

Solving the "Green Gap" in LED Technology

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Future Chips Constellation
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Rensselaer Polytechnic Institute
Troy, NY

D. Hanser and E. Preble

Kyma Technologies, Raleigh, NC

Transformations in Lighting
2008 DOE
SOLID-STATE LIGHTING
R&D WORKSHOP

why not change the world?

Atlanta Jan 29 - 31, 2008



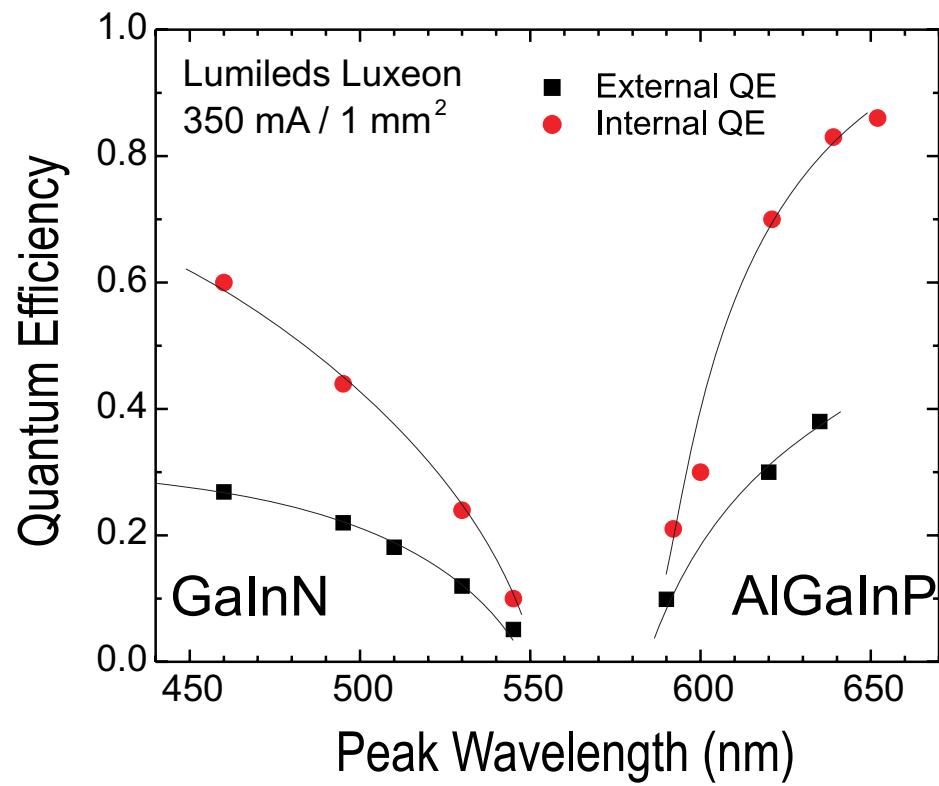
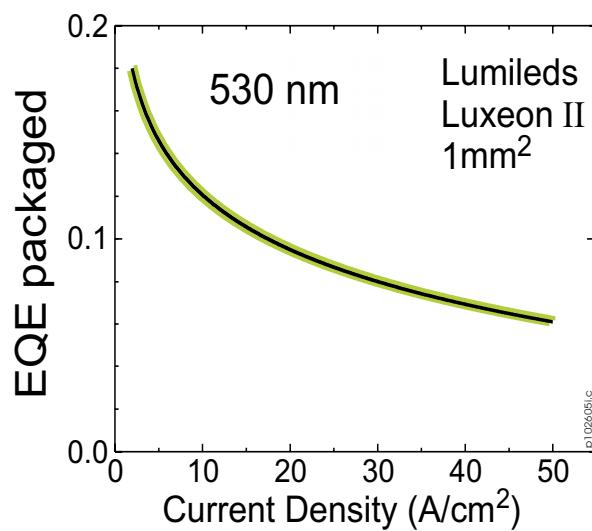
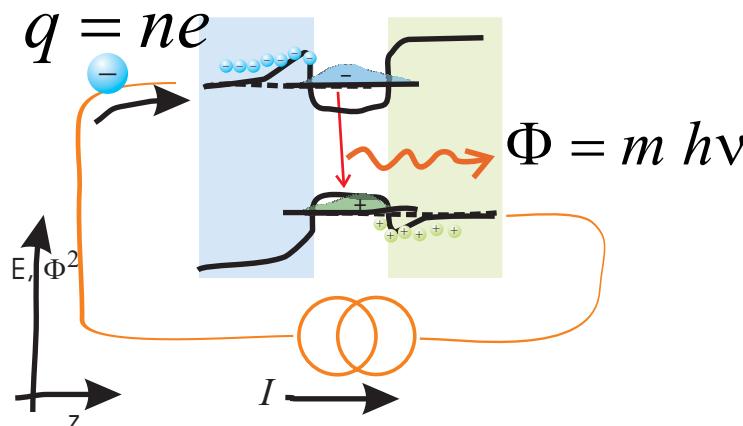
C. Wetzel

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Quantum Efficiency Achieved *the green gap*

$$\text{Quantum Efficiency} = \frac{m}{n}$$

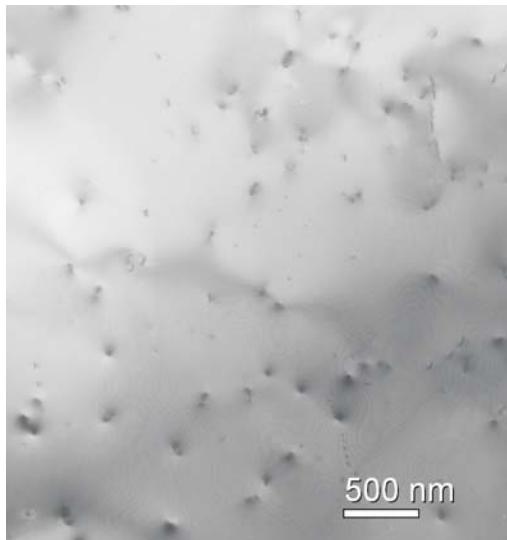
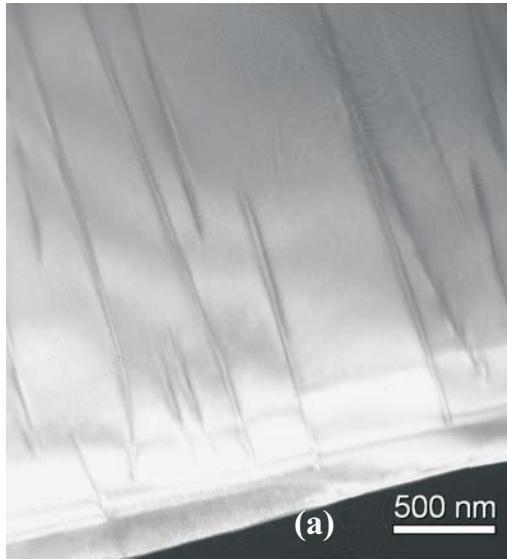


