An Overview of GaN-related Materials and Devices and Work on Power LED Chips at ASTRI

S. M. Zheng, H. S. Chu, Joe Chan, Iris Sit, S. Yuan, L. M. Lin, X. F. Shao, G. Liu, and F. Lee

LED Devices Division

Device Fabrications, MPT Group

Hong Kong Applied Science and Technology Research Institute

(ASTRI,香港应用科技研究院)

Dr. Shu Yuan, Nov. 27, 2009 For ASTRI Seminar

MPT: Key Technologies & Accomplishments

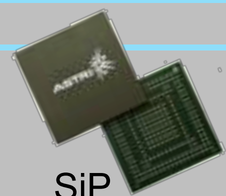
Display Systems

Intelligent Display

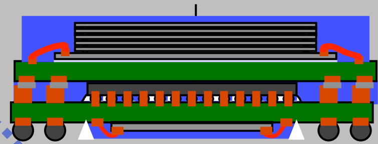
Backlight, TV & Touch Panel

Pico-Projector

Advanced Packaging Technologies



SiP



3D Packaging

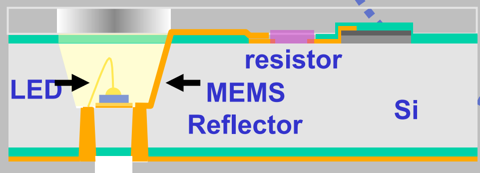
Energy Harvesting By Piezo

- 111 US patents filed
- 70 industry contracts
- HK$35M industry contributions

LED Lighting

Street Lamp

Intelligent Indoor Lighting



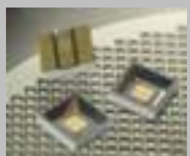
WL Packaging

Healthcare Electronics

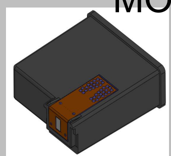
Tyre Pressure Monitoring System

Device Fabrications

MOEMS



Vertical LED



Ink Jet Head

Green Battery

Wind Charger

Photonic Components

Anti-Shaking Camera

PV Module

WL Actuator

LED Devices Division

Industry

NANOFILM

新世紀光電股份有限公司
Genesis Photonics Inc.

ROHM AND HAAS

WEC Superabrasives
捷斯奧企業有限公司

KINIK COMPANY Ltd.

世纪晶源科技有限公司
Century Epitech Co., Ltd.

EPISTAR corporation
晶元光電股份有限公司

Largest compound semiconductor device maker in China, a Hong Kong company

ASTRI

Universities

香港城市大學
City University of Hong Kong

The Chinese University of Hong Kong

香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

國立交通大學
National Chiao Tung University

THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

ANU THE AUSTRALIAN NATIONAL UNIVERSITY

World's largest red LED chip maker, Asia ex-Japan 's largest GaN LED chip maker (> 150 MOCVDs!)

ASTRI Technology Licensees

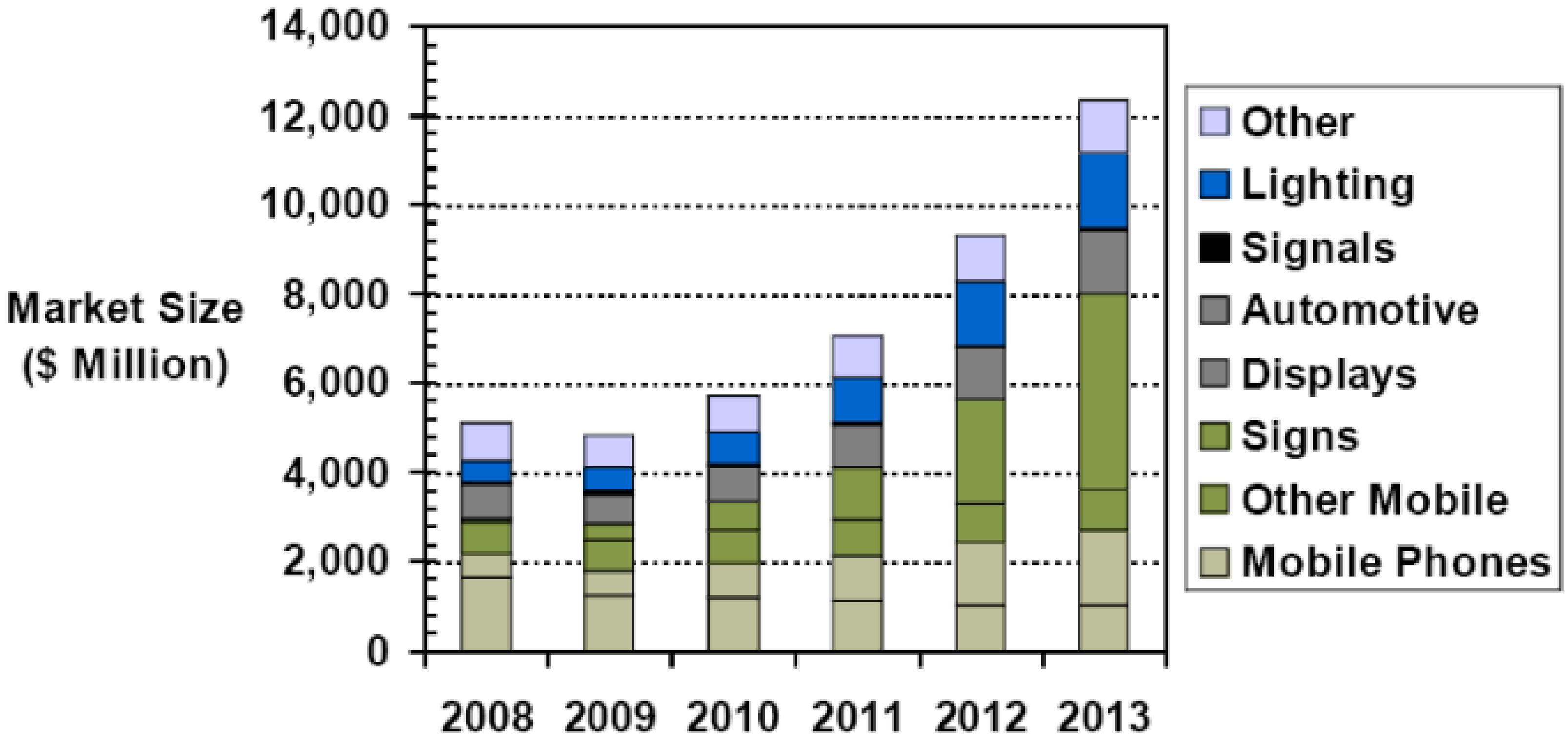
ASTRI

Outline

1. Introduction to GaN Devices
2. GaN and Related Materials
3. GaN LEDs
4. Work on Power GaN LEDs at ASTRI
5. Conclusions

High Brightness LED Market Forecast

HB LED Market Forecast 2009-2013



Source: Strategies Unlimited, Blue 2009, June 2009

Common Semiconductors

Group IV: Silicon (Si), Germanium (Ge)

Integrated Circuits (ICs) , photodetectors (digital cameras)

Group III-V: **GaN**, GaAs, InP, MCT (HgCdTe), ...

Optoelectronic devices

Light emitting diodes (LEDs): mobile phones, lighting, …

Laser diodes: Blu-ray DVDs, fiber-optic communications

Photodetectors, modulators, …

Electronic Devices

Transistors (mobile phones, wireless basestation)

Group IV-VI: PbTe, PbSe, ...

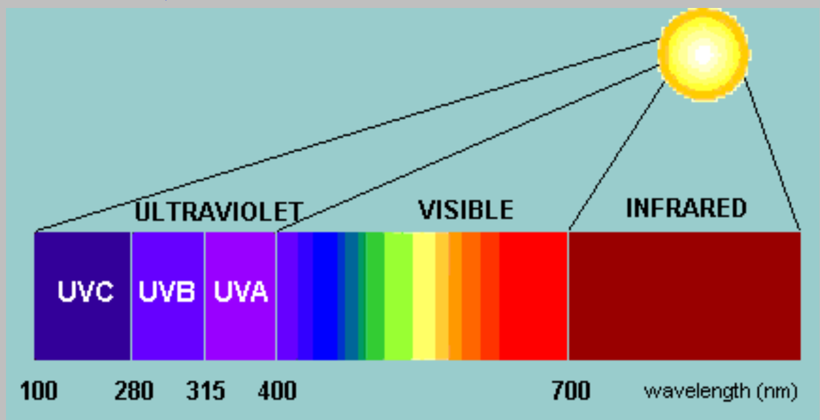
Optoelectronic devices

GaN Optoelectronic Devices

light emitting diodes (LEDs)

blue/UV laser diodes

GaN only (since 1994)



Without GaN, the full color spectrum is not complete!

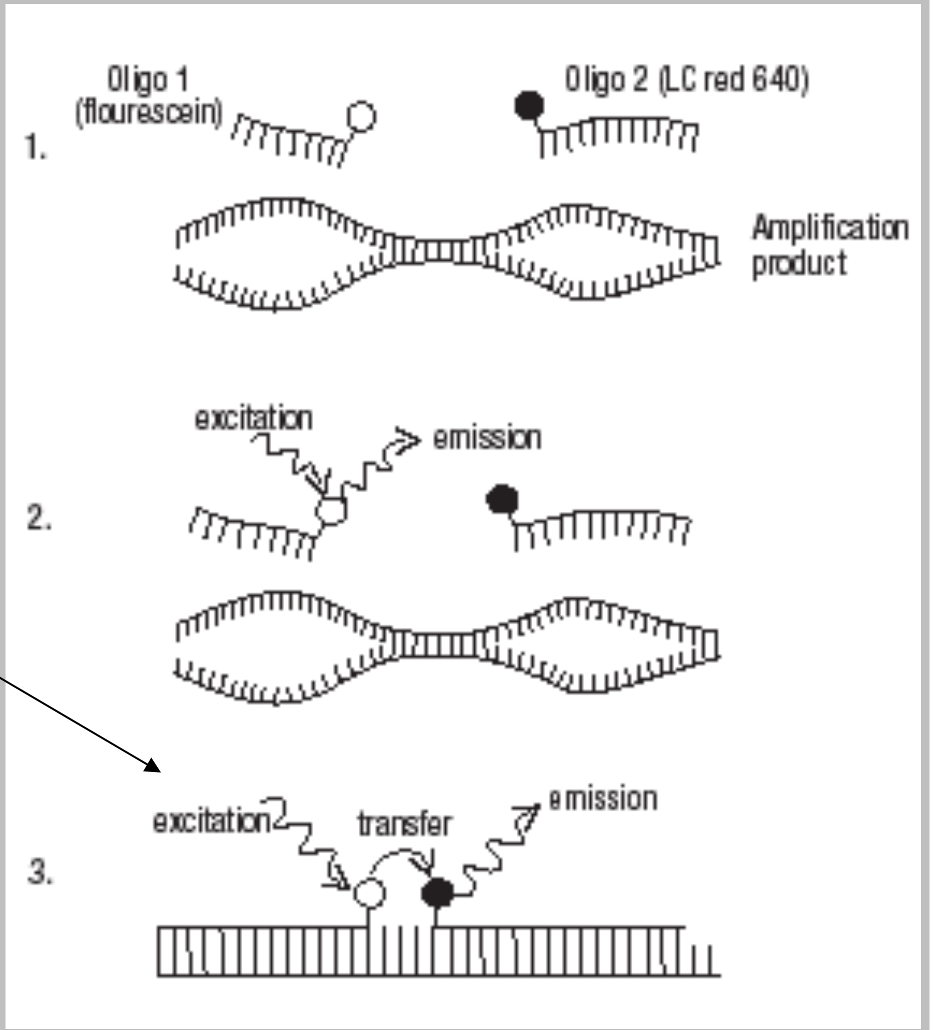
older semiconductors (since 1960's) (GaAs, InP, etc.)

GaN Blue/UV Lasers

Blu-ray DVD:

