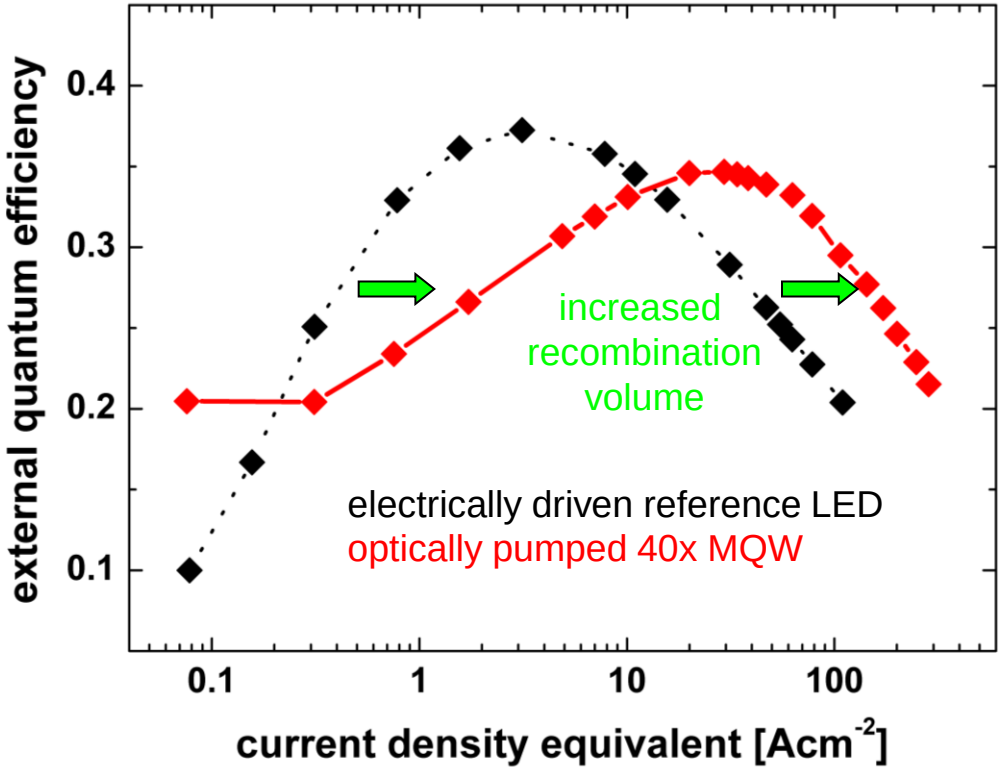

very similar curve for EL and PL with comparable peak EQE

shift on current axis works as intended by increasing number of active QWs

need to operate >20 QWs in electro-luminescence to eliminate Stokes loss and get (1-IQE)loss only in emitter and not in emitter and pump LED

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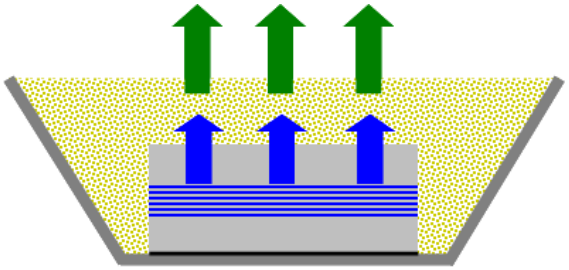
closing the green gap