Data: W. Goetz, Lumileds, www.lumileds.com

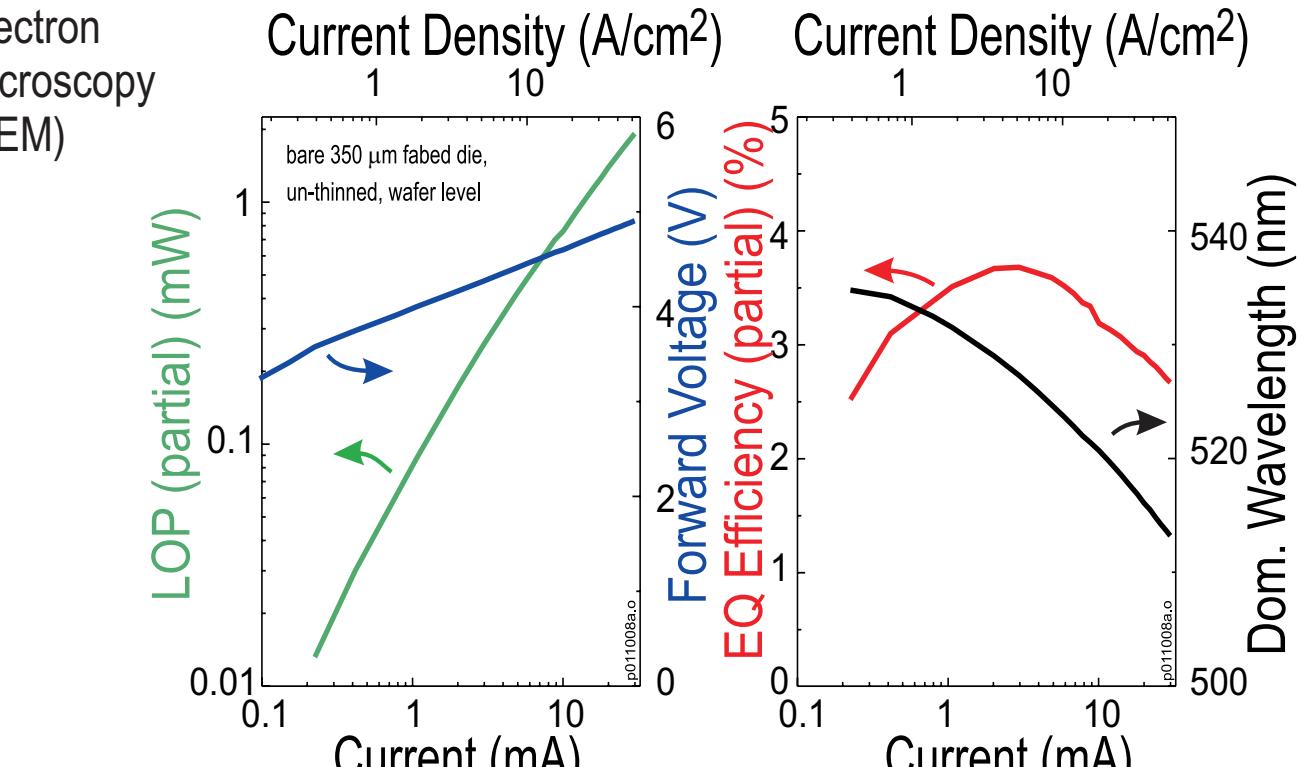


Performance Green LED on Sapphire

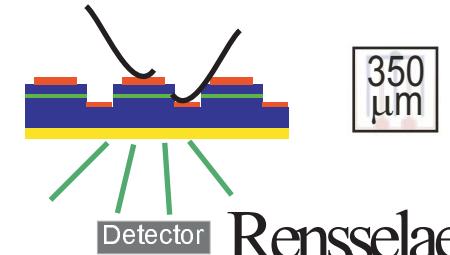
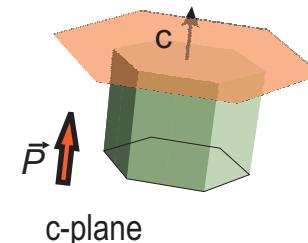
standard process, fabed die



Transmission
Electron
Microscopy
(TEM)



bare 350 μm fabed die, un-thinned, wafer level
20 mA: 4.8 V 516 nm dom. 1.4 mW



Title: High Performance Green LEDs by Homoepitaxial MOVPE

project objectives

Prime Recipient: Rensselaer Polytechnic Institute

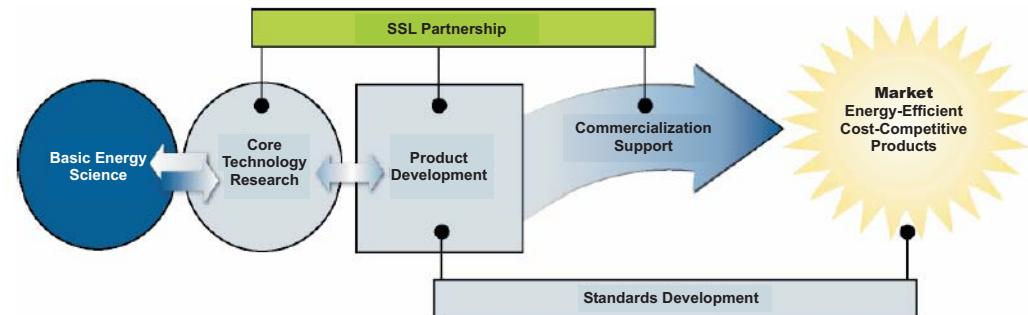
Sub Contract: Kyma Technologies

Agreement Number: DE-PS26-05NT42478-01

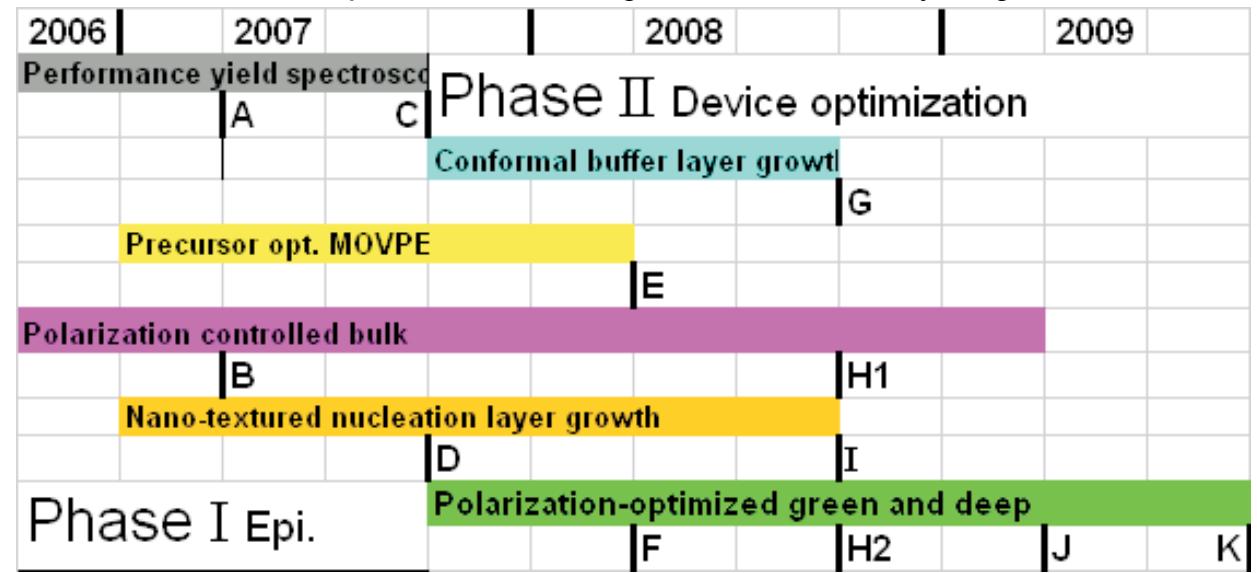
NETL Project Manager: Brian Dotson/
P. Morgan Pattison

Team: C. Wetzel PI,
E.F. Schubert Co-Pi,
T. Detchprohm Epitaxy

- to double or triple the light output power
- from green and deep green AlGaN LEDs dies
- within 3 years
- in reference to the Lumileds