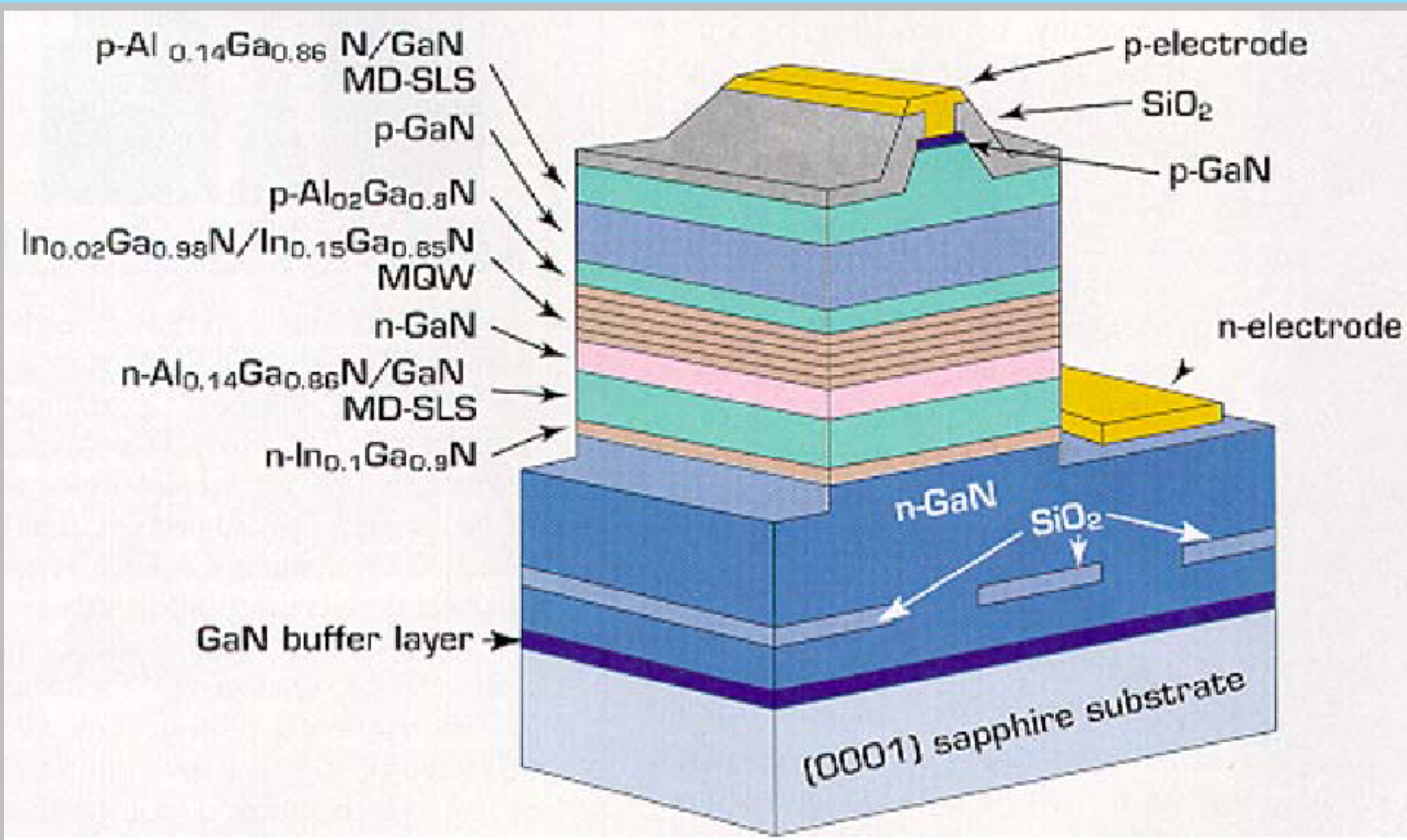
Playstation 3

GaN laser diodes inside as light source



Biochips

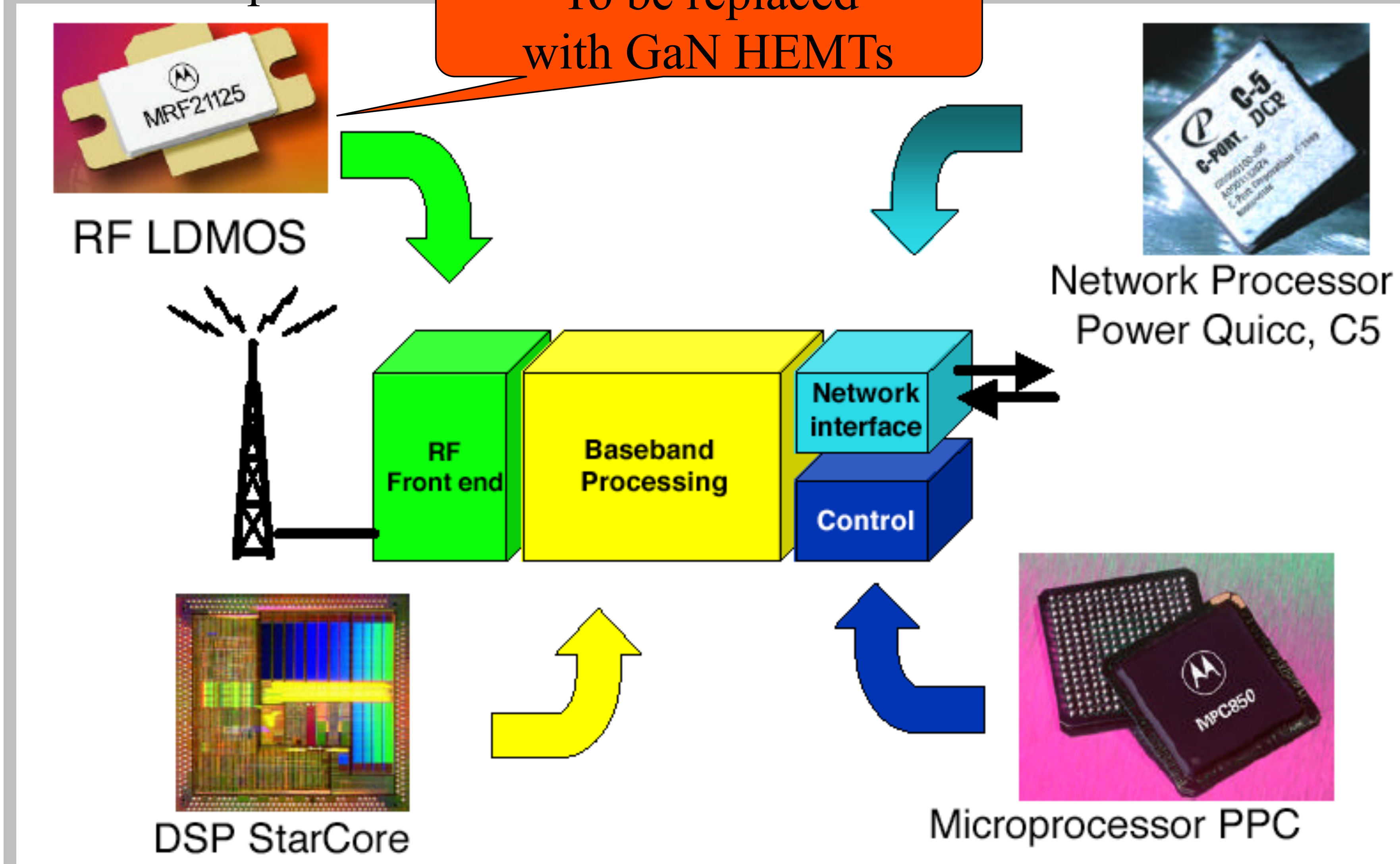
Schematic Structure of GaN Lasers



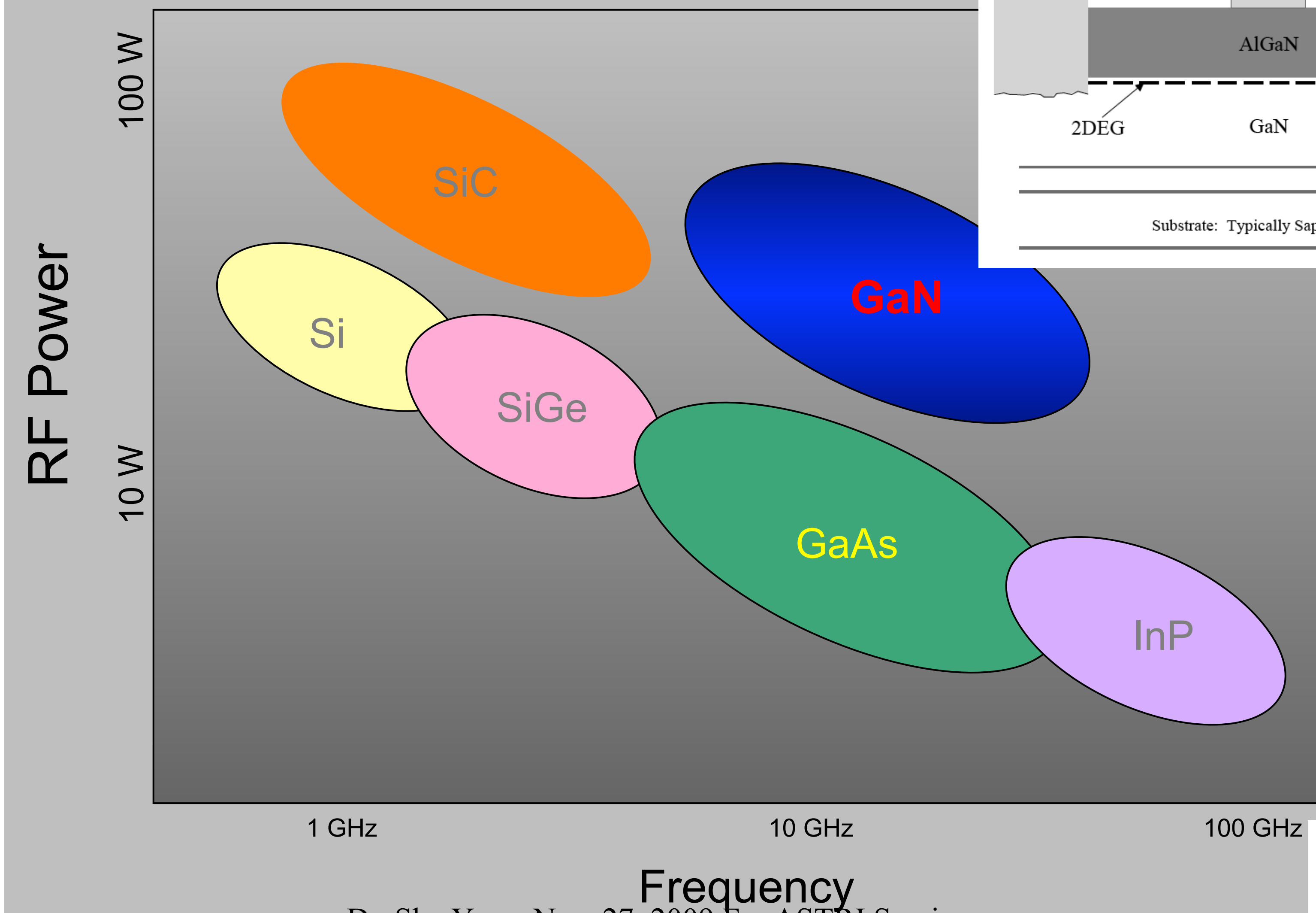
Wireless Base Station Architecture

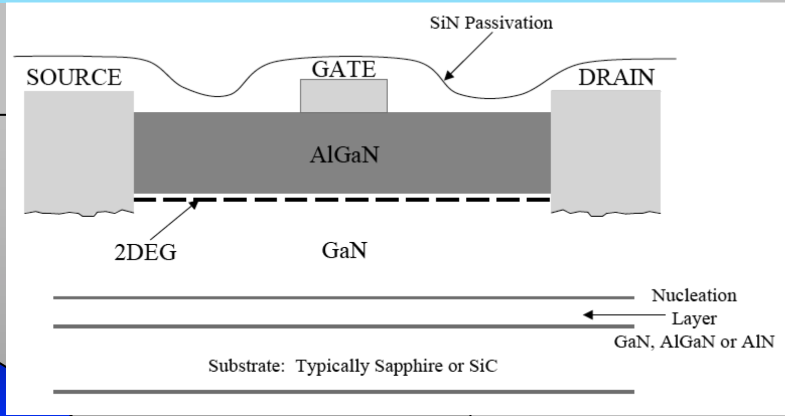
Power Amplifier

To be replaced with GaN HEMTs



Electronic Devices (RF Power Transistors)

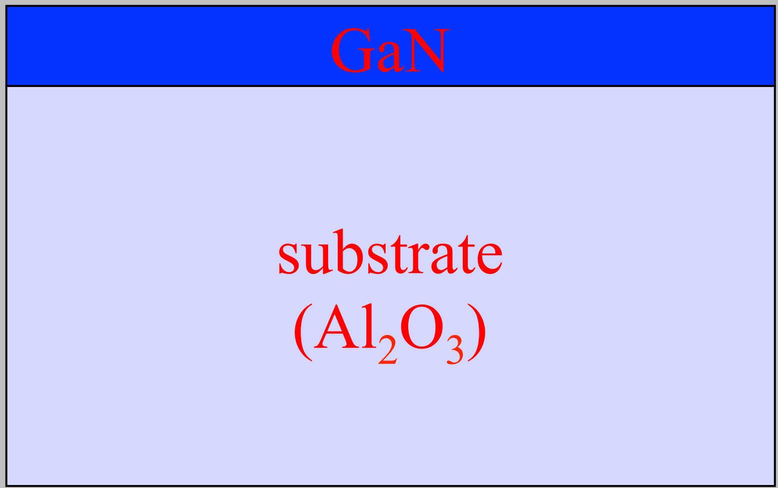




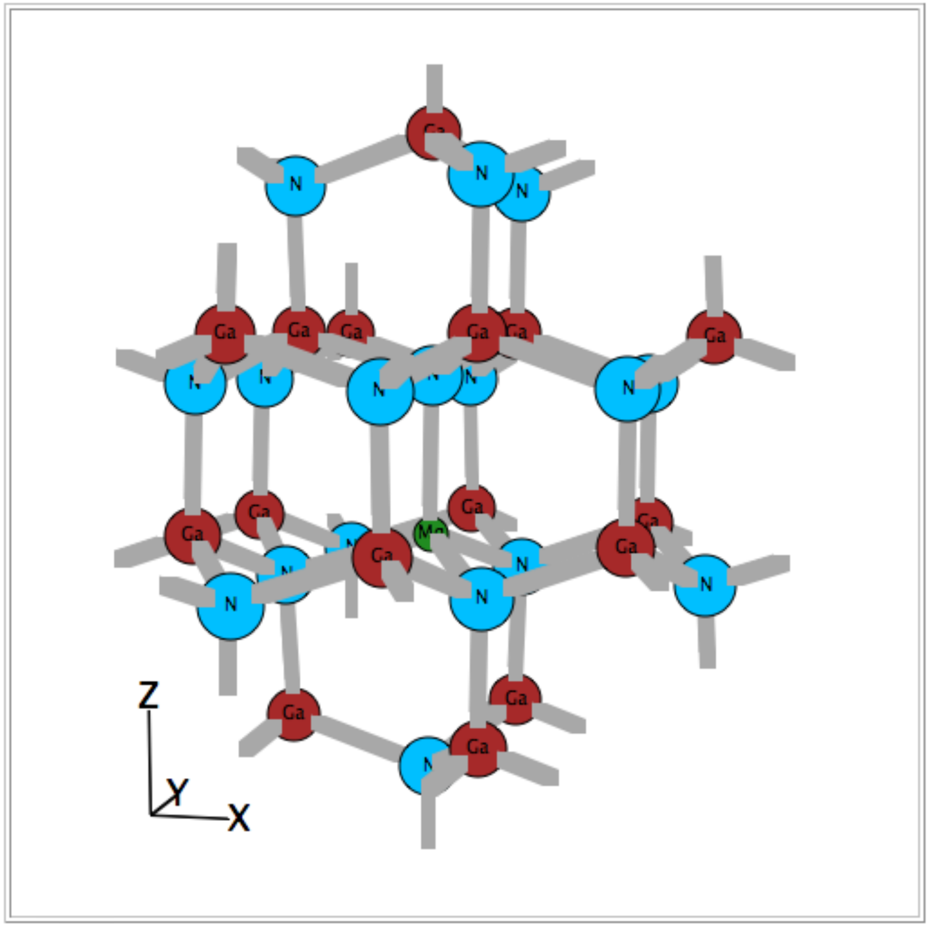
Outline

1. Introduction to GaN Devices
2. GaN and Related Materials
3. GaN LEDs
4. Work on Power GaN LEDs at ASTRI
5. Conclusions

GaN and Related Materials



GaN is deposited (grown) on a substrate like sapphire (Al_2O_3) or SiC due to lack of native (cheap) GaN or AlN substrate.

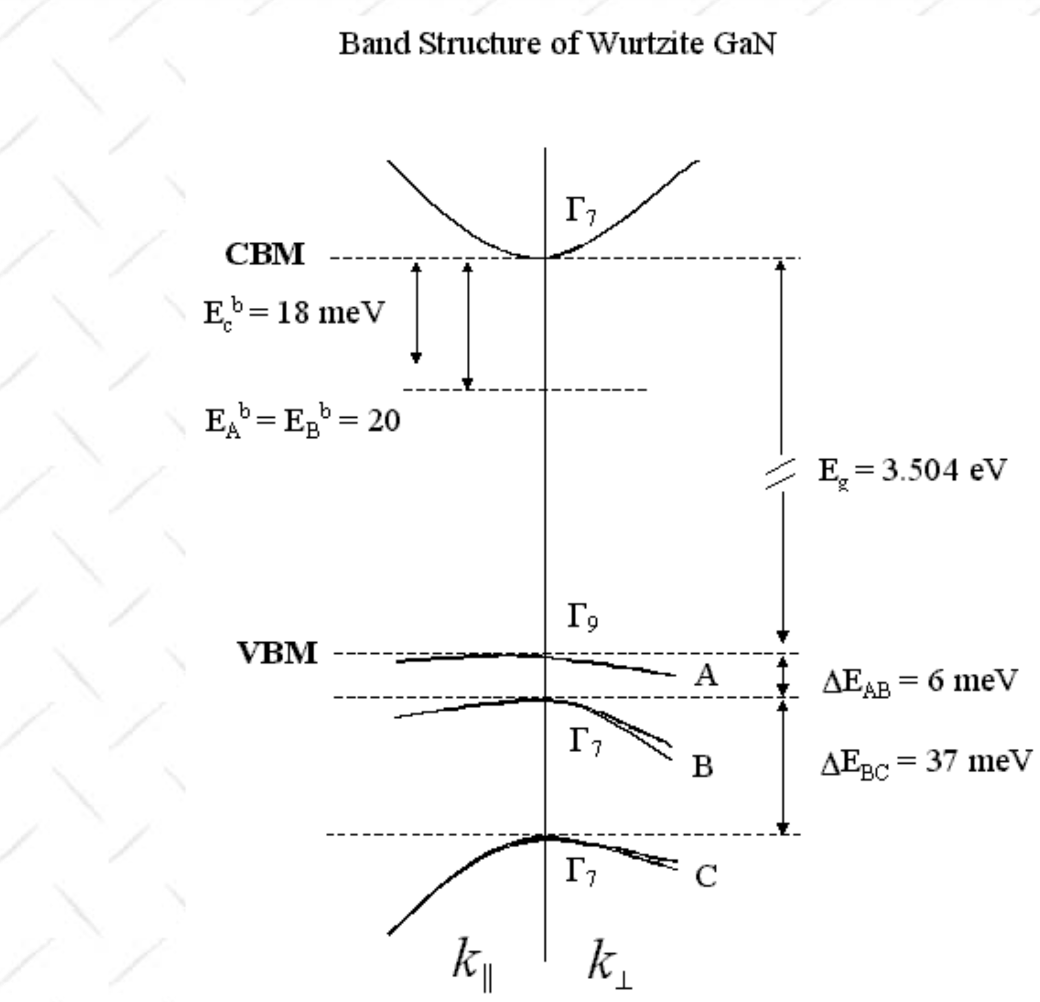


GaN crystal structure

http://newton.ex.ac.uk/research/qsystems/people/fall/gan.html

GaN Band Structure and Band Gap

Direct band gap semiconductor, Eg ~ 3.5 eV (λ ~ 350 nm)



Band struct

ASTRI

GaN Alloys: AlGaN, InGaN, AlGaInN

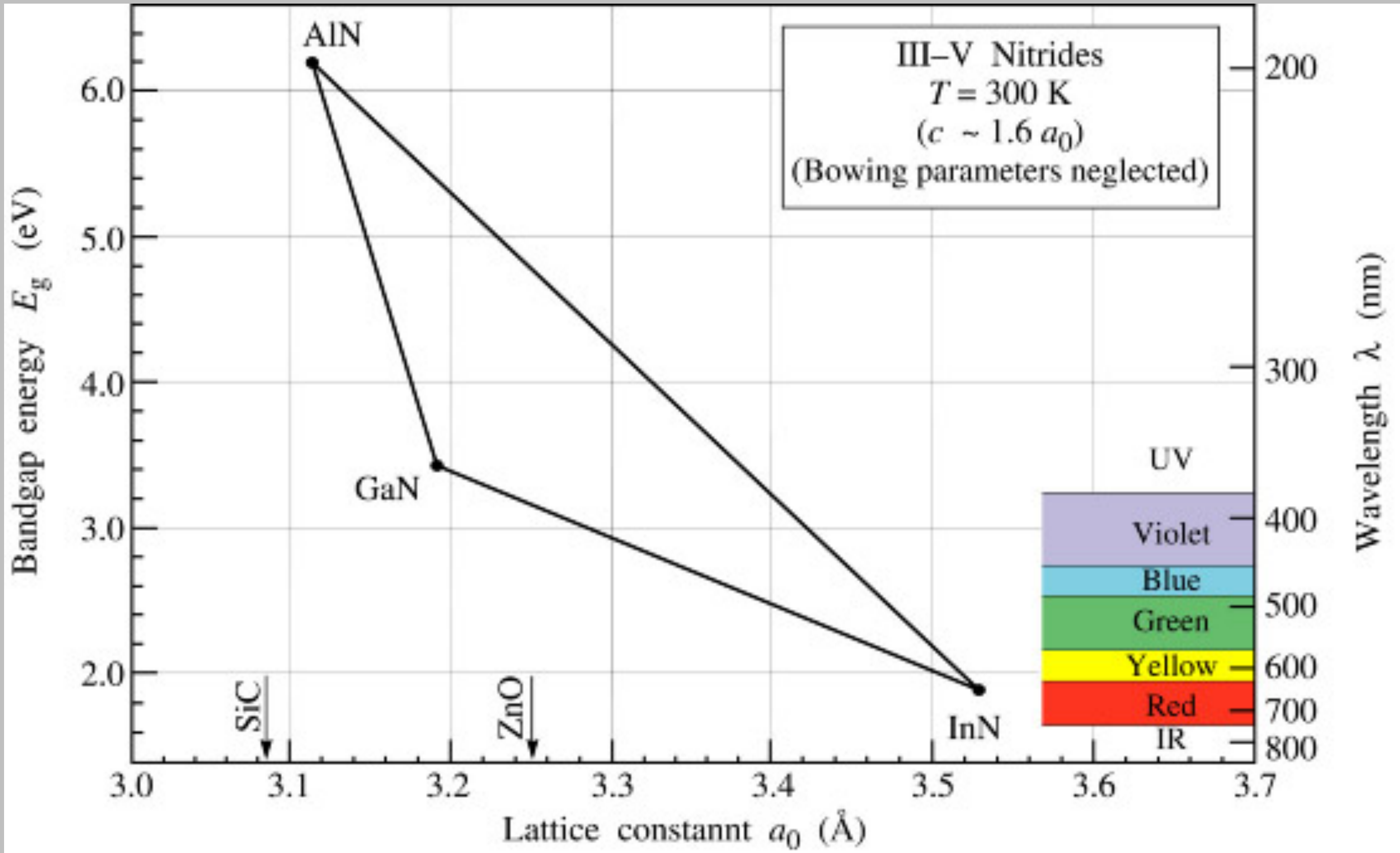
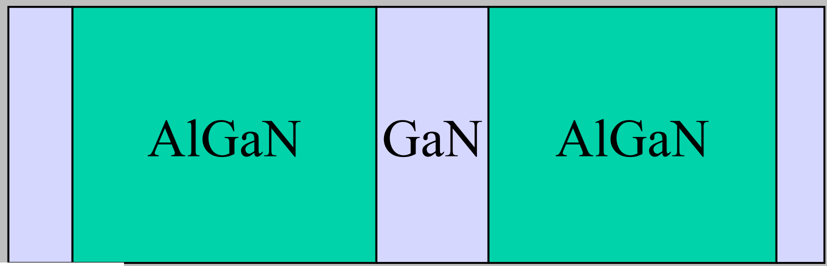
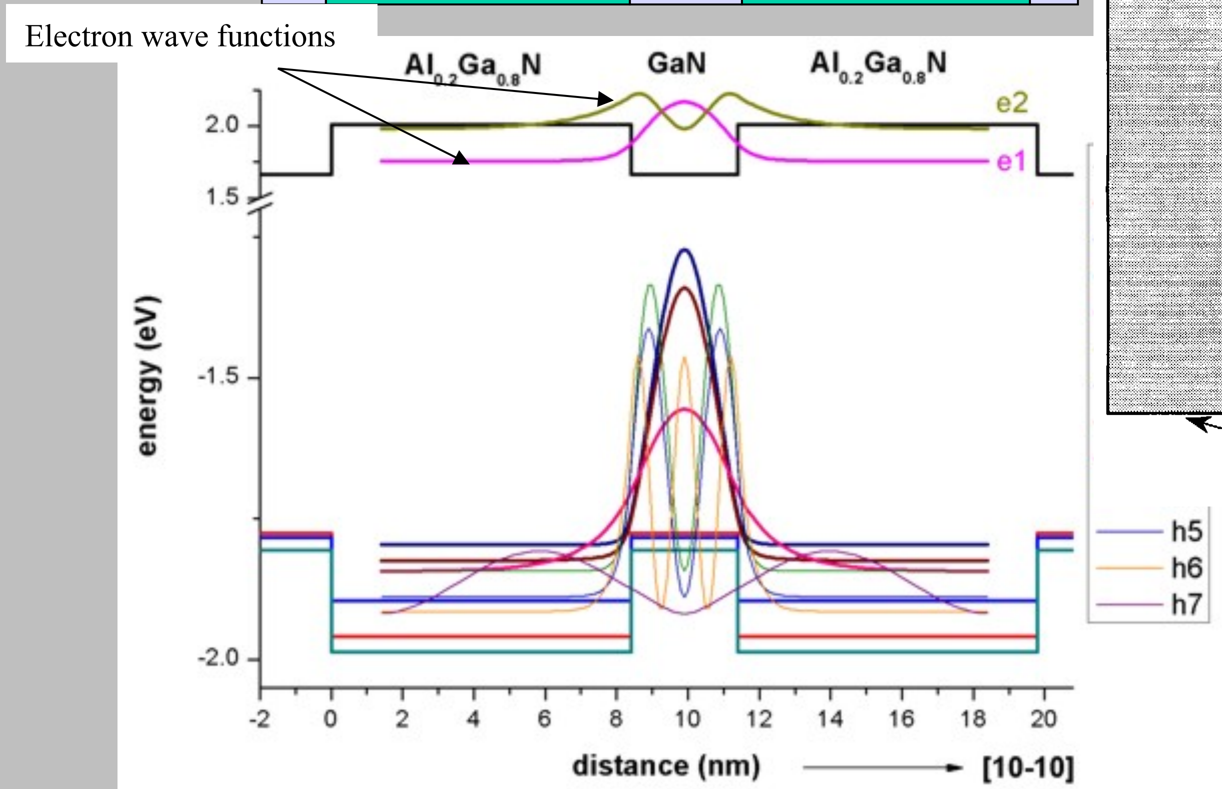
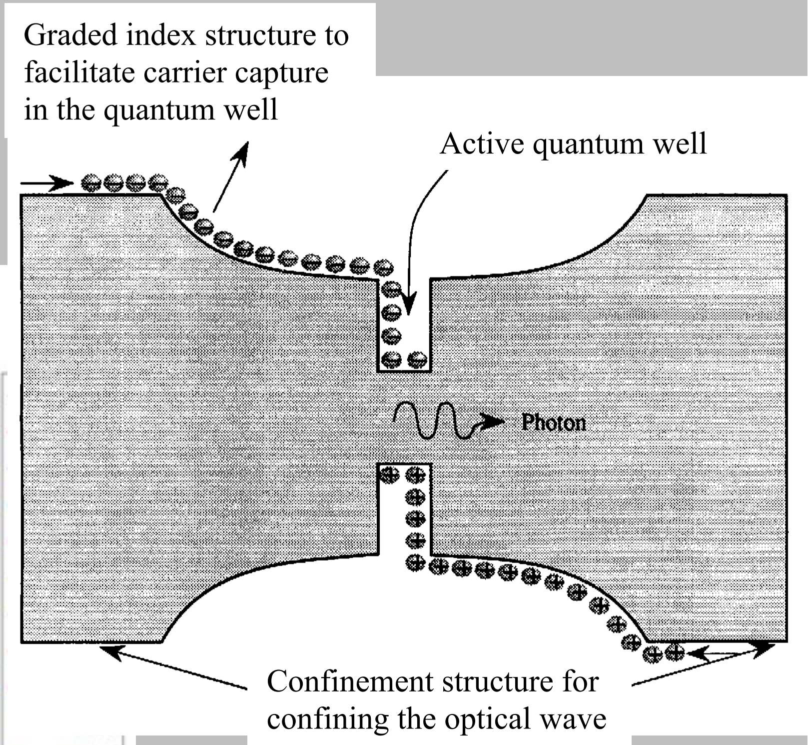