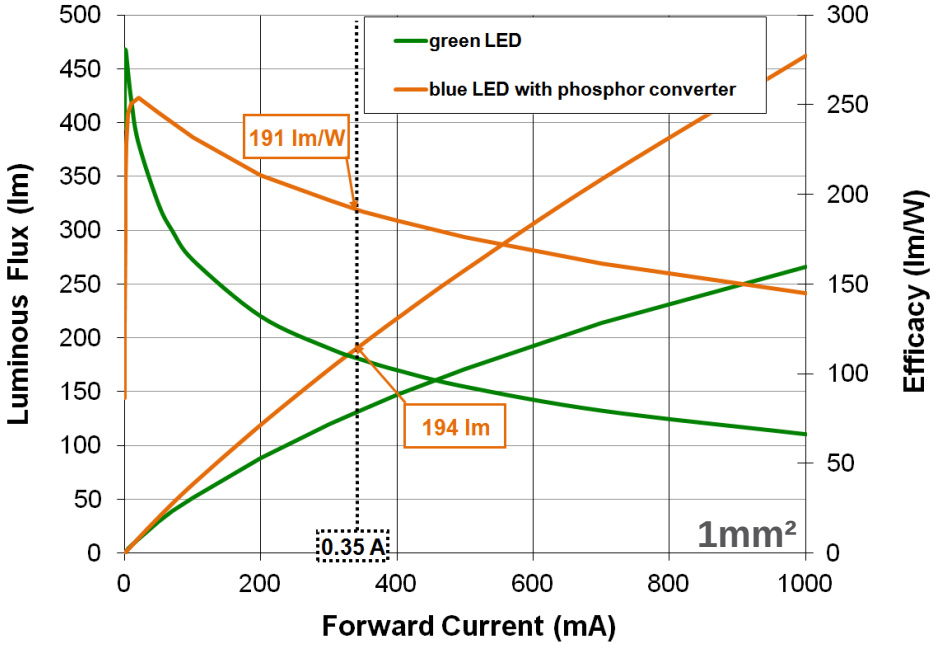
currently pursued approaches at OS

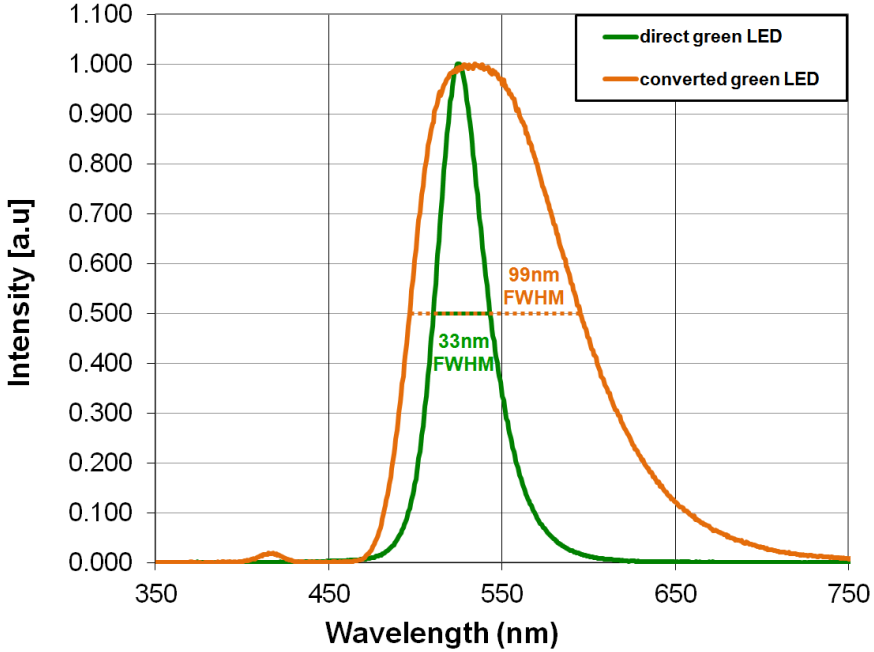
closer look

phosphor converted blue LEDs

+ currently superior efficacy – increased spectral FWHM







→ about 40% increase in efficacy; tripled FWHM @530nm

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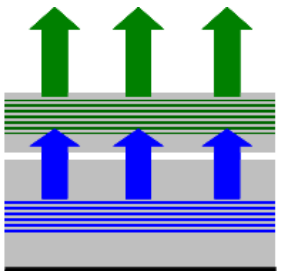
closing the green gap