Emphasis on internal generation efficiency of light



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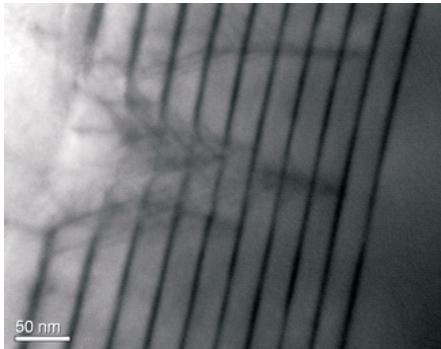
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Morphology of MQW

avoid non-uniformity / avoid V-defects

with V-defects

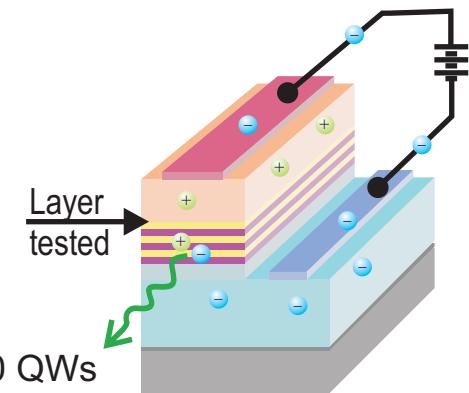
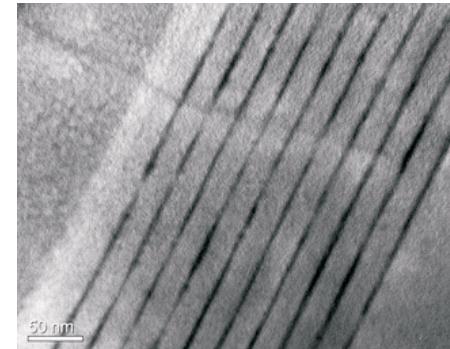
well width
+ 60 %
barrier width
+ 37 %



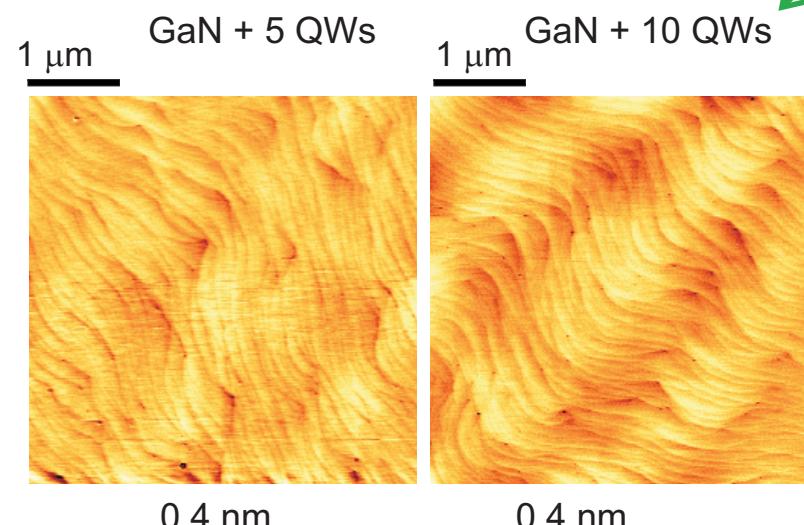
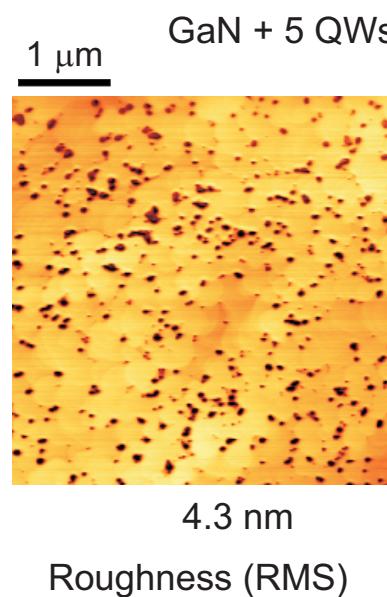
TEM

virtually without V-defects

all
uniform



AFM



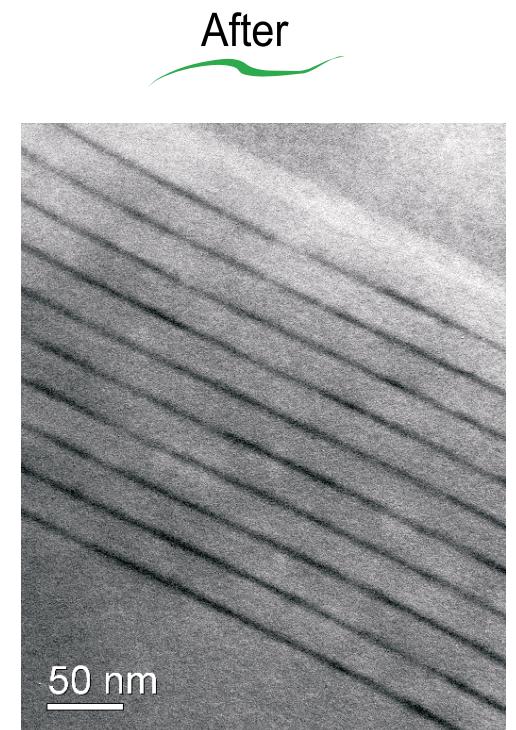
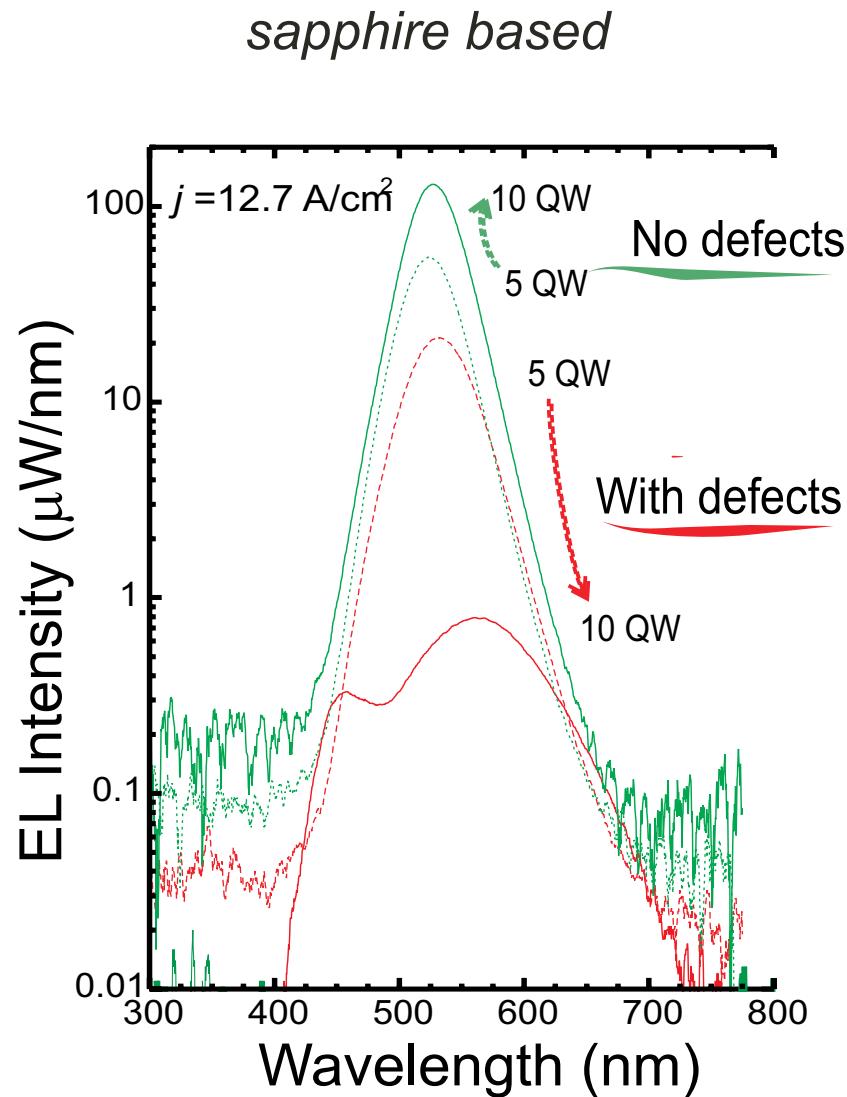
M. Zhu, et al.
phys. stat. sol. (2008 *in print*)