Fig. 7.12. Bandgap energy versus lattice constant of III-V nitride semiconductors at room temperature.

GaN Heterostructures: Core of GaN Devices







Light generation in a quantum well

Electron and hole wave functions in GaN/AlGaN quantum wells

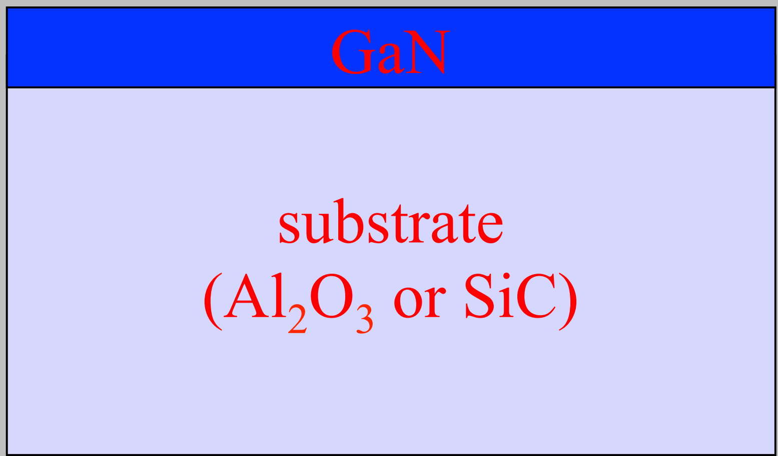
(no strain along this growth direction)

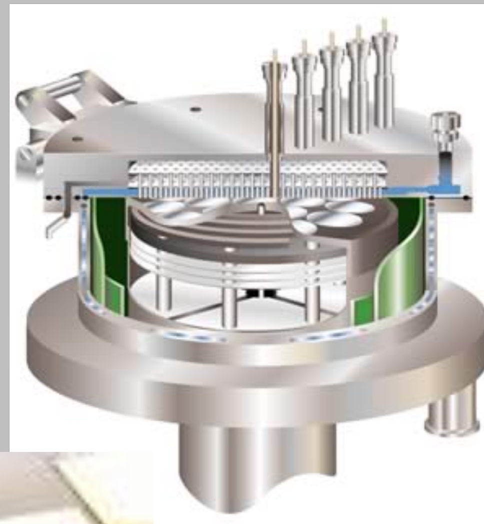
(Source: http://www.nextnano.de/nextnano3/tutorial/1Dtutorial_GaN_AlGaN_QW_dispersion.htm)

Growth of GaN Epitaxial Layers

Growth of GaN by metal organic chemical vapor deposition (MOCVD) or by molecular beam epitaxy (MBE)

$$(CH_3)_3Ga + NH_3 \rightarrow GaN + CH_4\uparrow + H_2\uparrow$$

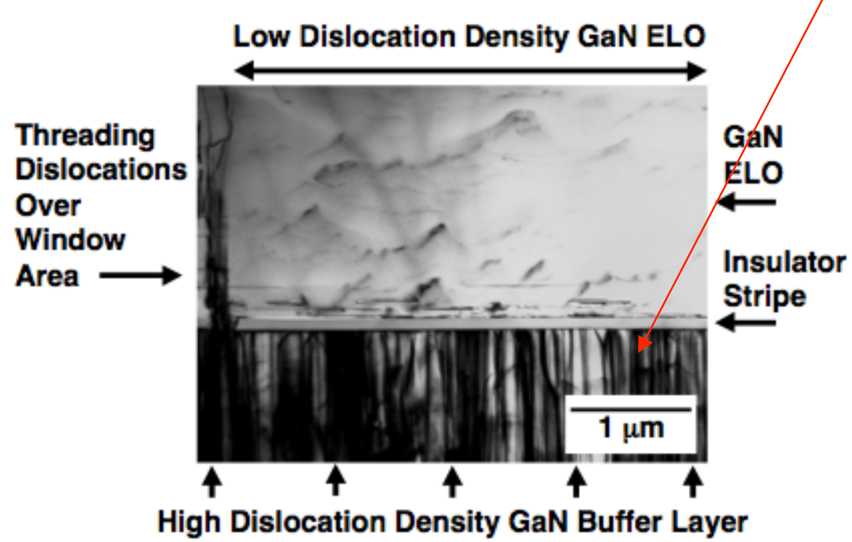


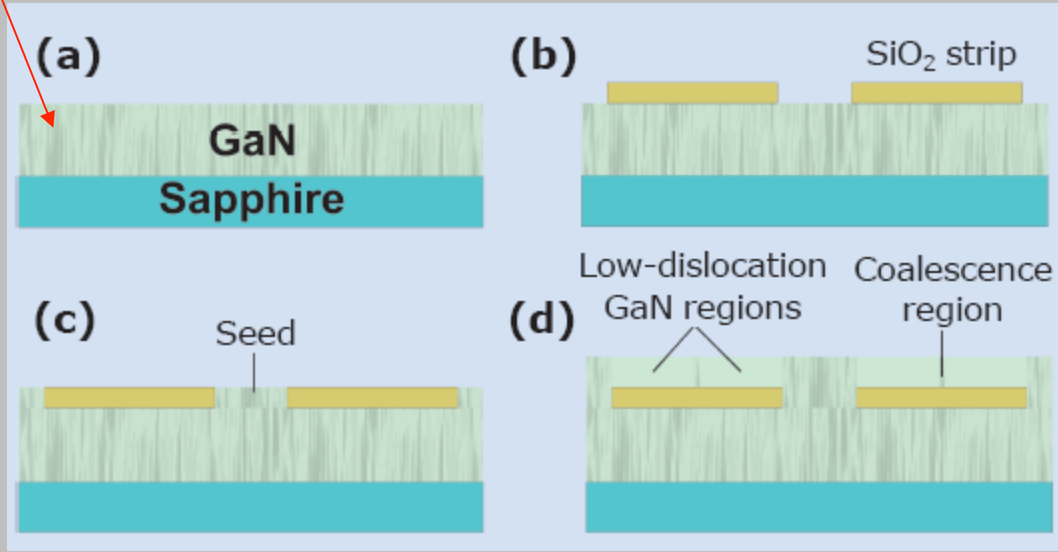


An MOCVD reactor

Defects and Defects Reduction in GaN

Extraordinarily high defect density in GaN is a big problem.



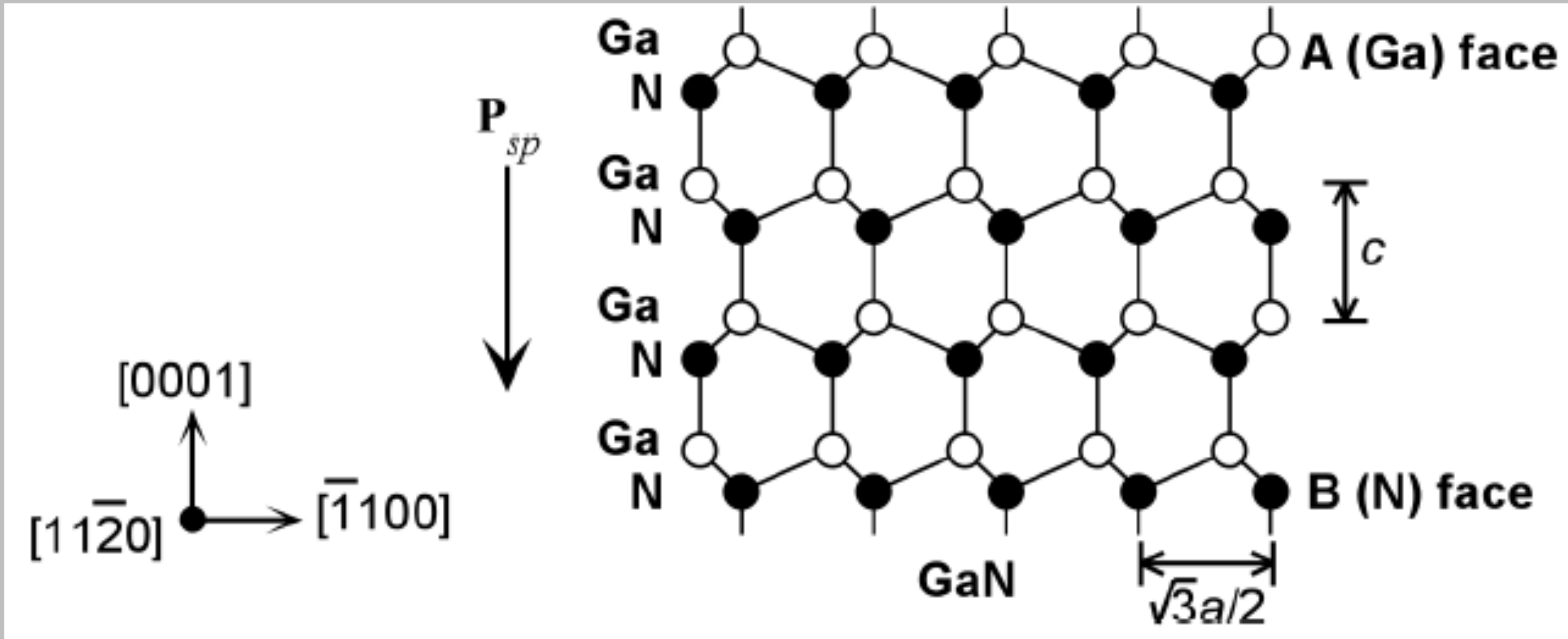


(a) First growth (b) deposition of SiO_2
(c) Second growth, (d) Final product, lower defect density on top of the oxide stripes

Dislocations grow mainly vertically, so epitaxial lateral overgrowth (ELO) is used widely to reduce defect density.

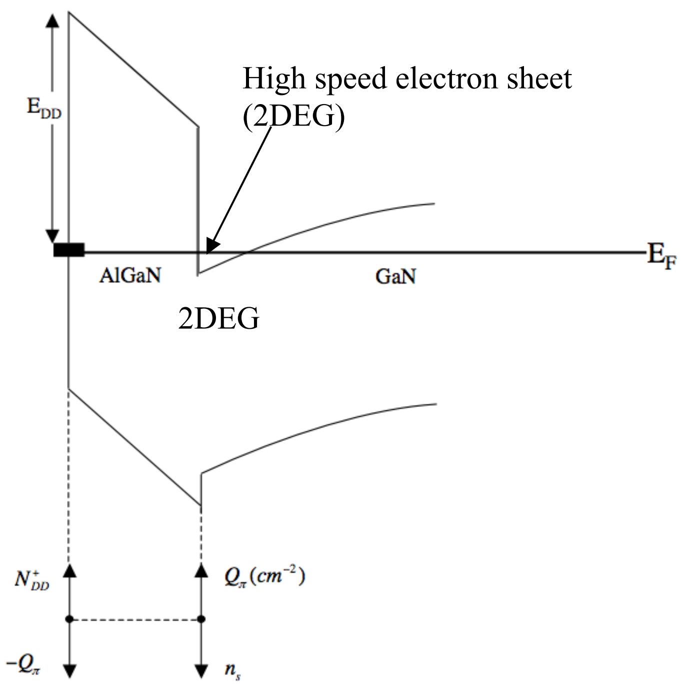
Polarization Effects

Spontaneous polarization : dipole moment between Ga and N

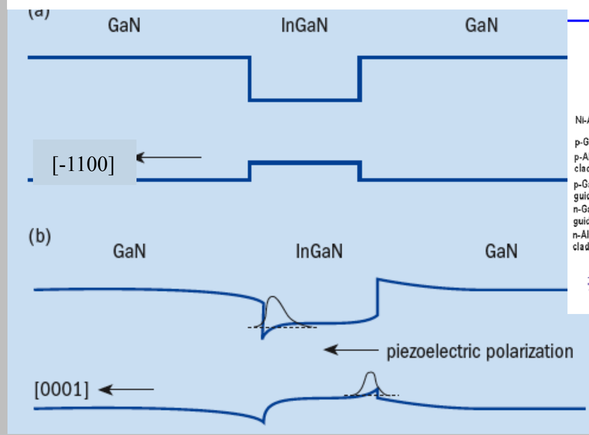


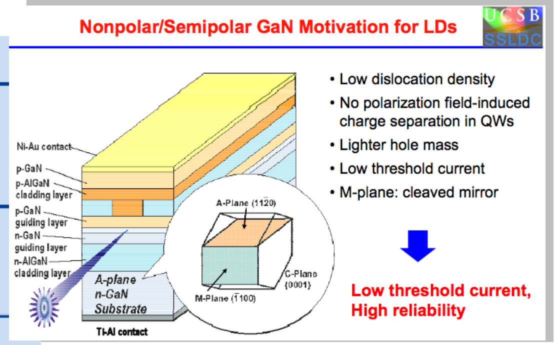
Polarization Effects on Transistors and LEDs

Good for high speed electronic devices (HEMT)