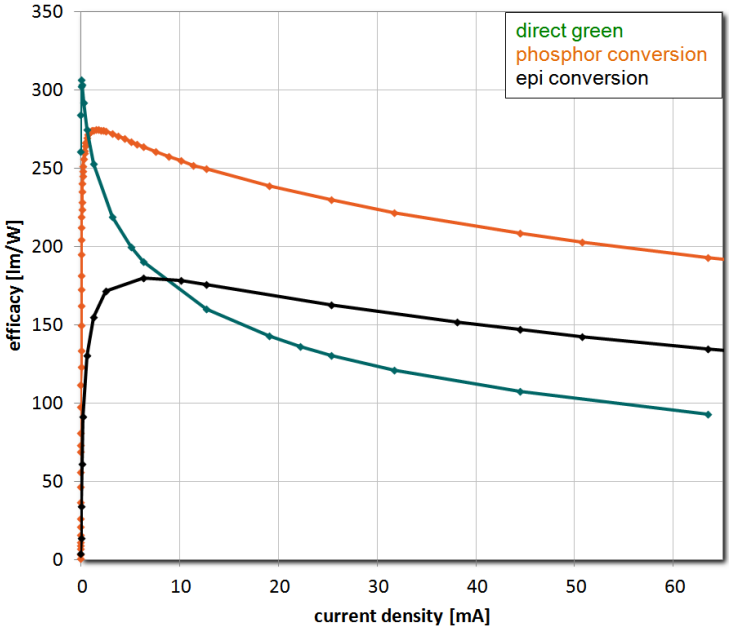
currently pursued approaches at OS

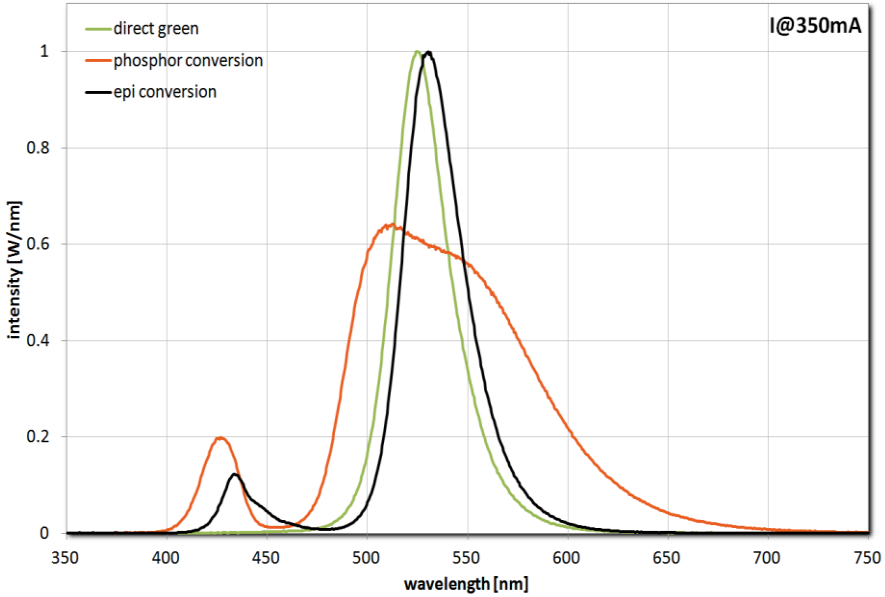
closer look

epi converted blue LEDs



+ FWHM comparable to direct emitting LEDs
o efficacies outperform direct green LEDs in some applications





→ about 40% increase in efficacy; FWHM matching direct green

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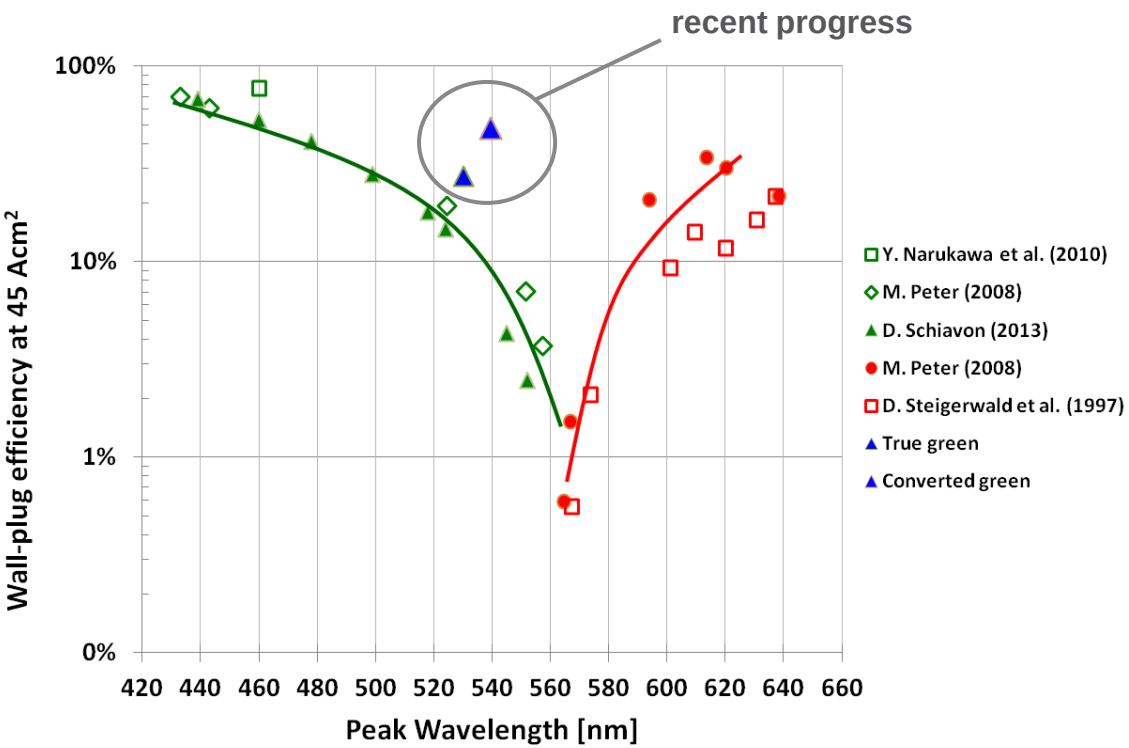
The Green Gap
Recent Progress



direct green LEDs can still be improved significantly if resources for epi development are available

for very high power applications, converted green will be the way to go in foreseeable future

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Summary

- **efficiency droop in InGaN-based *commercial-grade* LEDs dominated by Auger recombination**

- **When considering *peak efficiency,* InGaN green external quantum efficiency is >50% despite *very limited industrial R&D***
  → *c*-plane is no fundamental blocking point

- **crucial for cost- and energy-efficient direct green LEDs**
  → further understanding of Auger recombination to improve *B* vs. *C* coefficient
  → keep carrier density low by optimizing transport processes
  →improve epitaxial quality of very indium-rich QWs

Thank You!

GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

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