Y. Xia et al.
unpublished (2007)

C.Wetzel

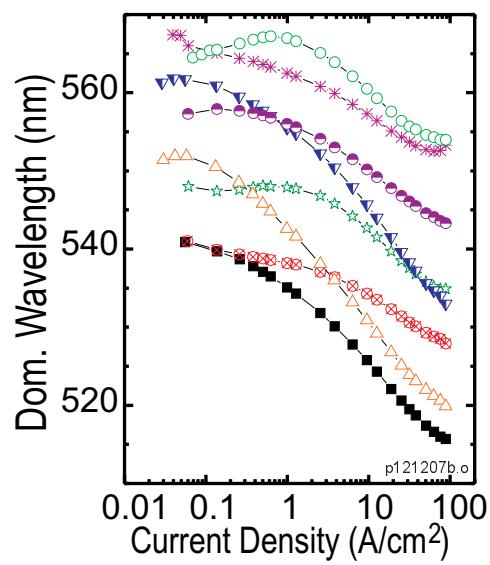
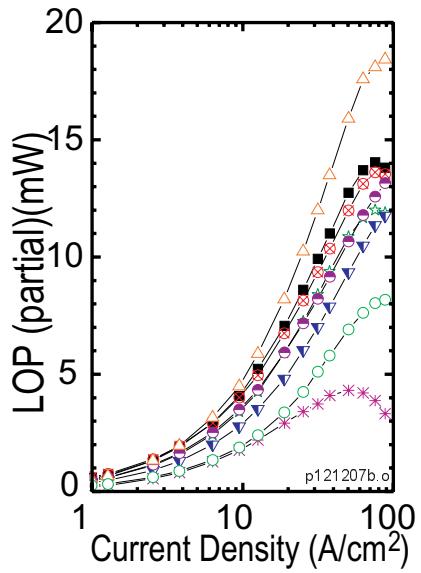
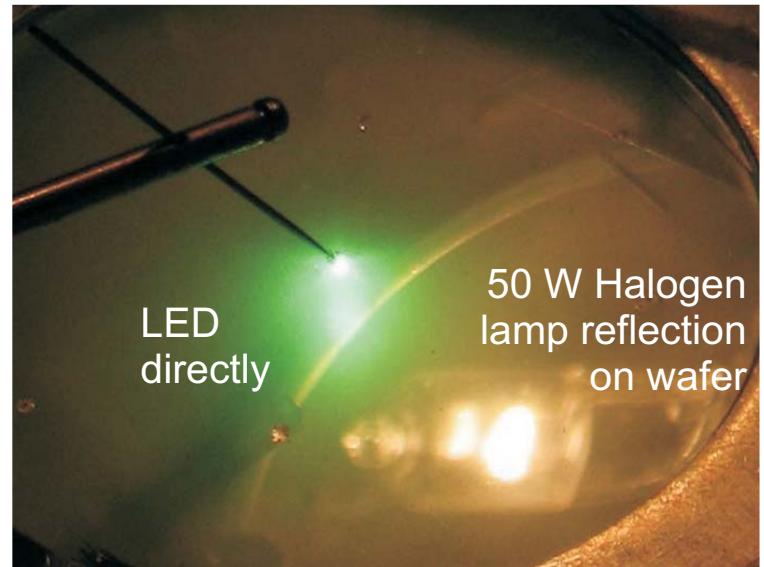
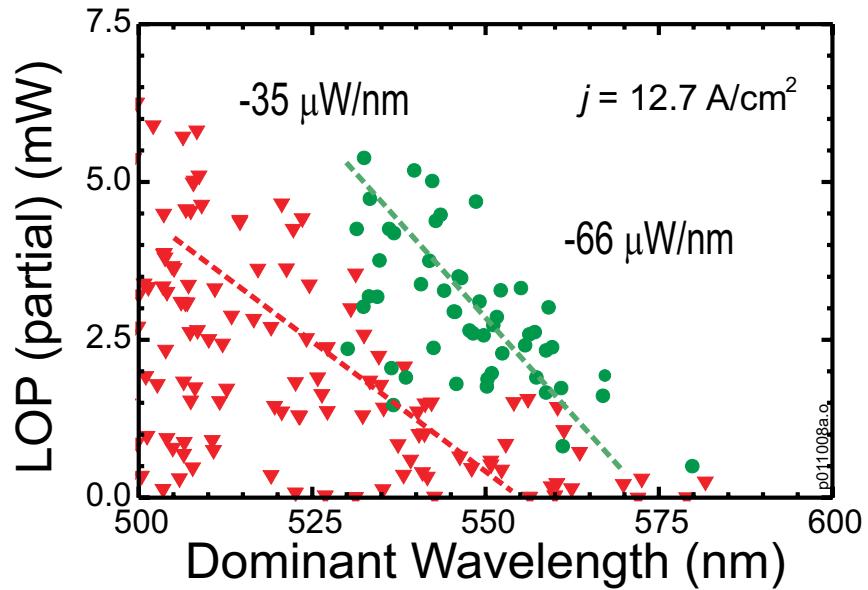
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Reducing Defects in Green LEDs



Green Performance without V-Defects

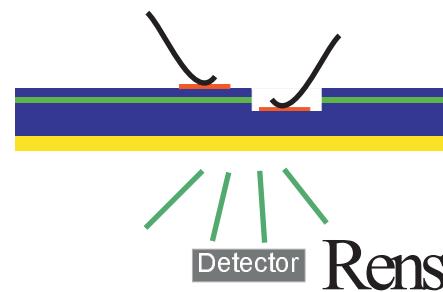
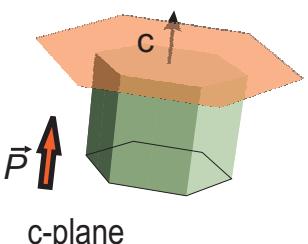
scratch diodes