Bad for LEDs and lasers

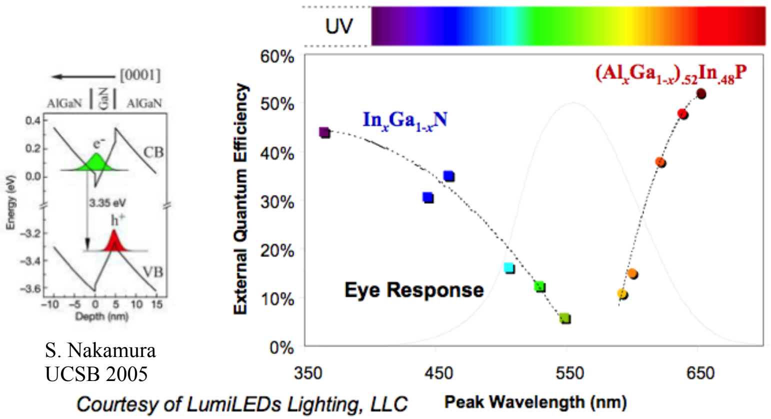




Removing polarization by growth on nonpolar GaN substrate

Polar GaN: LED Efficiency vs. Wavel

- Polarization fields in QWs create problems in **green, ultraviolet**



S. Nakamura UCSB 2005

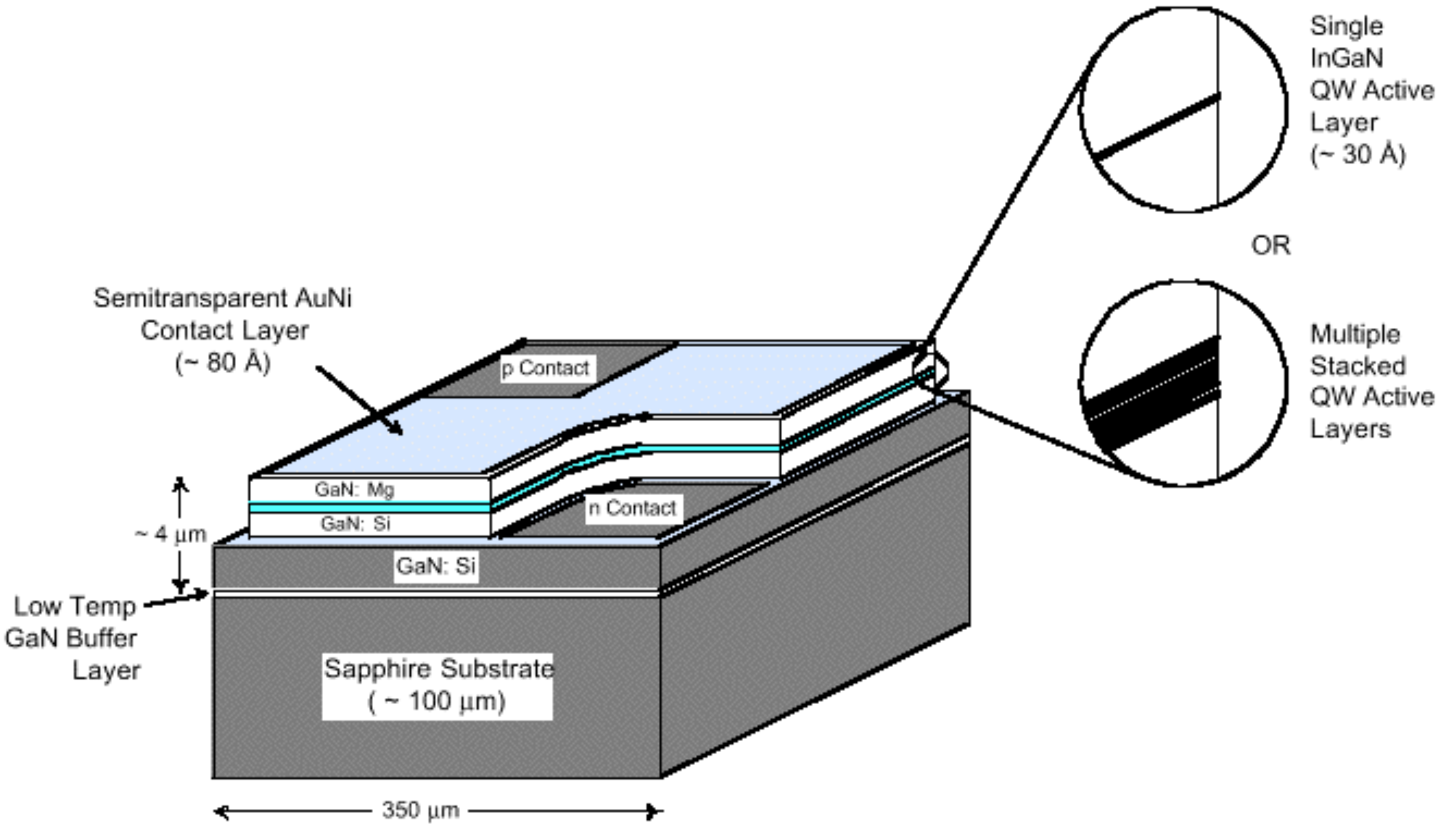
Courtesy of LumiLEDs Lighting, LLC

Outline

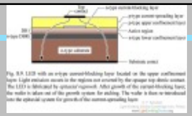
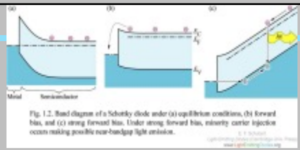
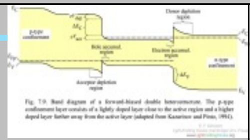
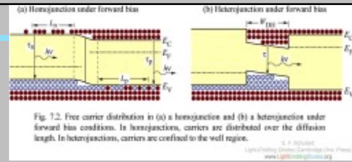
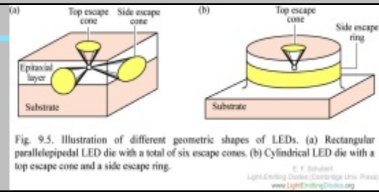
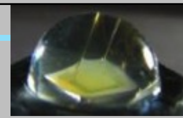
1. Introduction to GaN devices
2. GaN and related materials
3. GaN LEDs
4. Work on power GaN LEDs at ASTRI
5. Conclusions

Standard GaN LEDs

- Standard LEDs: ~ 20 mA (< 0.1 W)
  Mostly Asia companies (China/Taiwan, Korea, Japan)
- Power LEDs: ≥ 350 mA (>1W)
  Only a few US/German companies in mass production (Cree, Phillips Lighting, Osram)



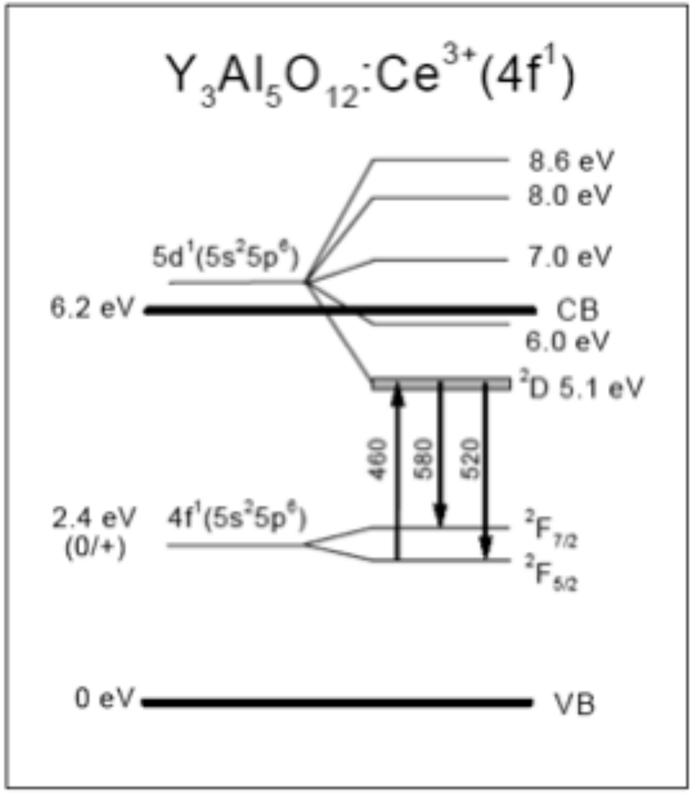
Physics in the LED Chip (Electronic & Optical Processes)

	 				
Event	Electrical power input into the chip	Current going to the active region	Light generation by electron & hole recombination	Light emission from the chip	Light conversion to white light by phosphor
Parameters	(a) Injection current I_f (b) Forward voltage V_f (c) Input electrical power P_{in} (d) Heating power $P_{Heating}$	(a) Current that reached the active region I_A (b) Injection efficiency η_{inj} (c) Number of electrons N_e	(a) Internal quantum efficiency η_{in} (b) Number of photon N_{Ph} (c) Generated Optical Power P_g	(a) Optical output power P_{out} (b) Extraction efficiency $\eta_{extract}$ (c) External quantum efficiency η_{ext} (d) Wall plug efficiency WPE	Conversion efficiency $\eta_{phosphor}$
Relationship	$P_{in} = I_f V_f$ $P_{Heating} = P_{in} - P_{out}$	$\eta_{inj} = I_A / I_f$ $I_A = e N_e$ ~ 90%	$N_{Ph} = \eta_{in} N_e$ $P_g = \frac{2\pi hc}{\lambda} N_{Ph} = \frac{2\pi hc}{e\lambda} I_f \eta_{in} \eta_{inj}$ ~ 70%	$P_{out} = \eta_{extract} P_g$ $\eta_{ext} = \eta_{in} \text{ x } \eta_{extract}$ WPE $= \frac{P_{out}}{P_{in}} = \frac{2\pi hc}{e\lambda} V_f \eta_{inj} \eta_{in} \eta_{extract}$ ~ 80%	$P_{white} = \eta_{phosphor} P_{out}$ ~ 60%

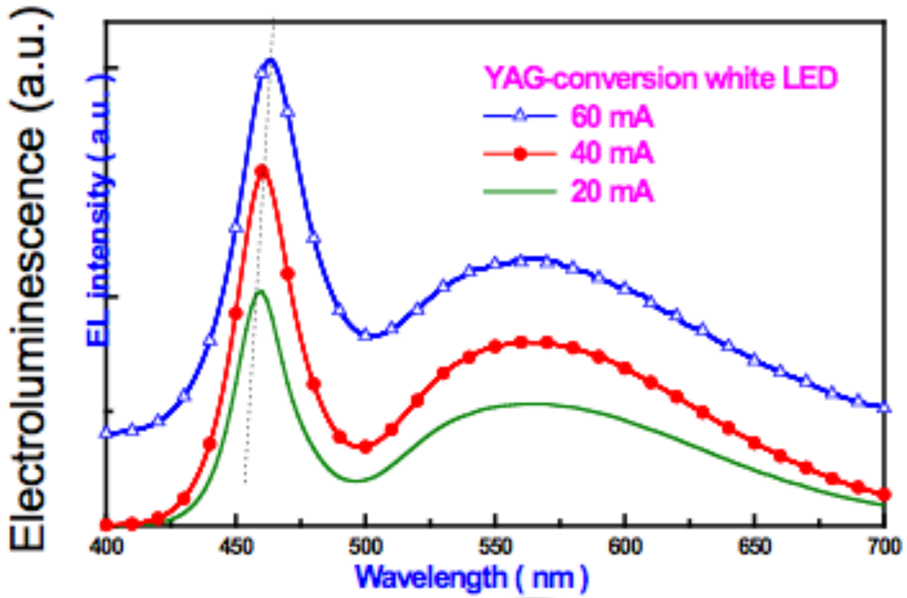
ASTRI

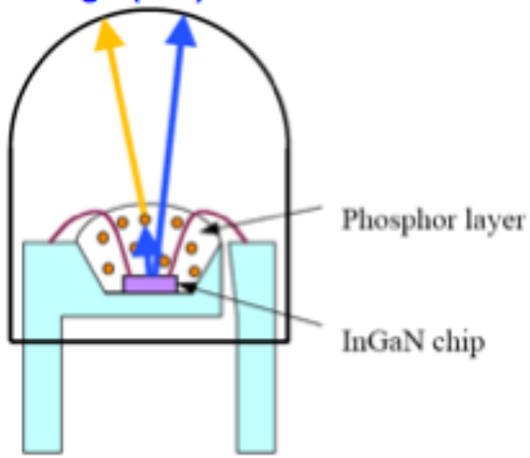
White LEDs : Converting Blue Light into Yellow by Phosphor

White LED Combined InGaN blue chip with YAG phosphor

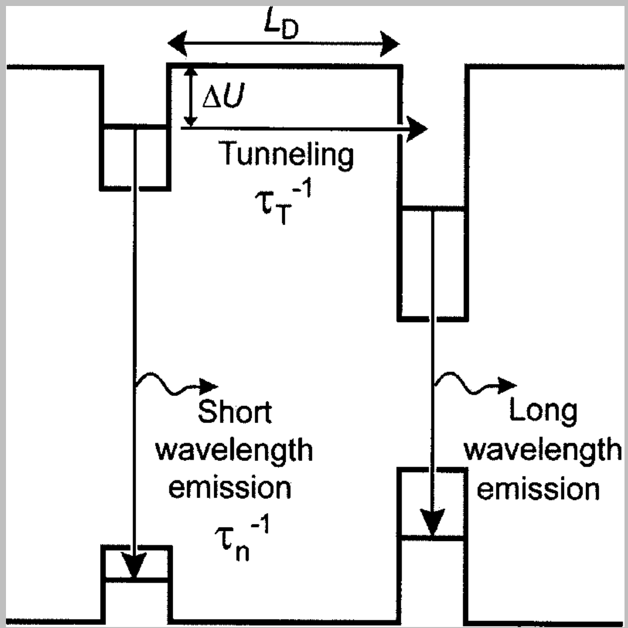


Energy levels of YAG:Ce phosphor

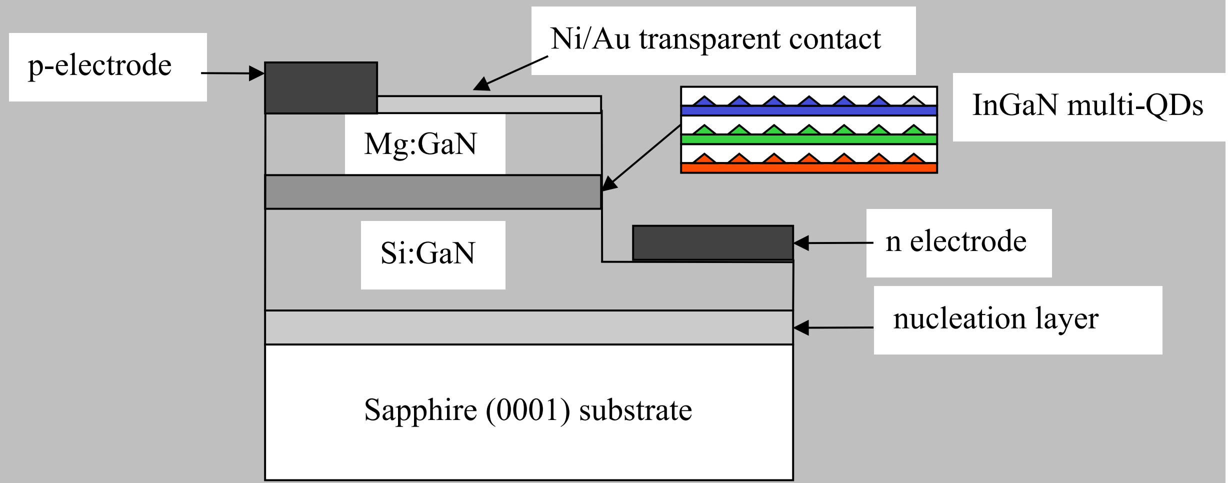




White LEDs Without Phosphor

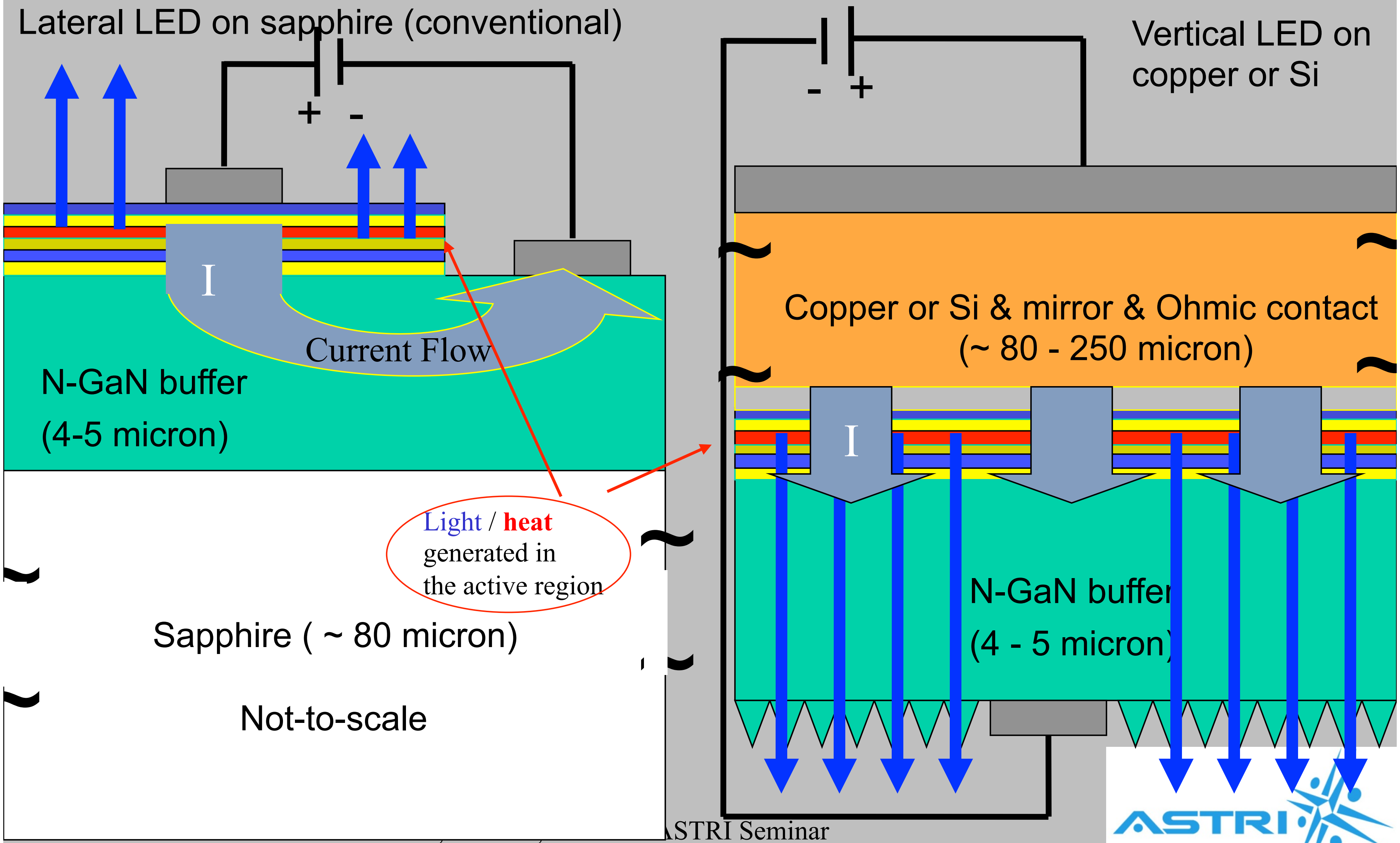


Two quantum well active regions

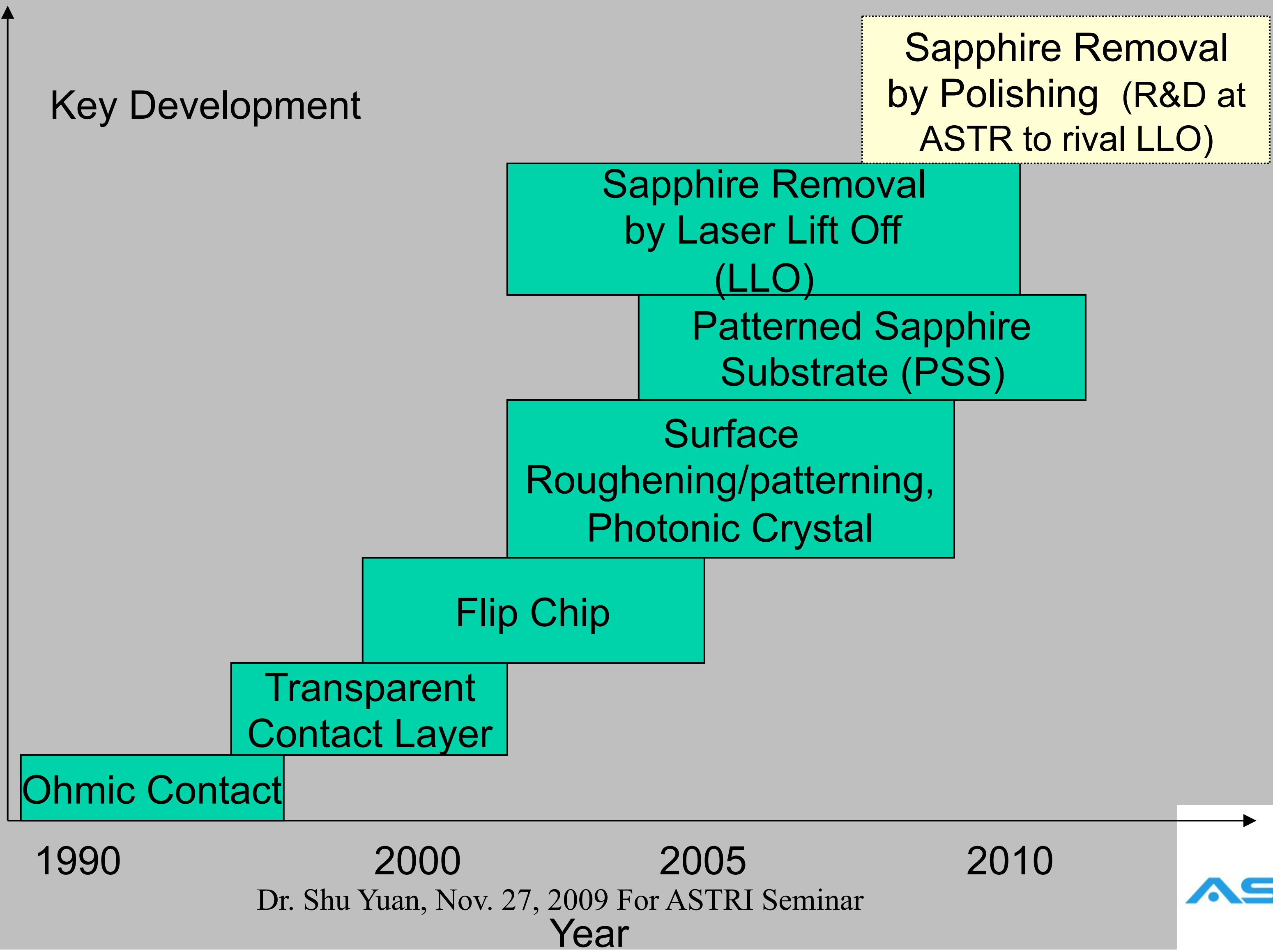


Quantum dots (QDs) active region

Conventional versus Vertical LEDs



GaN LED Chip Key Technology Development



Sapphire Removal by Polishing: Main Facilities

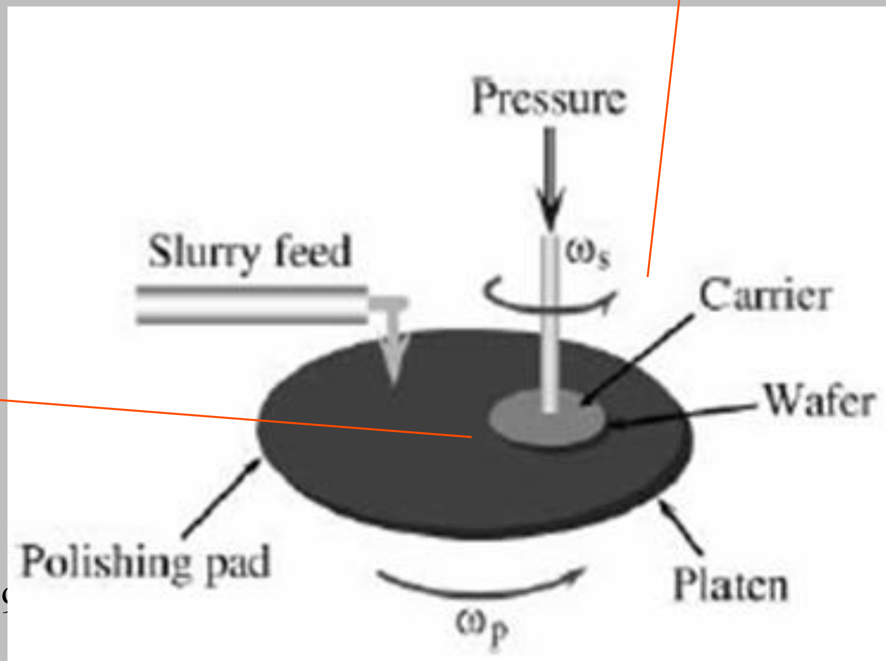
Wax Mounting

Grinding

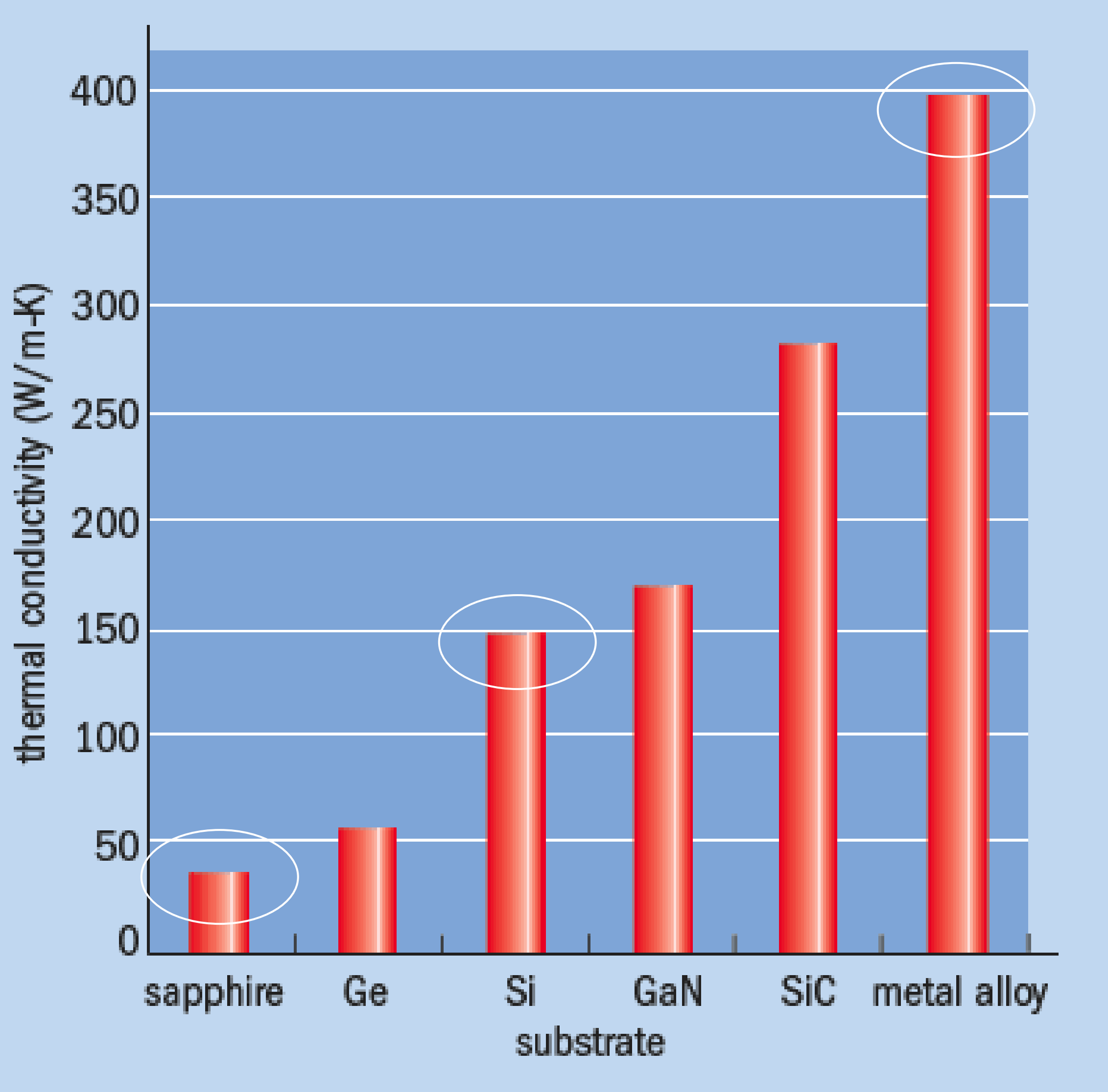
Lapping

Polishing

Multiple-wafer Batch Process
(For High Throughput /Low Cost)



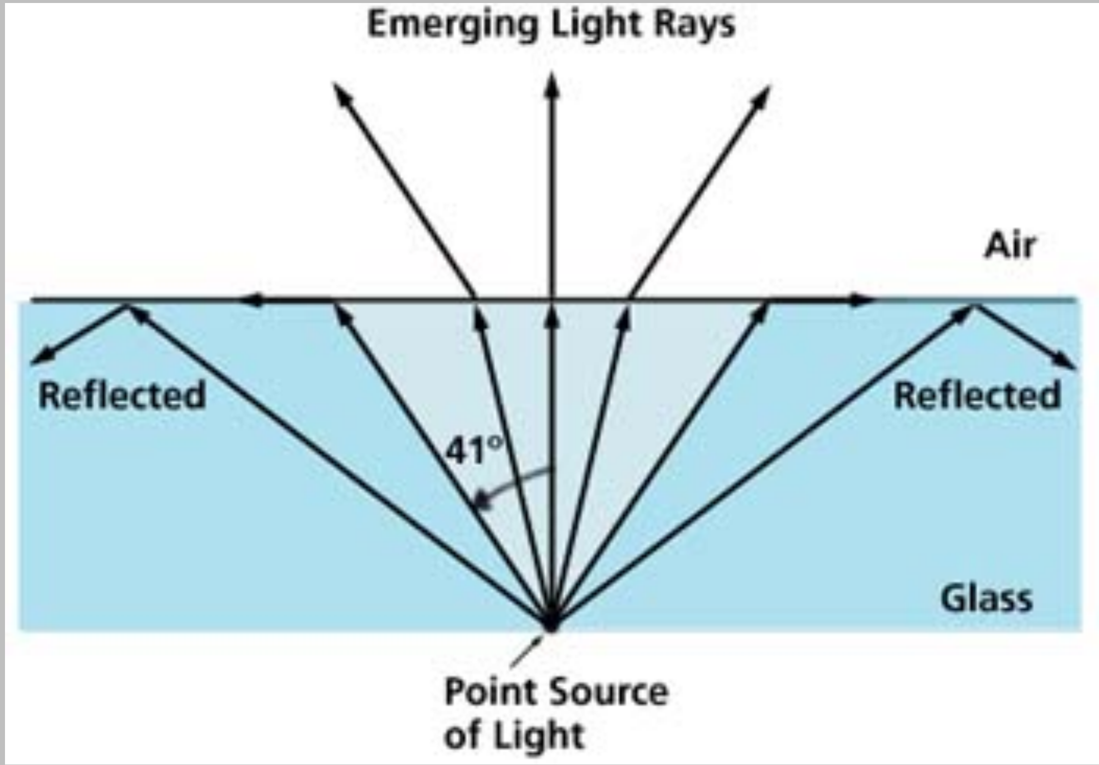
Power LEDs: Thermal Conductivity of Substrate Material

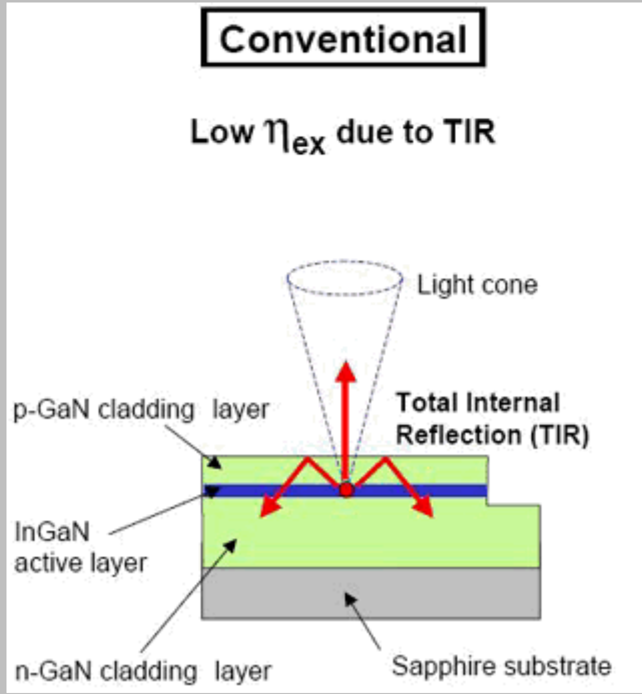


Sapphire << Copper

Sapphire < Si

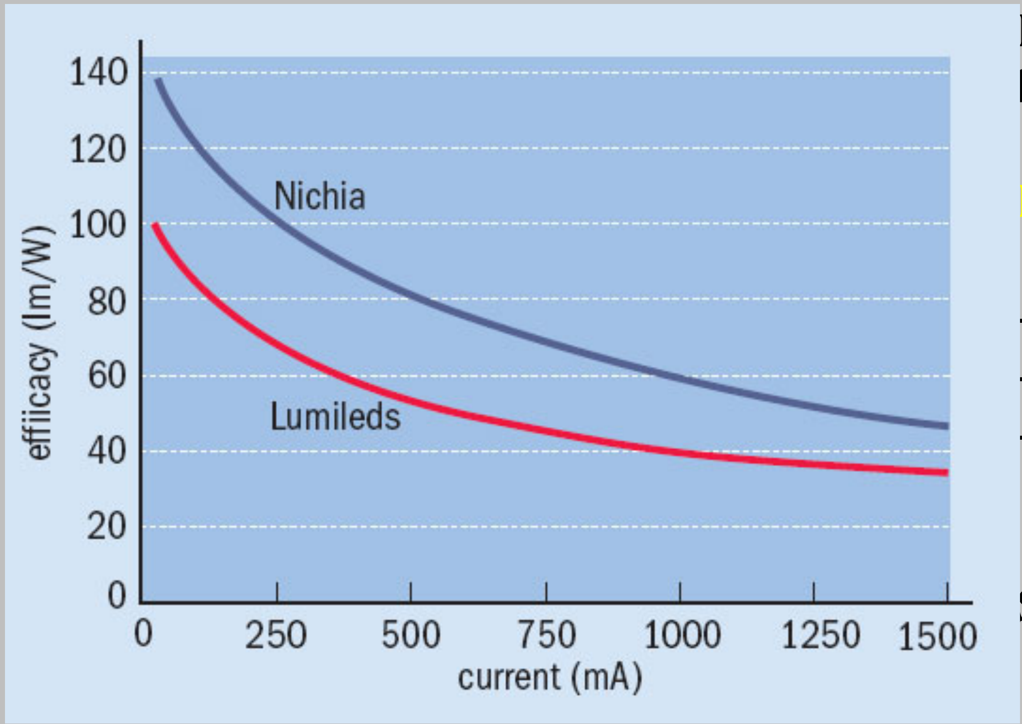
Light Extraction Efficiency





Most light is trapped inside by the total internal reflection (TIR).

Droop: Drop of Efficacy with Current



Droop: Efficiency/efficacy drop at high current levels.

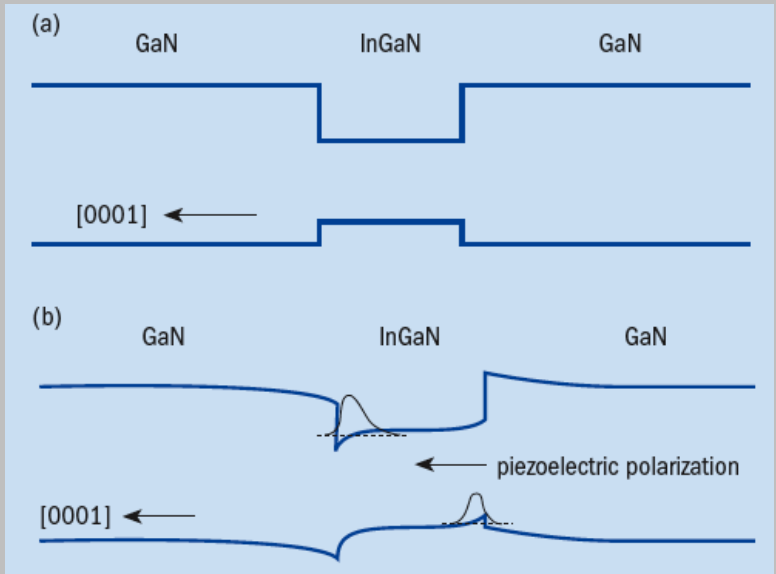
Possible causes: not confirmed!

- Auger effects
- Carrier leakage
- Etc.