$\lambda_{\text{dom}} (\text{nm})$
@ 12.7 A/cm^2

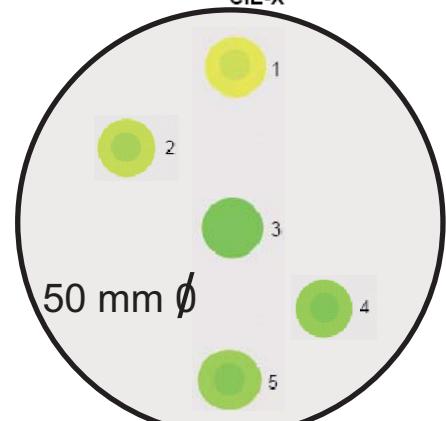
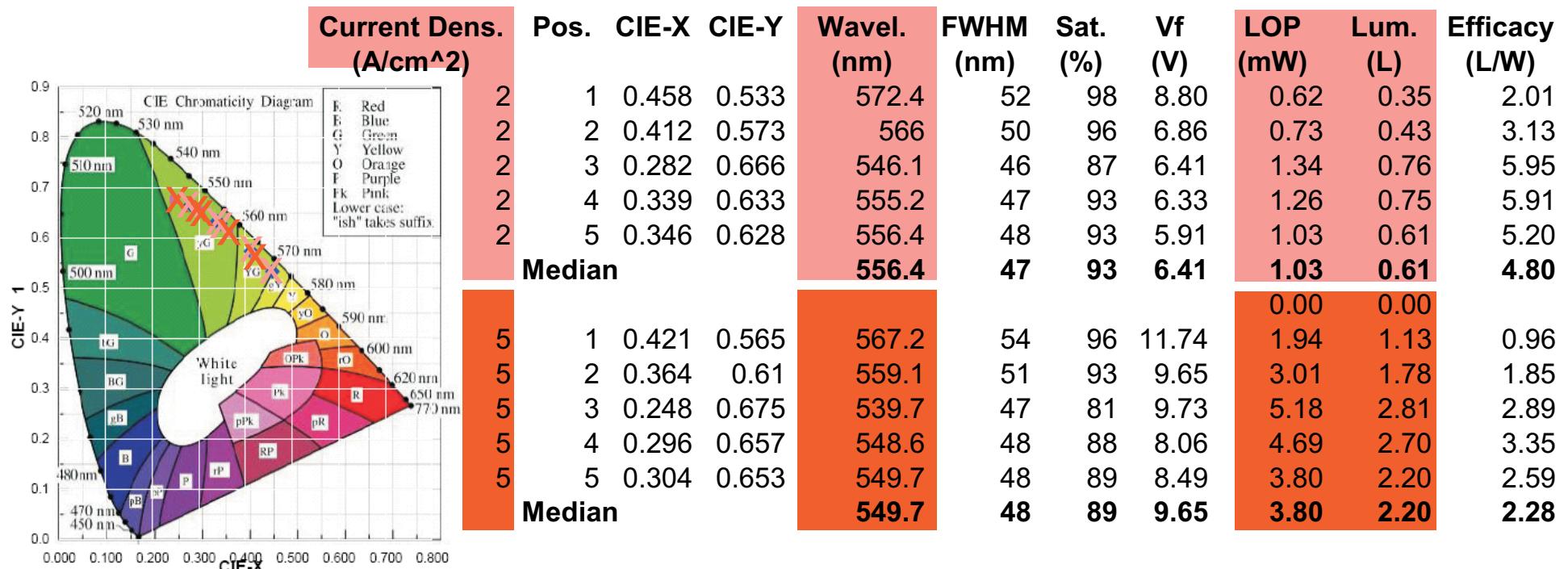
- 518
- △— 521
- ⊗— 528
- ★— 535
- 543
- ▽— 544
- *— 553
- 559

T. Detchprohm, et al.
phys. stat. sol. (2008 *in print*)

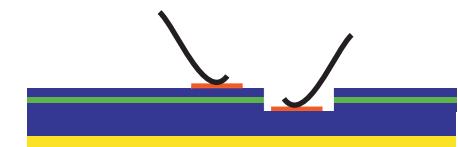
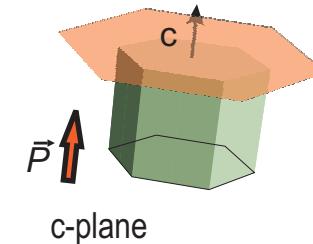


Green c-Axis LED Epi on Sapphire

current status, scratch diode



Quick Test Wafer	
Epi Run ID #:	Q10423A
Substrate ID#:	8.2E+07
Date:	9/19/2007 11:37
Measured by:	TD



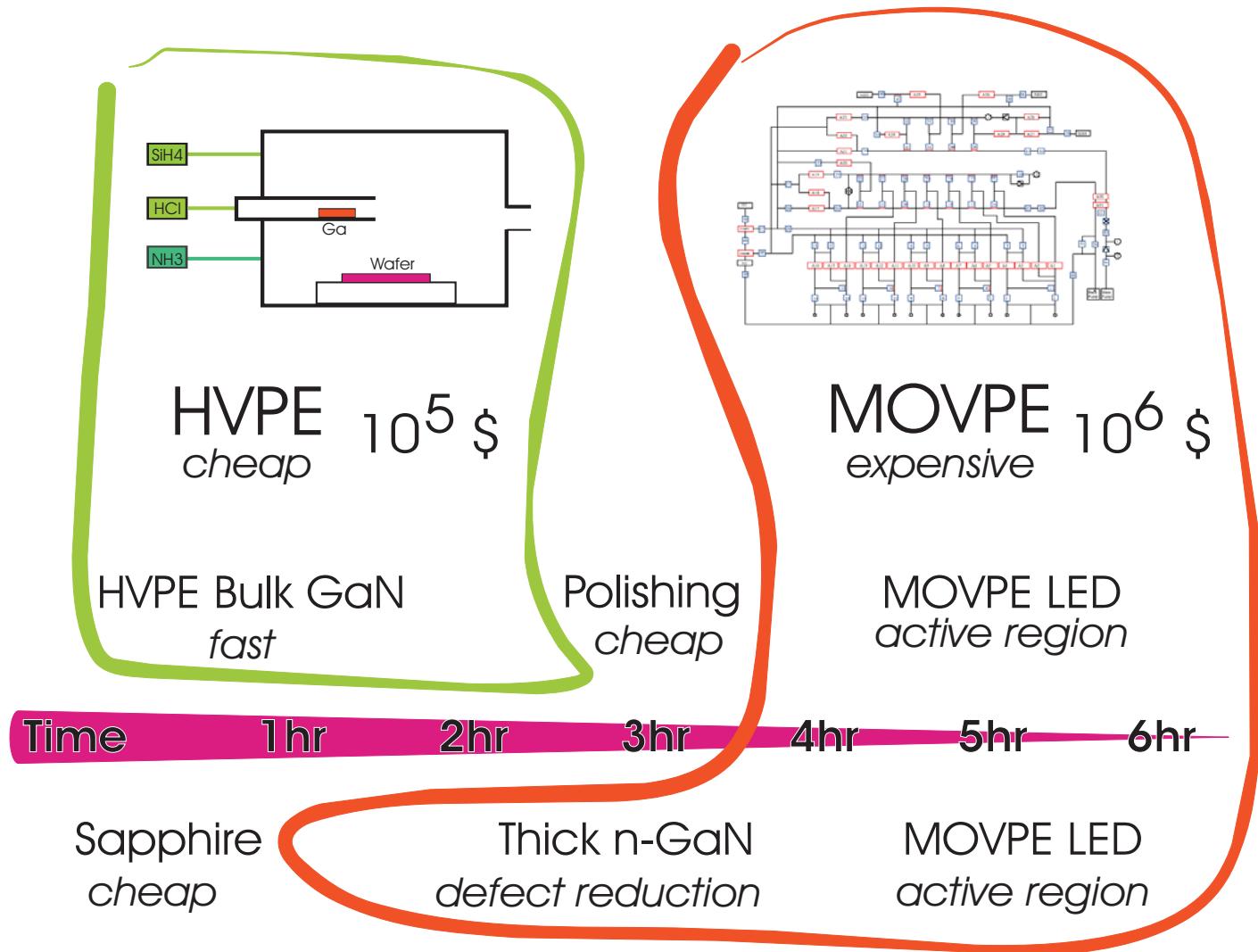
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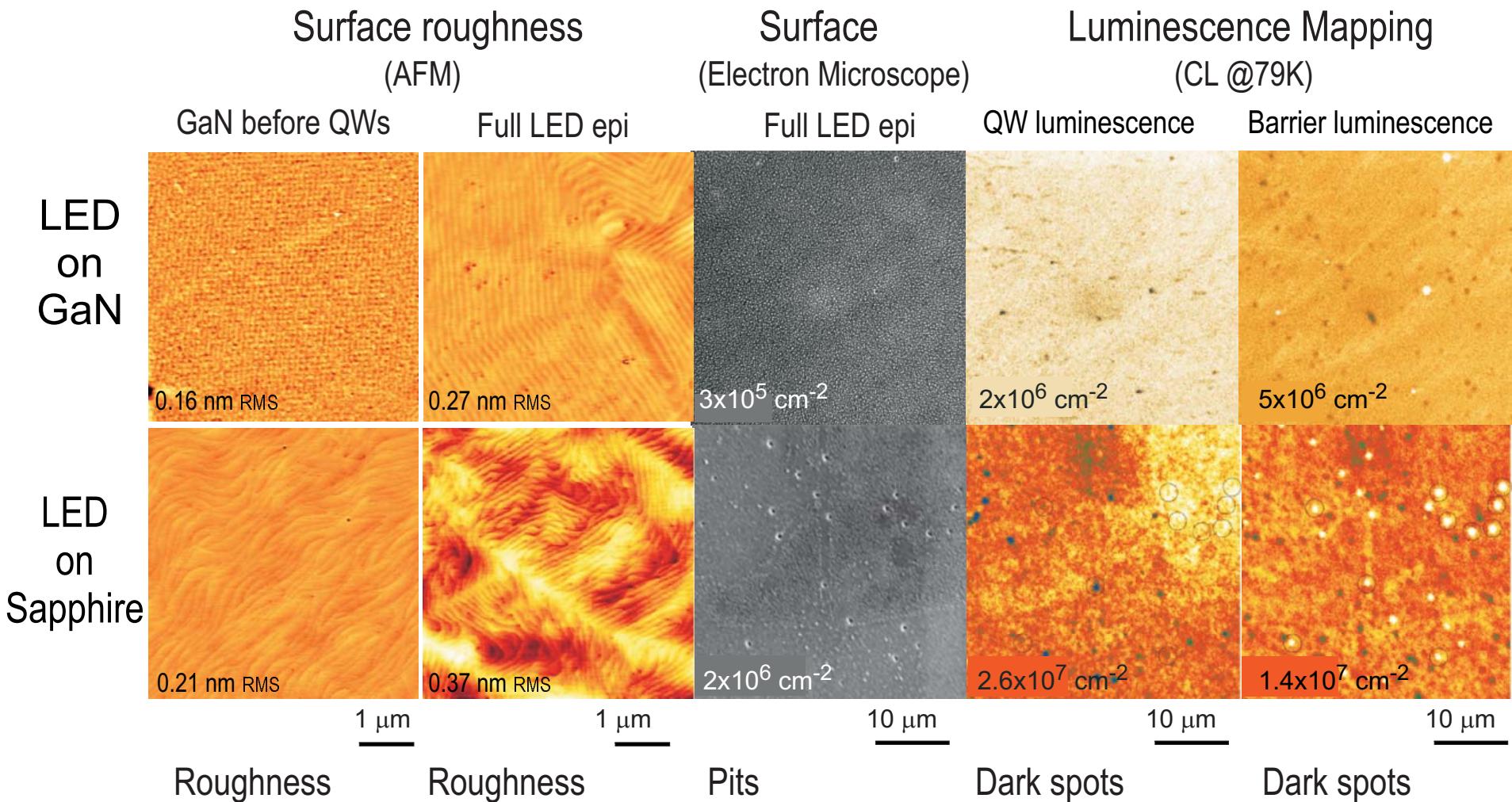
Cost Advantage of Homoepitaxy