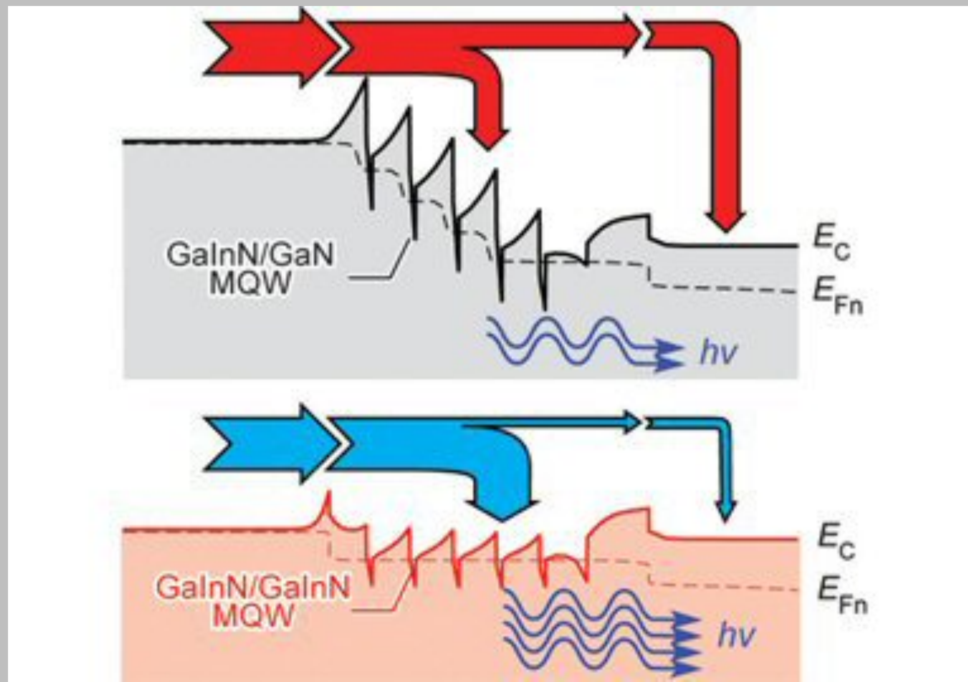
Suggested solutions:

- Thicker wells to lower current density
- Polarization matching

A Possible Solution to the Droop: Polarization Matching in the Quantum Wells



Reducing polarization field to minimize carrier leakage

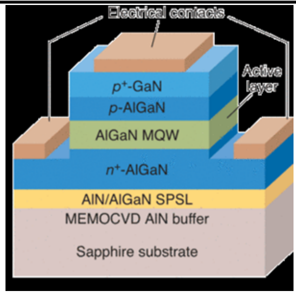
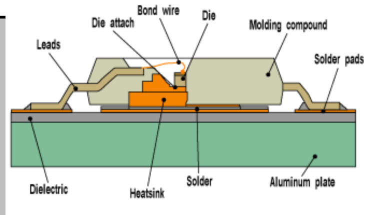


Source: RPI, Jan. 2009

Outline

1. Introduction to GaN devices
2. GaN and related materials
3. GaN LEDs
4. Work on Power GaN LEDs at ASTRI
5. Conclusions

Current and Future Project's Technology Focus

	Epitaxy		2nd Full Project (To start soon)
	LED Chips	1st Full Project (Completed)	
 5. Golden Dragon white LEDs manage heat removal via a copper slug beneath the chip's die. The chip is mounted on an aluminum substrate. (Source: Osram Optoelectronics)	Packaging		
	Applications		

Research Areas to Focus

Source: Lumileds' CTO's presentation at Blue 2009, 6/2009

PHILIPS

Key Limitation for LED Mass Adoption: Cost

Vertical LEDs
for these requirements.
➔ **Substrate removal!**

Potential LED cost reduction

- Drive current (0.35 A/mm² ➔ 2 A/mm²): 4.5x
- LED efficiency (75 lm/W ➔ 150 lm/W): 2x
- Lower chip, packaging, and system cost: >2x

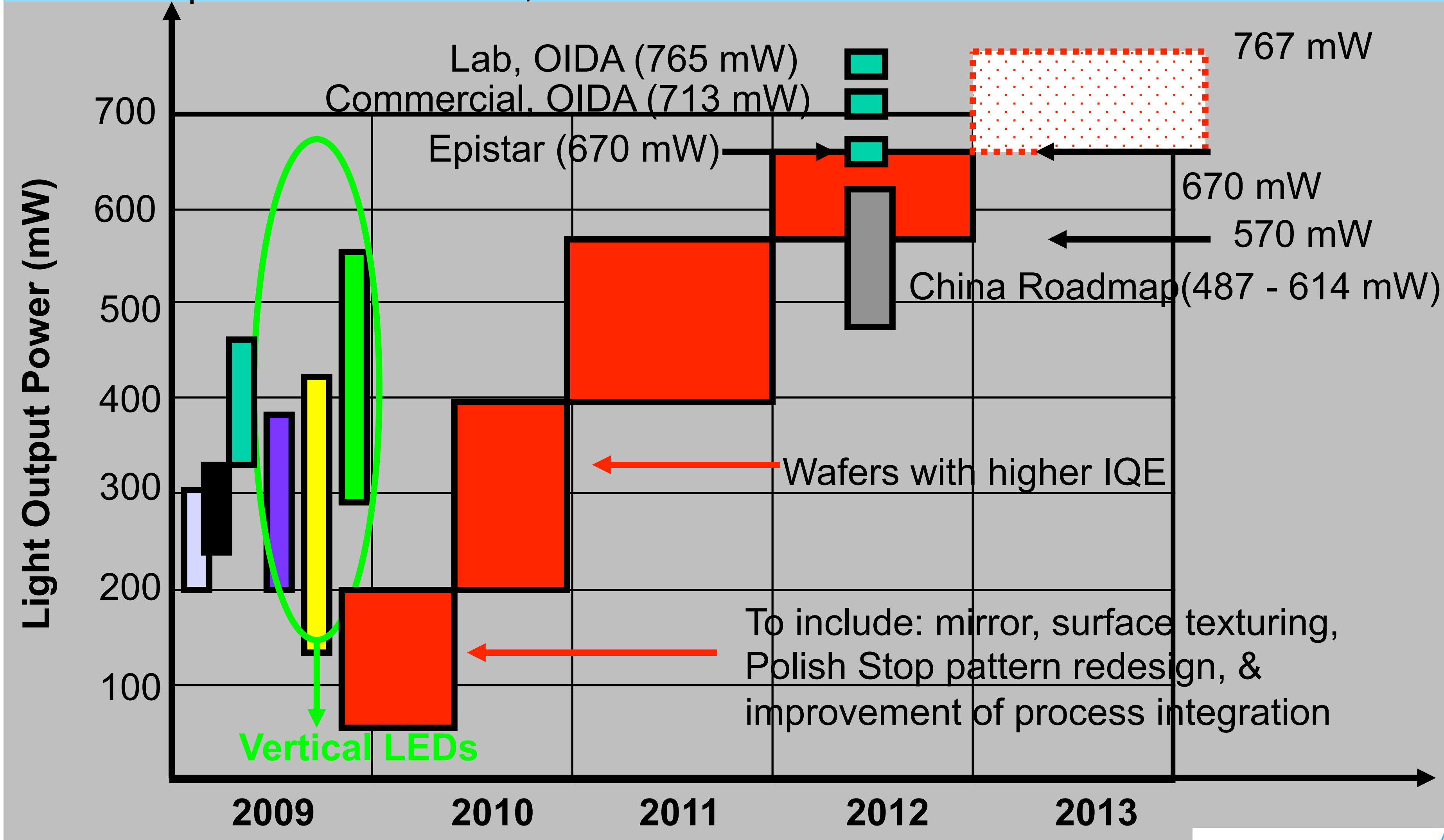
➔ >18 x

➔ **White LED performance target: > 150 lm/W @ 1000 lm**

ASTRI

High Efficiency Through Substrate Removal

Chip size: 1mm x 1 mm, If = 350 mA



APT, Bridgelux(45mil), Lumileds, Cree, Osram, SemiLEDs, ASTRI

Note: data from on-line datasheets of the companies. Lumileds (K2) & Osram (GoldenDragon&GoldDragonPlusCoolWhite) data in lm is divided by230 (lm/Optical W) to yield mW

Roadmap to Achieve High Power LEDs

Chip size: 1mm x 1 mm, I_f = 350 mA

Chip Power		400 mW	570 mW	670 mW	767 mW	
Efficacy		88 lm/W	121 lm/W	150 lm/W	178 lm/W	
Heat (Power Density)		76 W/cm^2	52 W/cm^2	38 W/cm^2	26 W/cm^2	
IQE (Internal Quantum Efficiency)	Lumileds 70% 2009, Osram 50% 2008, 72% OIDA 2007 cited by MaxKuo of Epistar2008	62%	76%	84%	86%	
LEE (Light extraction efficiency)	Lumileds 80% 2009, OIDA 80% 2007,	66%	79%	85%	91%	
V_f		3.3 V	3.1 V	3 V	2.94 V	
	2009	2010	2011	2012	2013	

Vertical LEDs for SSL: Areas to Focus

PHILIPS

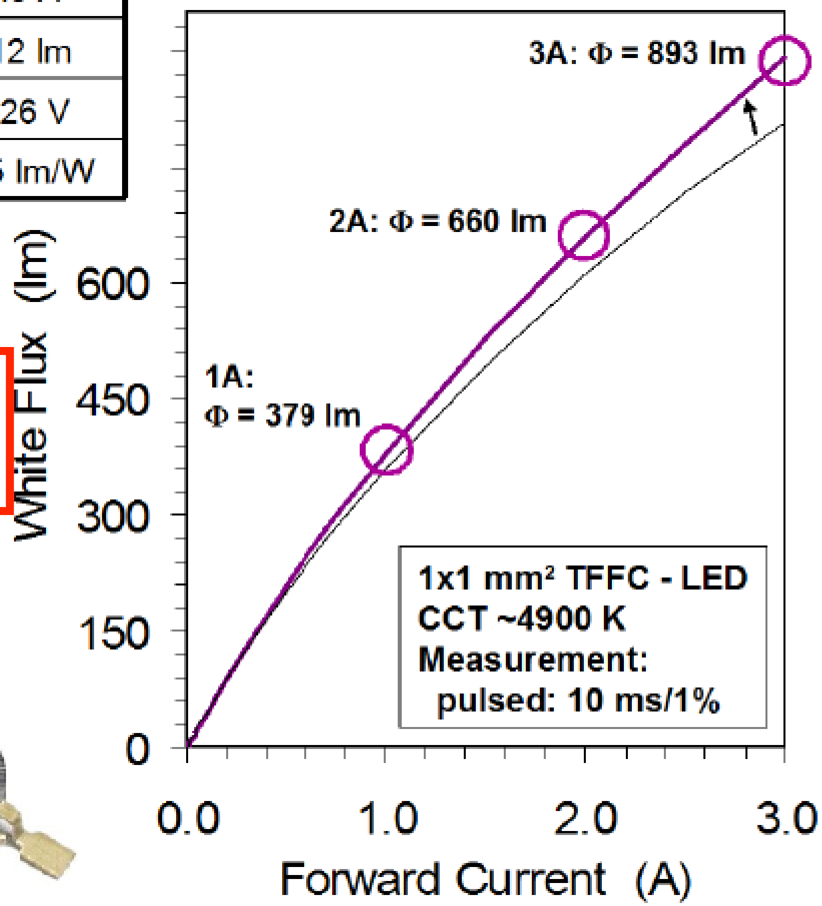
Source: Lumileds's CTO's presentation at Blue 2009

High-power LED Laboratory Results

Forward current	350 mA	1 A	1.5 A
White flux	149 lm	365 lm	512 lm
Forward voltage	2.85 V	3.10 V	3.26 V
Luminous efficacy	**150 lm/W**	118 lm/W	105 lm/W

CCT ~4900 K; chip size is 1x1 mm^2; pulsed measurement (pulse width: 10 ms, duty factor: 1 %)

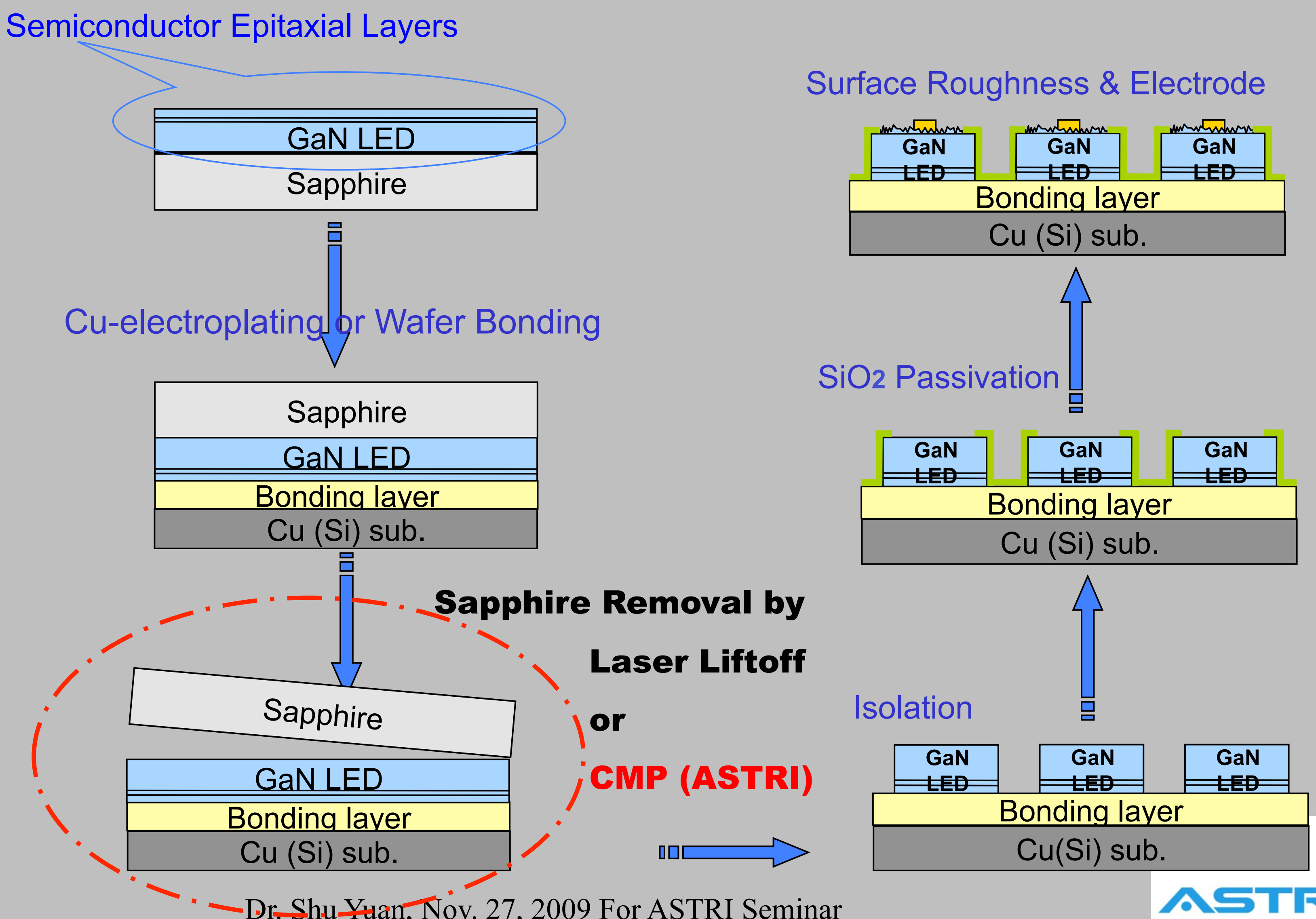
- Continued advancement especially at high drive current density
- Feasibility of single 1x1 mm^2 chip "light bulb"
  - 2A (~6.8 W): 611 lm
  - 40 W bulb: ~600 lm



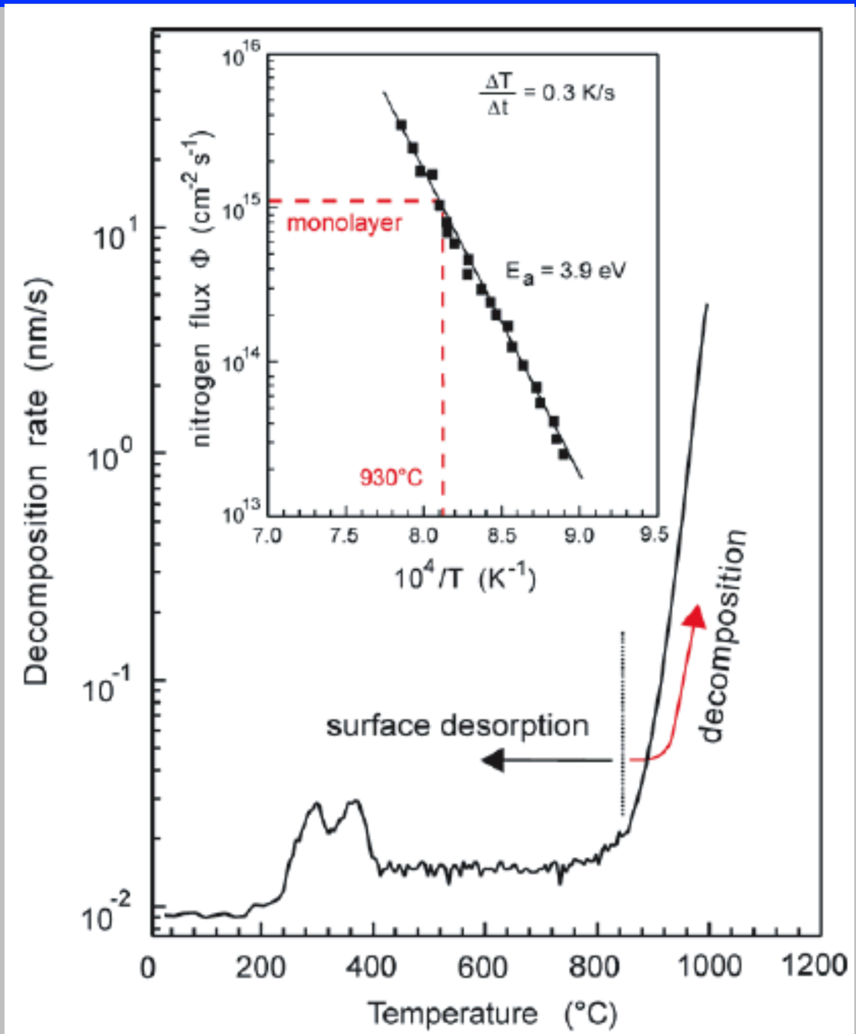
Power LEDs : Substrate Removal as a Key Technology

Company	Drive Current (mA)	Substrate	Key Technology	Remarks
Epistar (Taiwan)	Up to 350	Sapphire		
Toyoda Gosei (Japan)	Up to 150	Sapphire		
Nichia (Japan)	Up to 350	Sapphire		
Osram (Germany)	Up to 1400	Sapphire	Vertical LED	Sapphire removed by laser liftoff
Cree (USA)	Up to 1000	SiC	Vertical LED	SiC substrate removed
Phillips Lumileds (USA/EU)	Up to 1500	Sapphire	Flip-chip	Sapphire removed by laser liftoff
ASTRI	Up to 2000 (target)	Sapphire	Vertical LED	Sapphire removed by non-laser liftoff method

Generic Vertical LED Fabrication Process

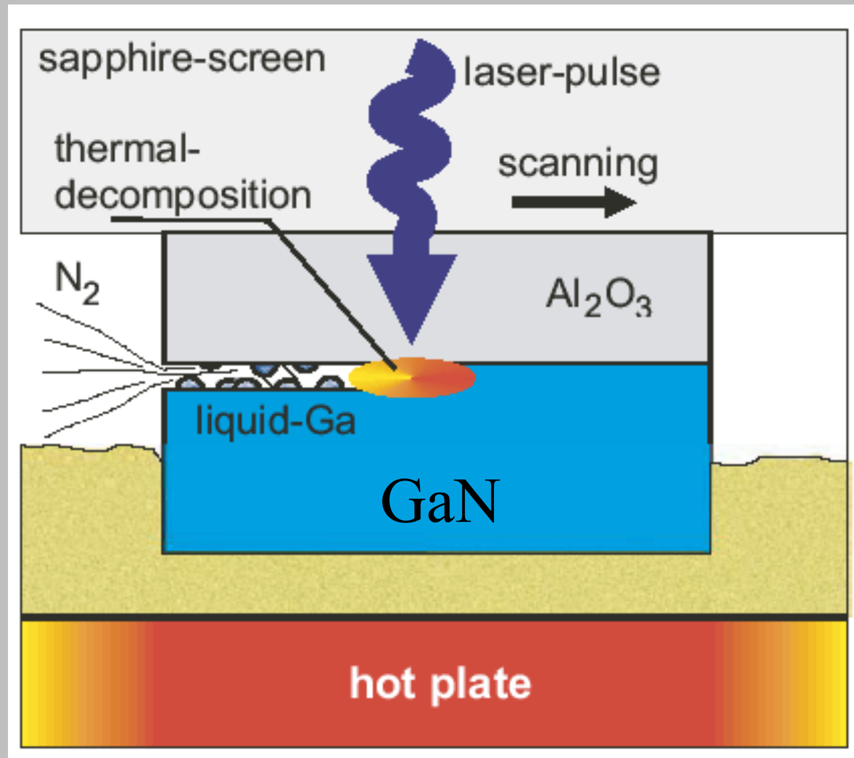


Removal of Sapphire by Laser Liftoff
-- A Non-ASTRI method, the mainstream technology NOW



Thermal decomposition of GaN

Most GaN devices are made from GaN epitaxial wafers on sapphire. Sapphire (Al_2O_3) is an insulator and not a good thermal conductor.



Removal of Sapphire by Laser Liftoff (A Non-ASTRI Method)

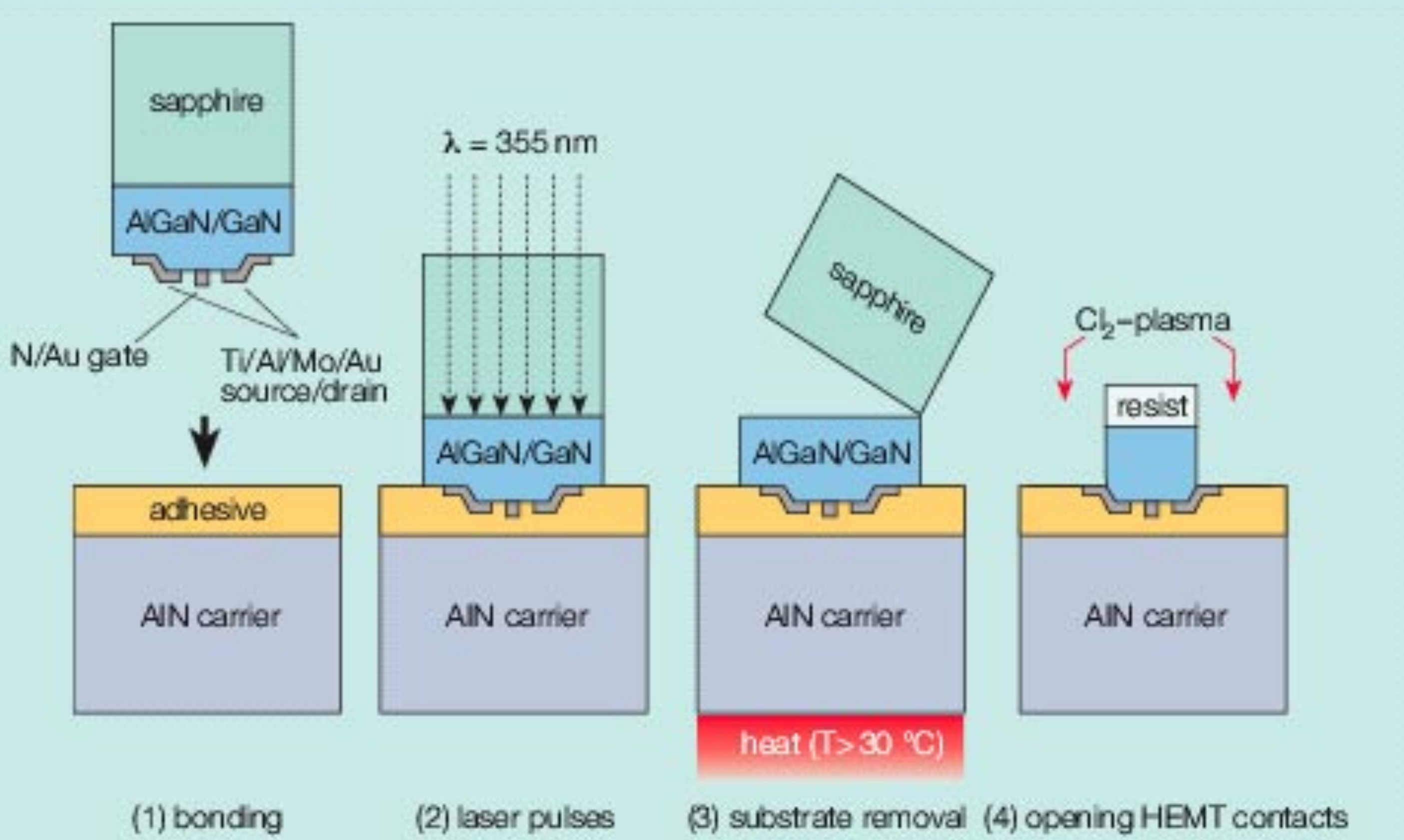
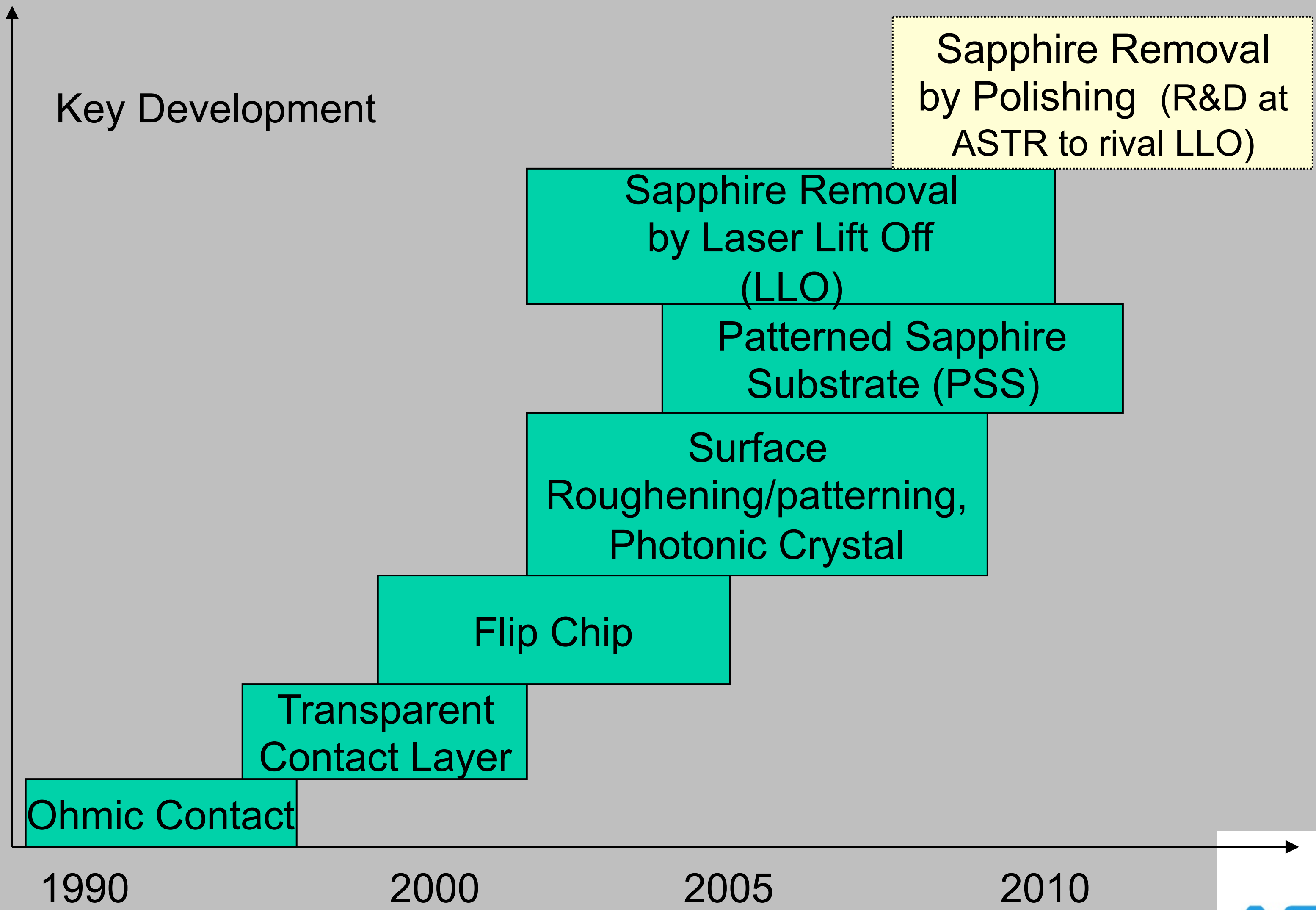


Fig. 1. IMEC's approach combines the benefits of epitaxial growth on cheap sapphire substrates and the excellent thermal properties of ceramic AlN.

GaN LED Chip Key Technology Development



Sapphire Removal by Polishing: Main Facilities

44

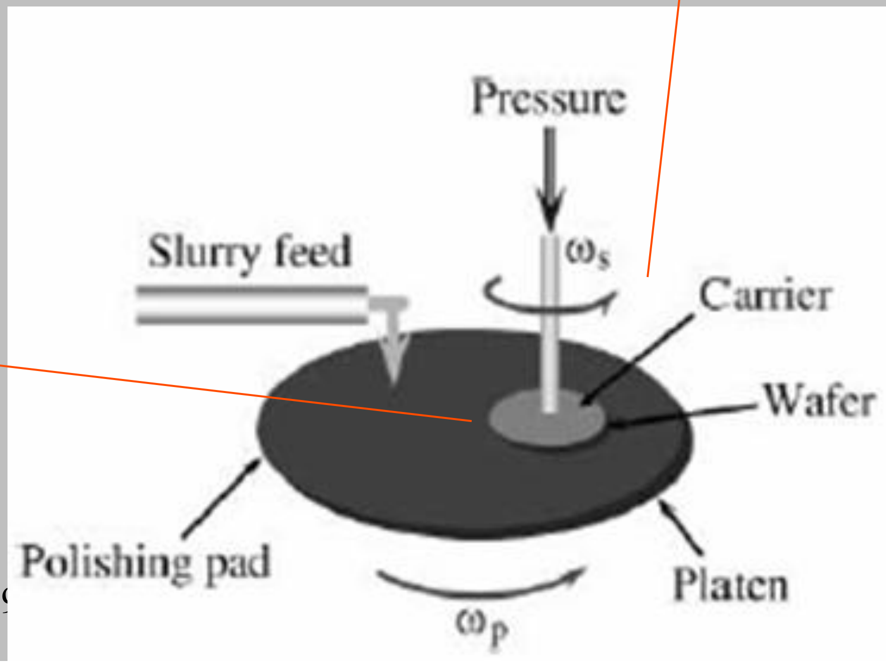
Wax Mounting

Grinding

Lapping

Polishing

Multiple-wafer Batch Process
(For High Throughput /Low Cost)

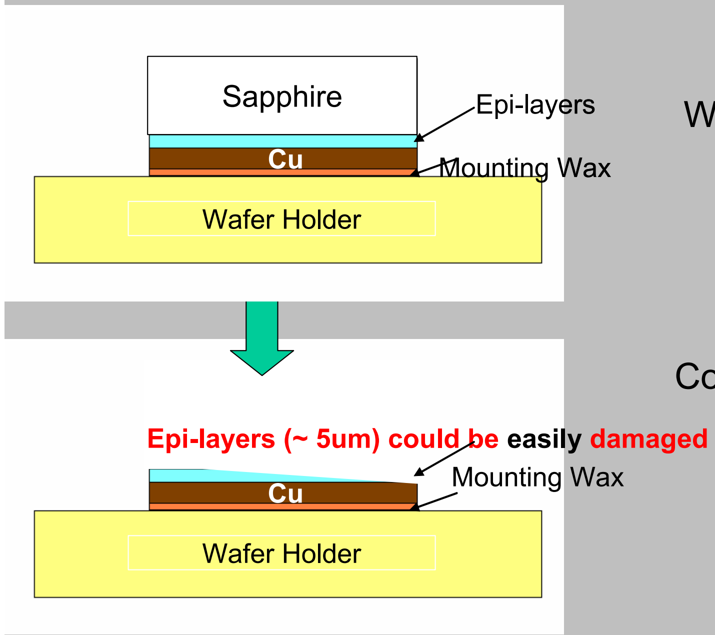


Polishing Method : Conventional versus ASTRI

Sapphire Removal by Conventional Mechanical Polishing

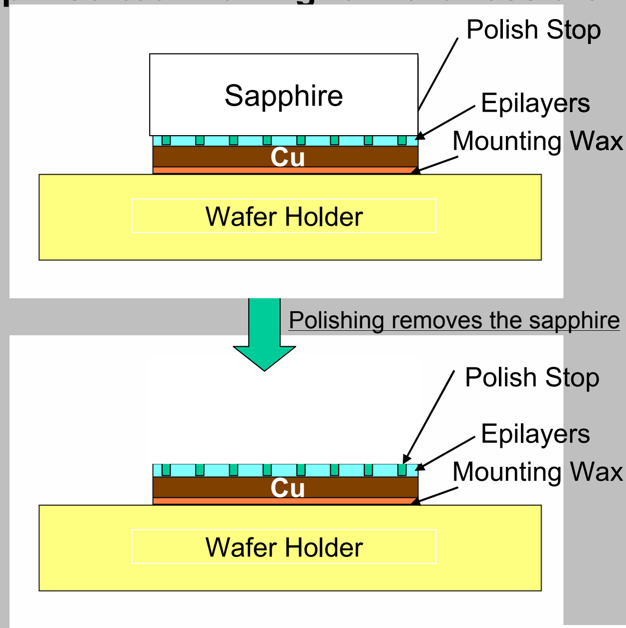
Wafer Mounting

Conventional Polishing



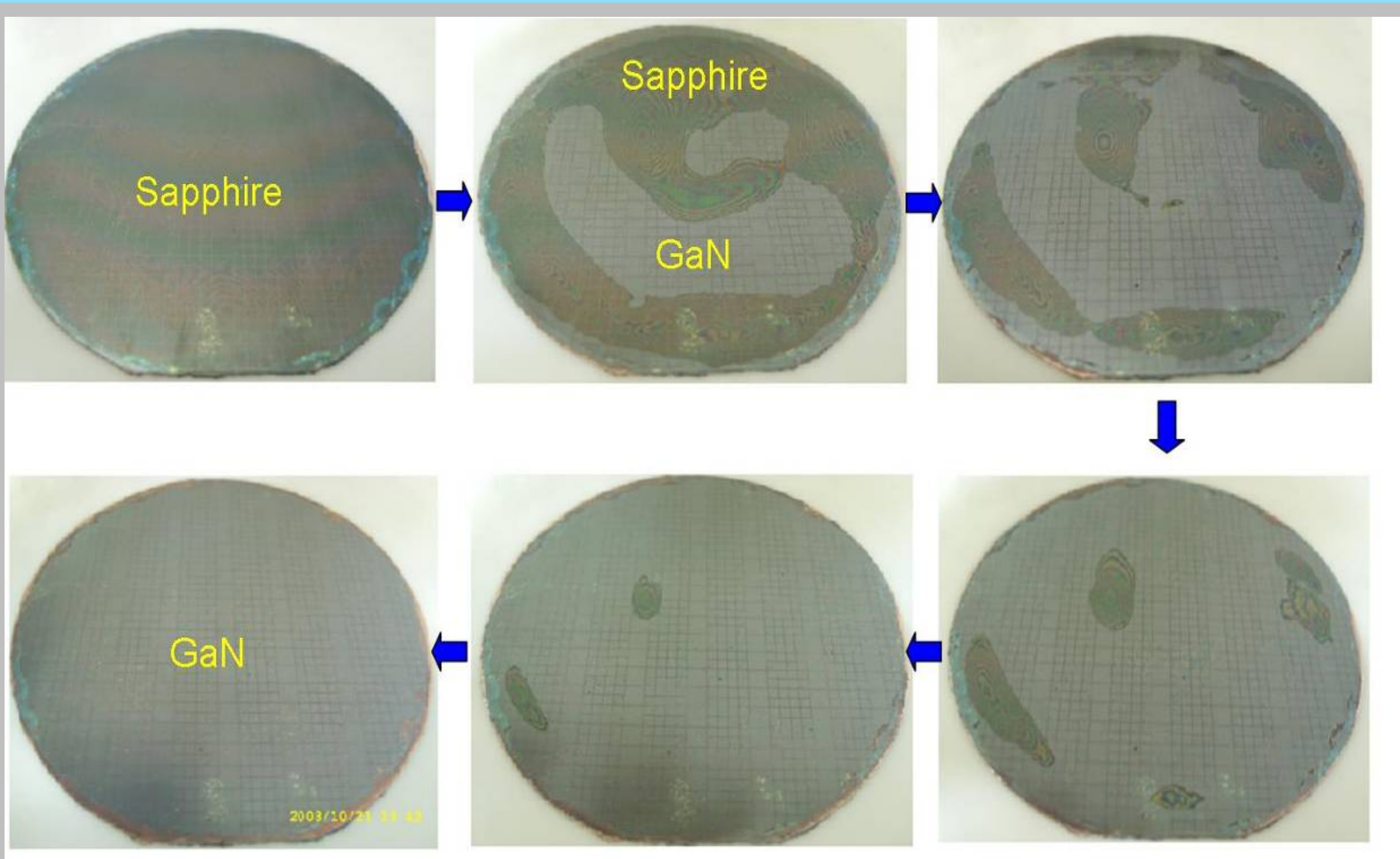
Sapphire Removal by ASTRI Method with Polish Stops

Polish stop inserted with higher hardness than GaN!