tool time to fight defects?



Sapphire and GaN Substrates in Comparison

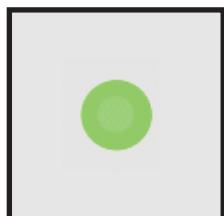
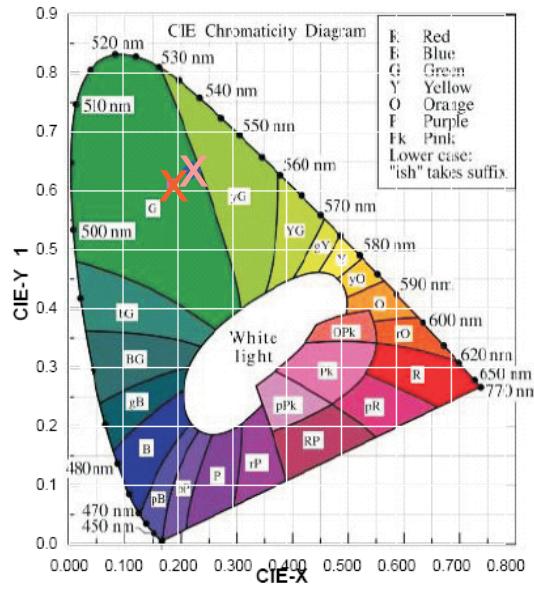
counting defects



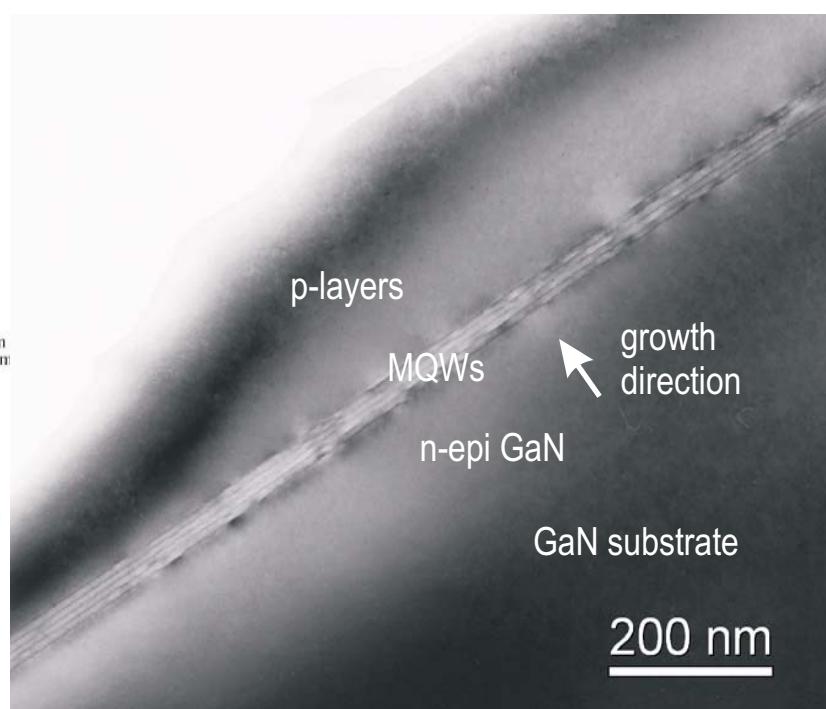
T. Detchprohm *et al.* J. Crystal Growth **298**, 272-275 (2007).

Green c-Axis LED Epi on GaN

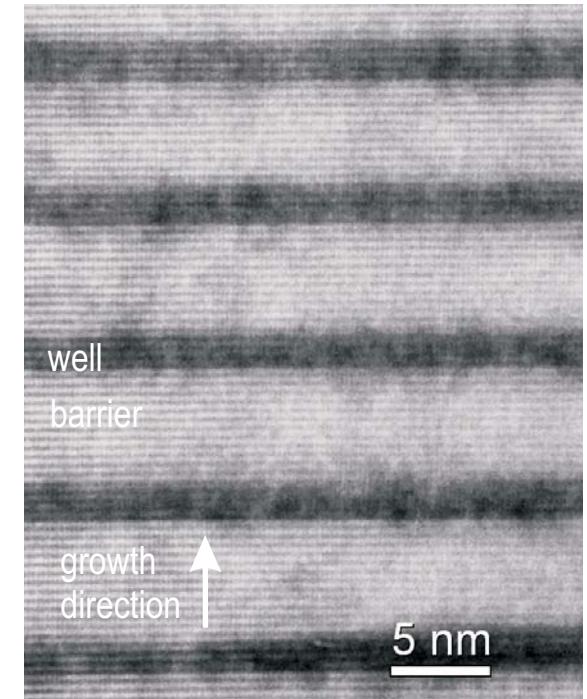
current status, scratch diode



1x1 cm²



Transmission electron microscopy (TEM)
cross-sectional views

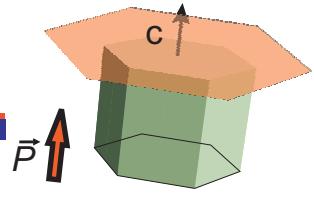
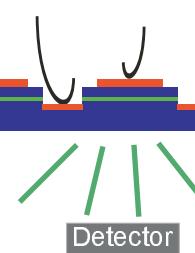


High resolution TEM

M. Zhu, et al.
Mater. Res. Soc. Symp. Proc. 1040E (2008)
J. Electron. Mater. (2008 *in print*)

Current Dens. (A/cm ²)	CIE-X	CIE-Y	Wavel. (nm)	FWHM (nm)	Sat. (%)	Vf (V)	LOP (mW)	Lum. (L)	Efficacy (L/W)
2	0.225	0.635	531.5	55	65	6.06	3.79	1.86	15.38
5	0.19	0.611	520.1	58	56	8.92	11.01	4.90	5.49

through substrate



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Prospect of Non-Polar Growth

control polarization

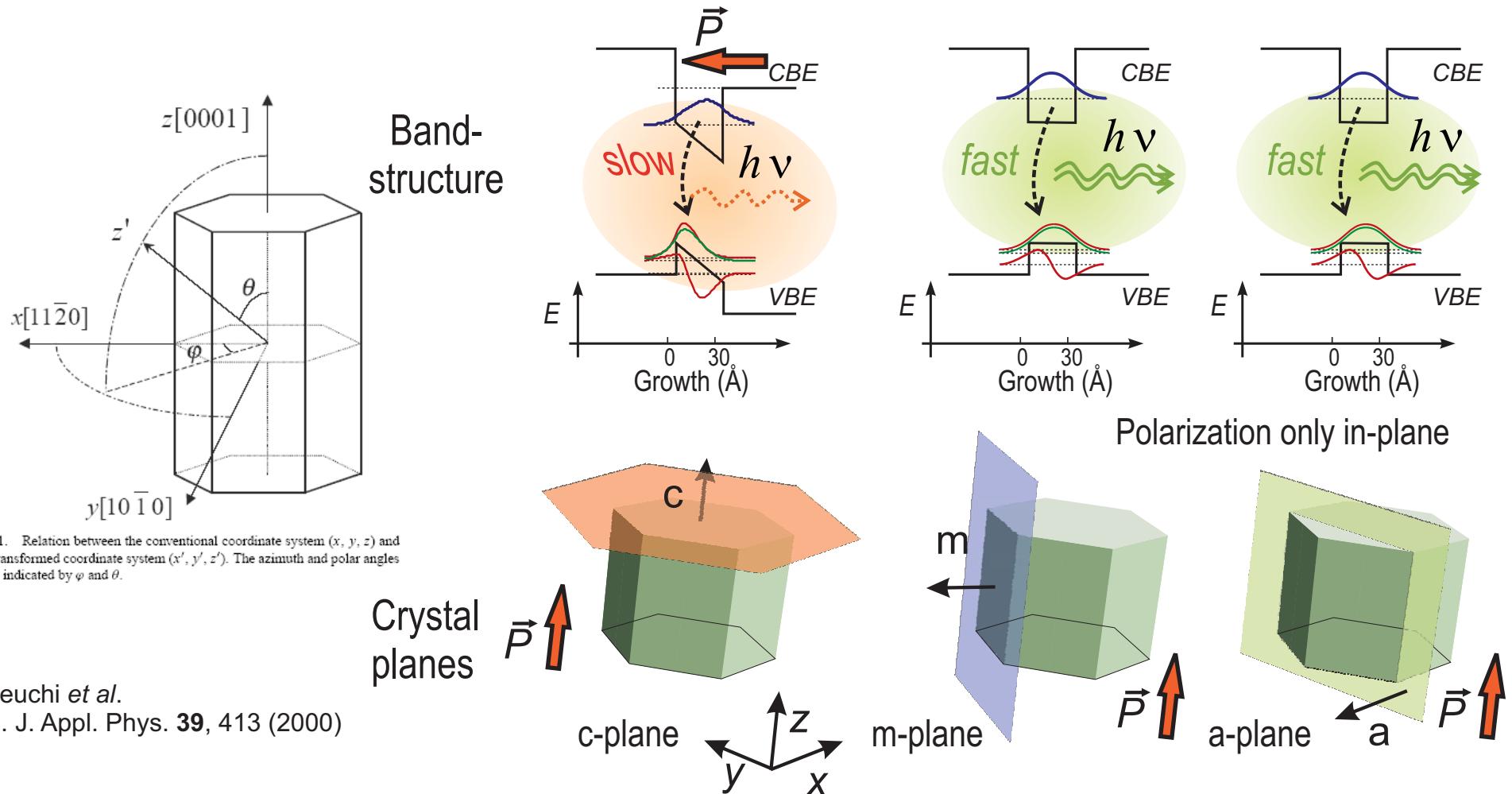


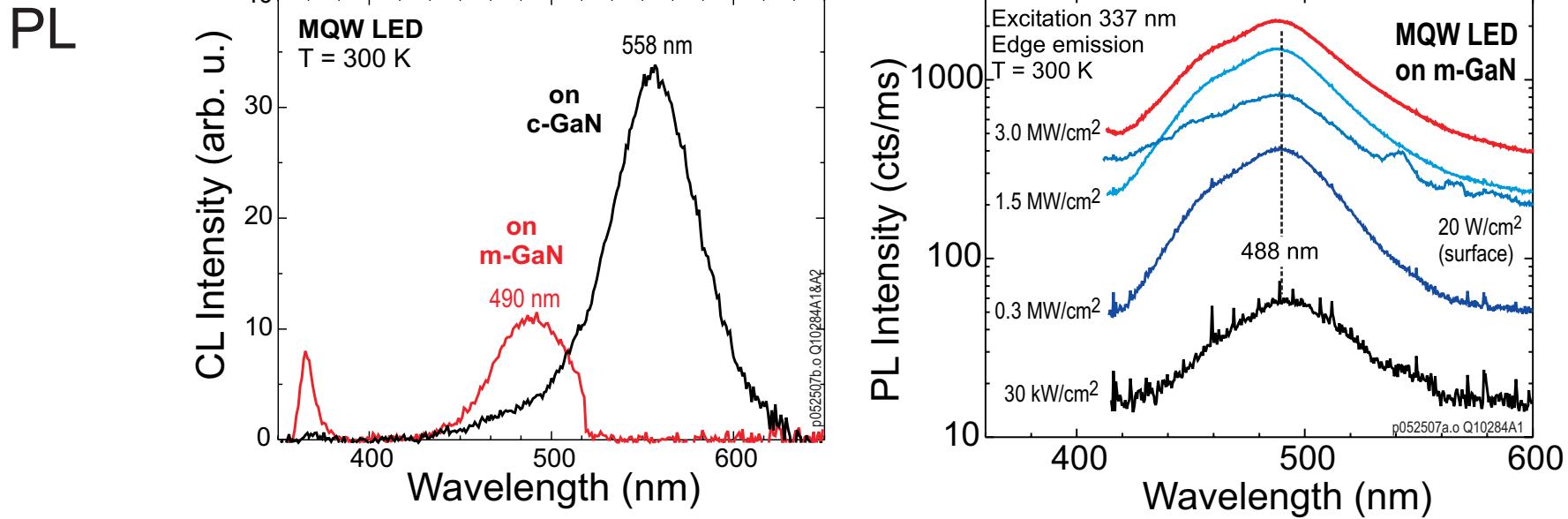
Fig. 1. Relation between the conventional coordinate system (x , y , z) and a transformed coordinate system (x' , y' , z'). The azimuth and polar angles are indicated by φ and θ .

Takeuchi *et al.*
Jpn. J. Appl. Phys. **39**, 413 (2000)

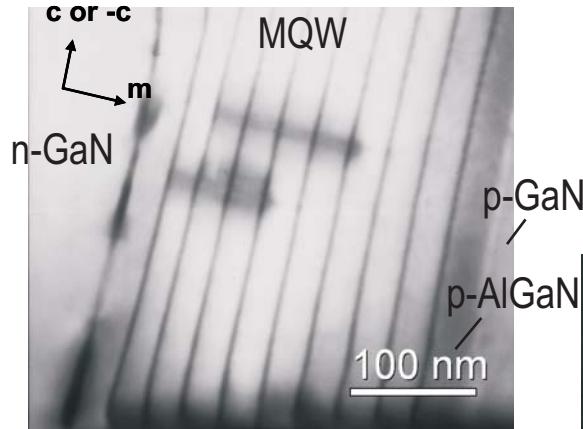
C. Wetzel *et al.*
5th Int Workshop Bulk Nitride Semicond. 2007

Non-Polar m-Plane Homoepitaxial LED

control polarization



TEM



M. Zhu, S. You, Y. Wang, et al.
unpublished (2007)

Shorter emission wavelength

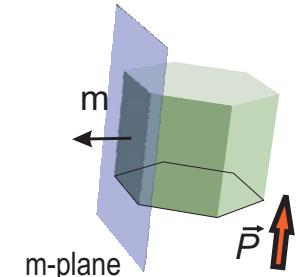
no polarization

No peak shift with excitation density

no QCSE

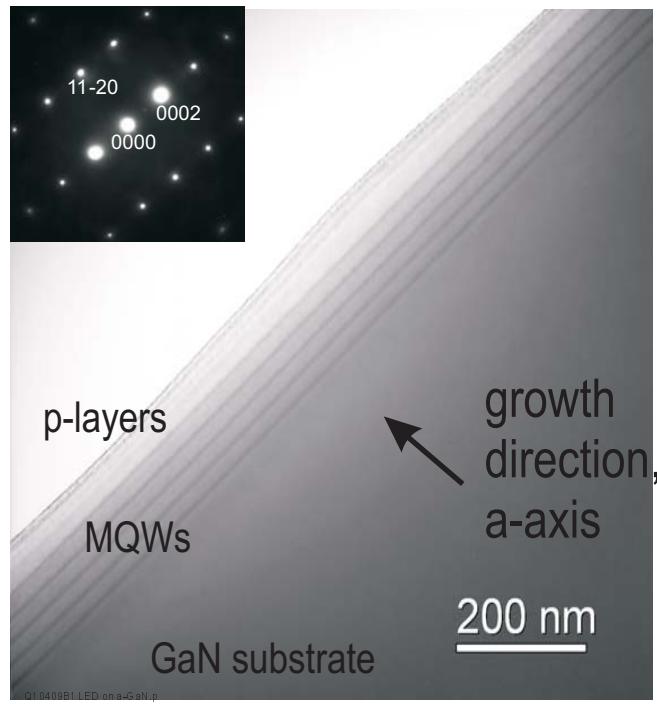


T. Detchprohm, J. Senawiratne et al.
5th Int Workshop Bulk Nitride Semicond. 2007



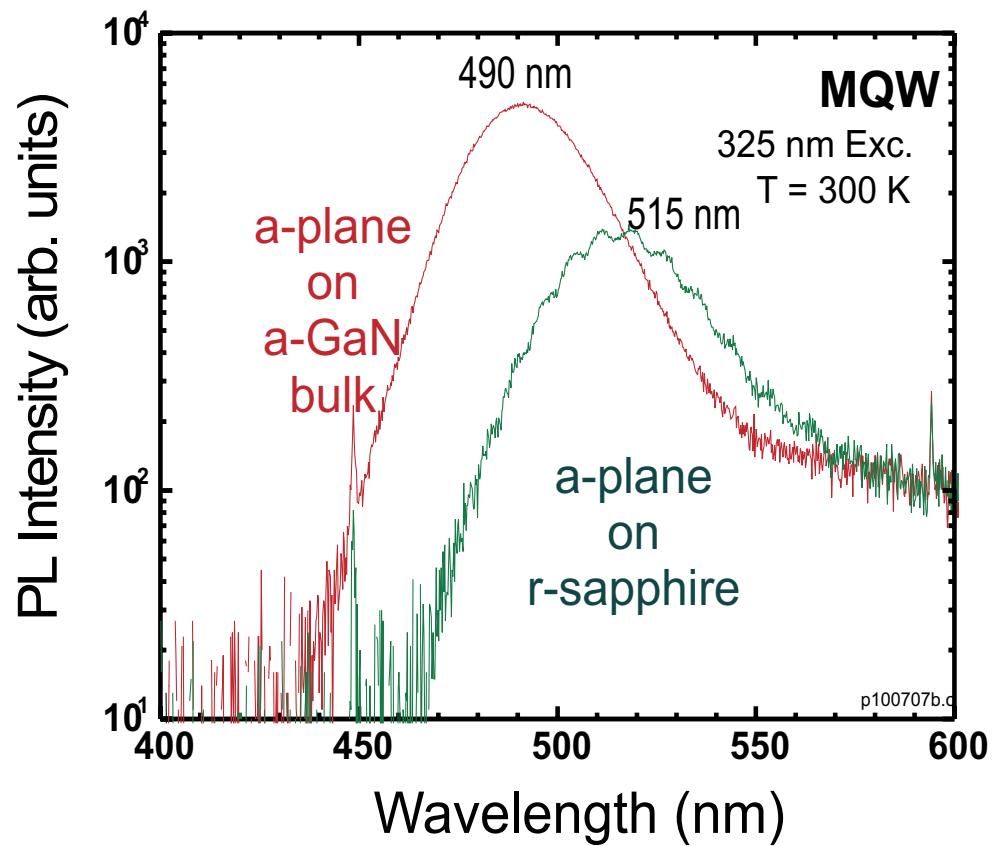
Non-Polar a-Plane Homoepitaxial LED

control polarization



TEM LED

M. Zhu, S. You, Y. Wang, et al.
unpublished (2007)

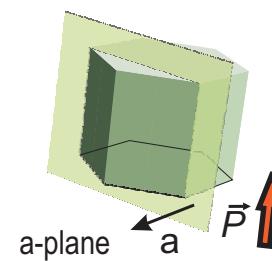


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P011507a.c

PL MQW

T. Detchprohm, et al.
5th Int Workshop Bulk
Nitride Semicond. 2007



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Summary

solving the “green gap” in LED technology

- Performance yield spectroscopy (not shown) direction for higher EQE
- V-defect avoidance in MOVPE lateral uniformity throughout yellow
- Low-dislocation density bulk GaN substrate $< 5 \times 10^6 \text{ cm}^{-2}$
- Conformal epitaxy replicate substrate quality throughout active region
- Polarization control polar c-axis, non-polar a- and m-axis growth
- Stabilize LED performance eliminate wavelength shift in non-polar axis growth



*fill-in
the
Green Gap !*