ASTRI

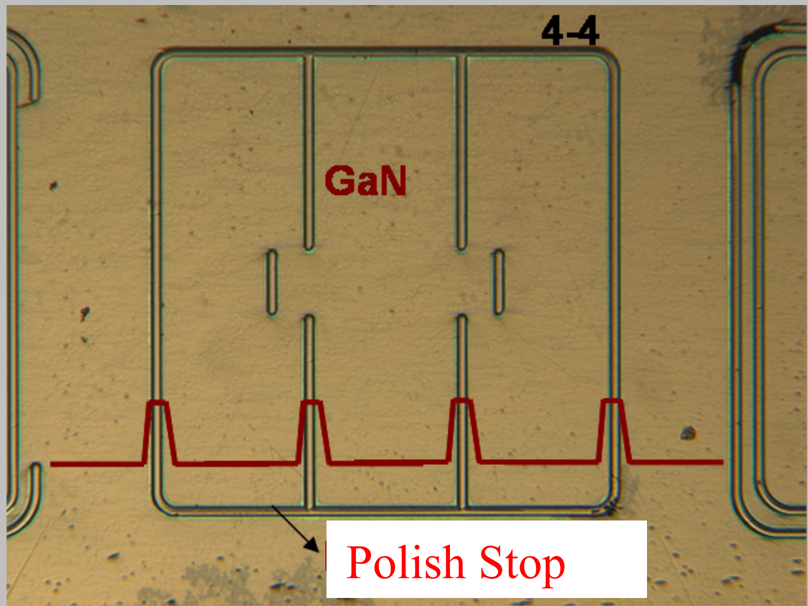
Sapphire Removal by ASTRI Polishing Method

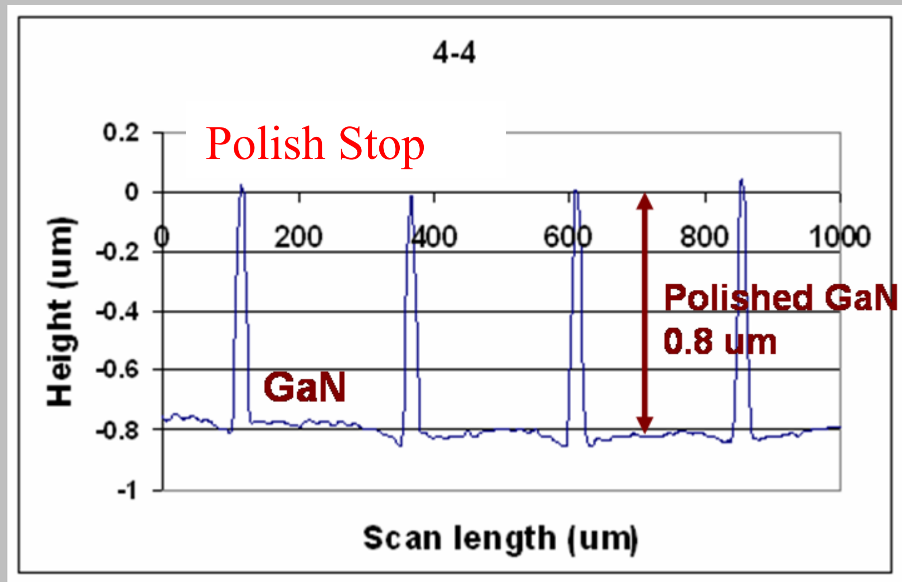


Visual Inspection as a low-cost method to determine sapphire is totally removed for manufacturing. (Latest duration for each step is shown in Appendix 2).

Sapphire Removal by ASTRI Polishing Method

Surface profiling: proof of complete sapphire removal





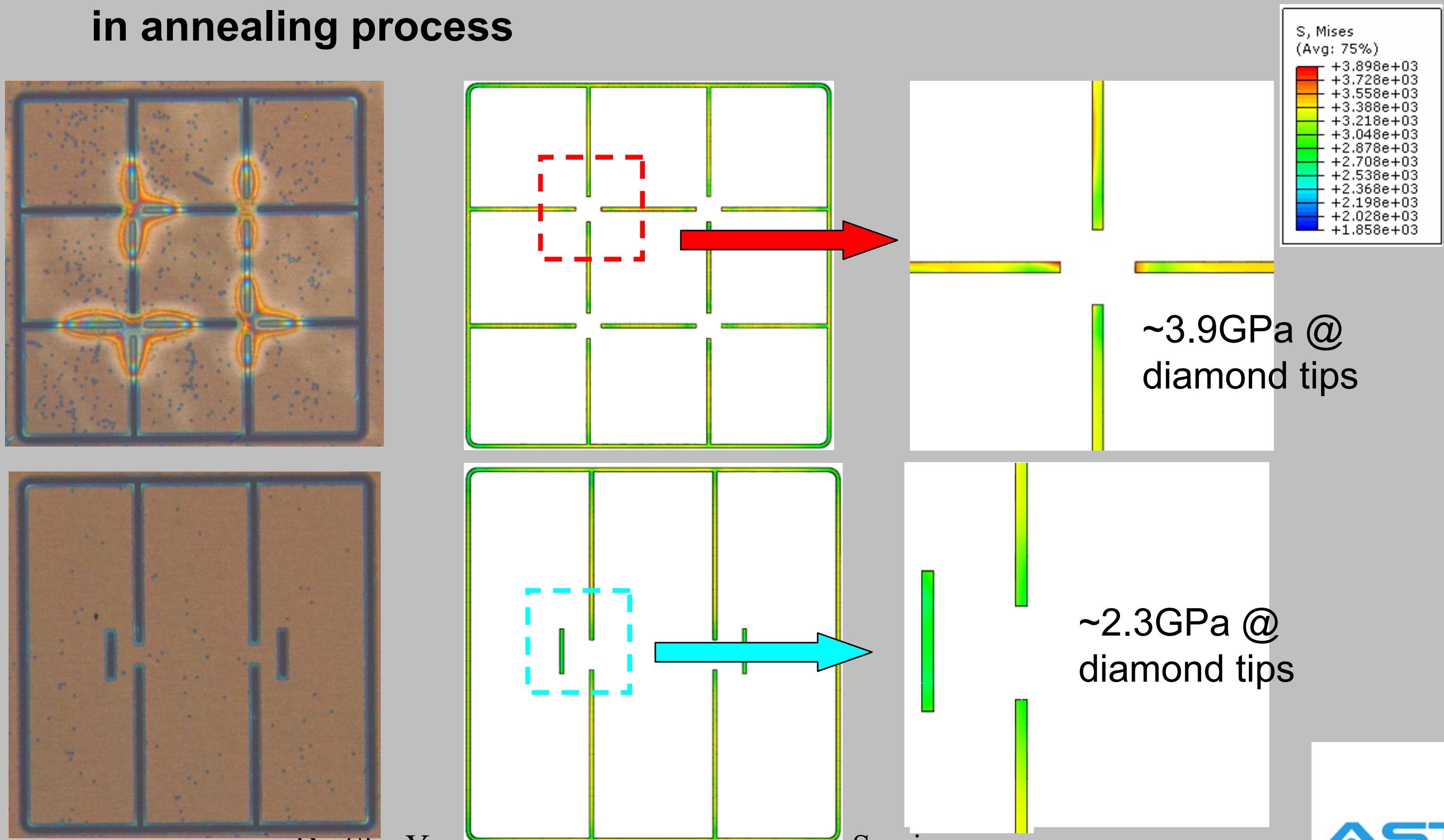
No clear relationship between device performance and the height of polished GaN has been established so far.

Sapphire Removal by ASTRI Polishing Method

Design of polish stop patterns to minimize stress

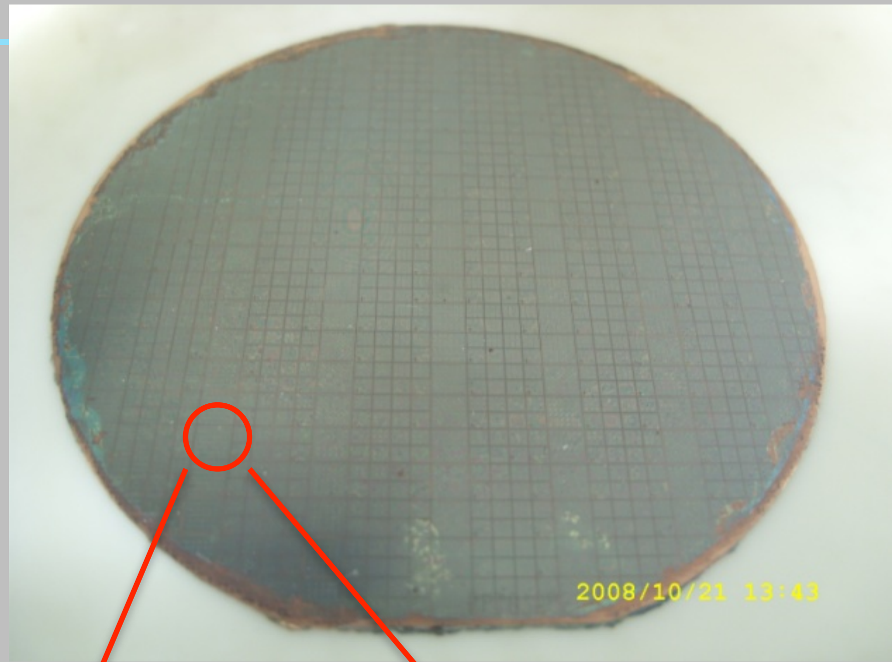
Simulation & Experiments

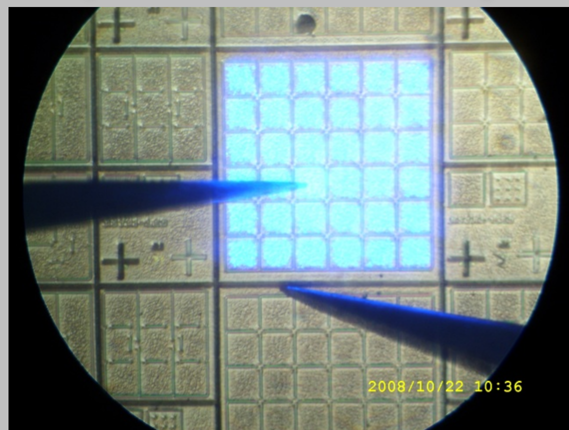
Stress of diamond in the diamond/sapphire interface @ 750^{o}C in annealing process



ASTRI

Removal of Sapphire by ASTRI Method: CMP

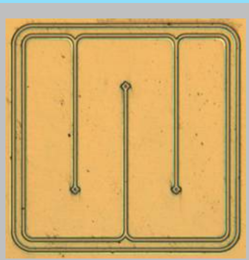
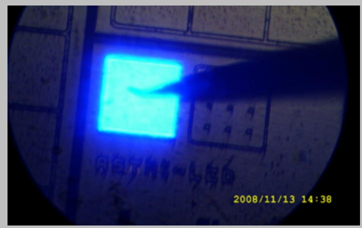
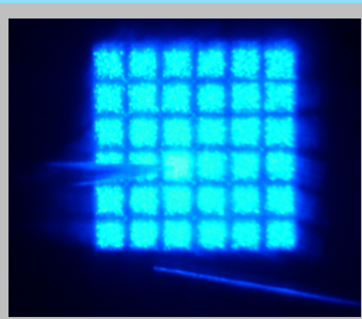




A 2mm x 2mm mesa

ASTRI

Removal of Sapphire by ASTRI Method: CMP

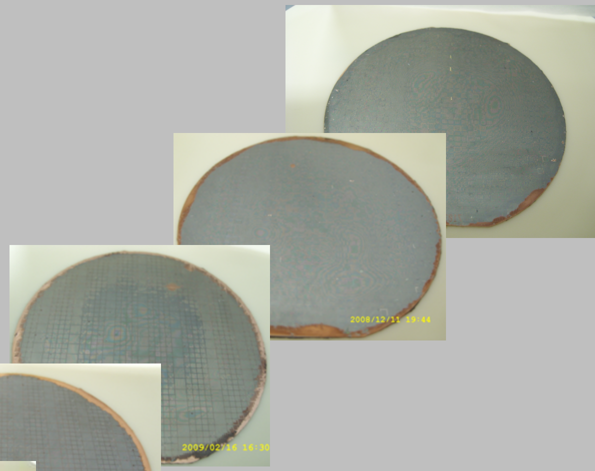
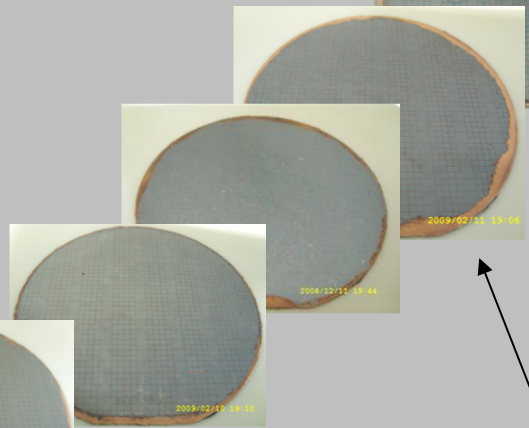
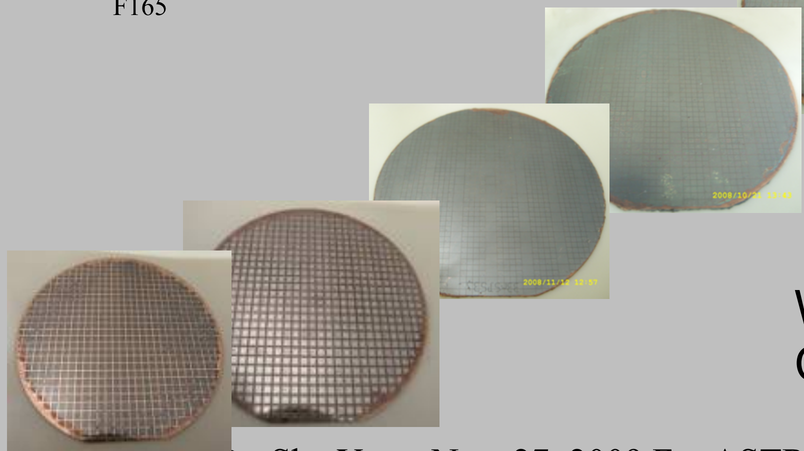




LED mesa 0.35mm x 0.35 mm 2mm x 2mm

Wafers: sapphire totally removed,
Copper is the new host substrate.

No.:

F021	F148
F041	F157
F060	F159
F065	F164
F066	F165
F070	
F073	
F074	
F075	
F076	
F078	
F084	
F097	
F119	
F123	
F124	
F125	
F140	

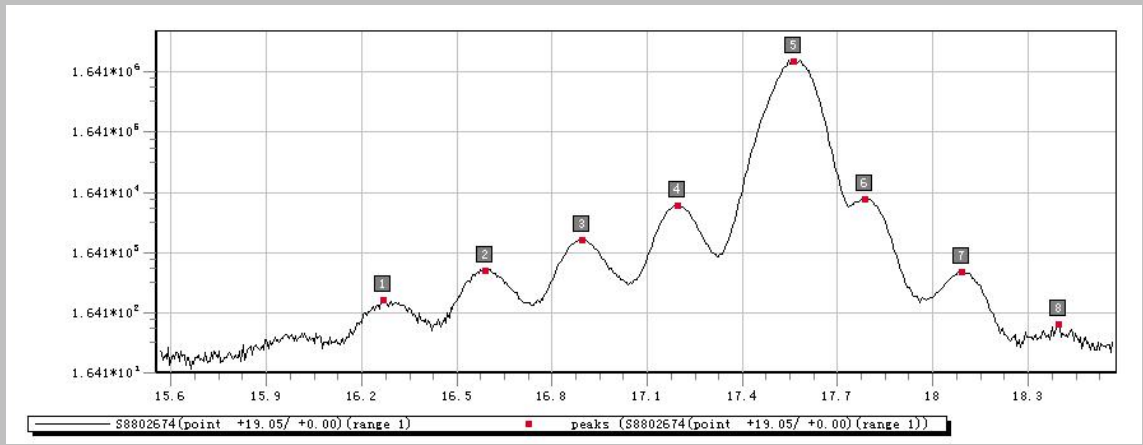




Wafers: sapphire is totally removed,
Copper is the new host substrate.

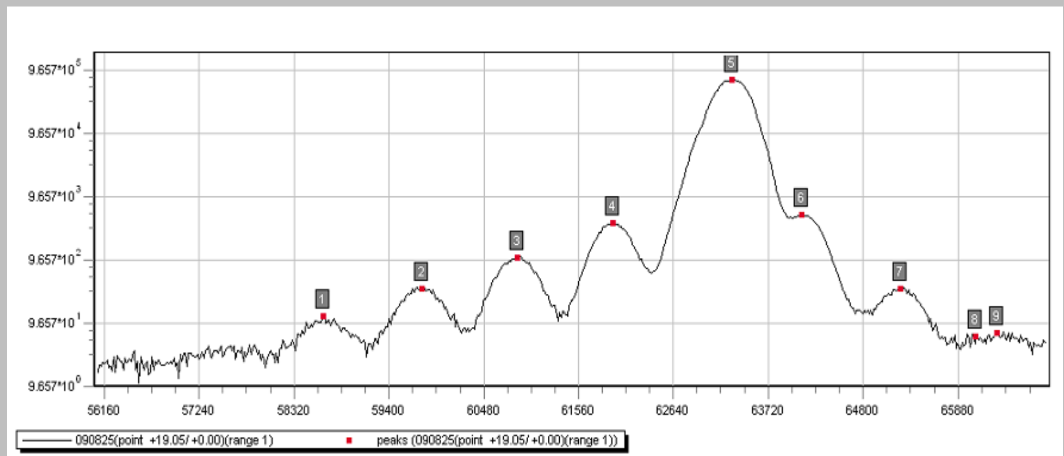
ASTRI

Removal of Sapphire by ASTRI Method: CMP

XRD: Proof of no crystal damage due to polishing



As-grown Wafer

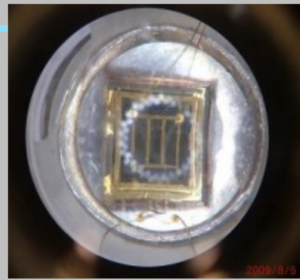


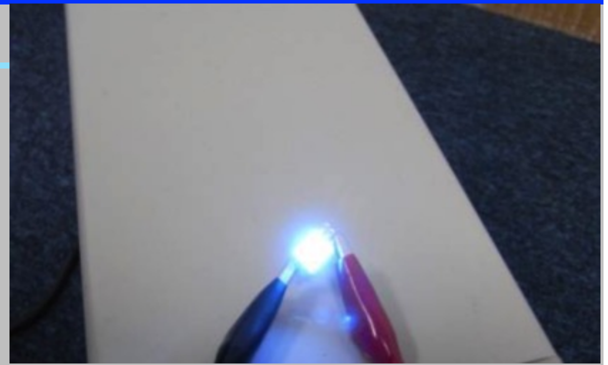
Post CMP Polishing

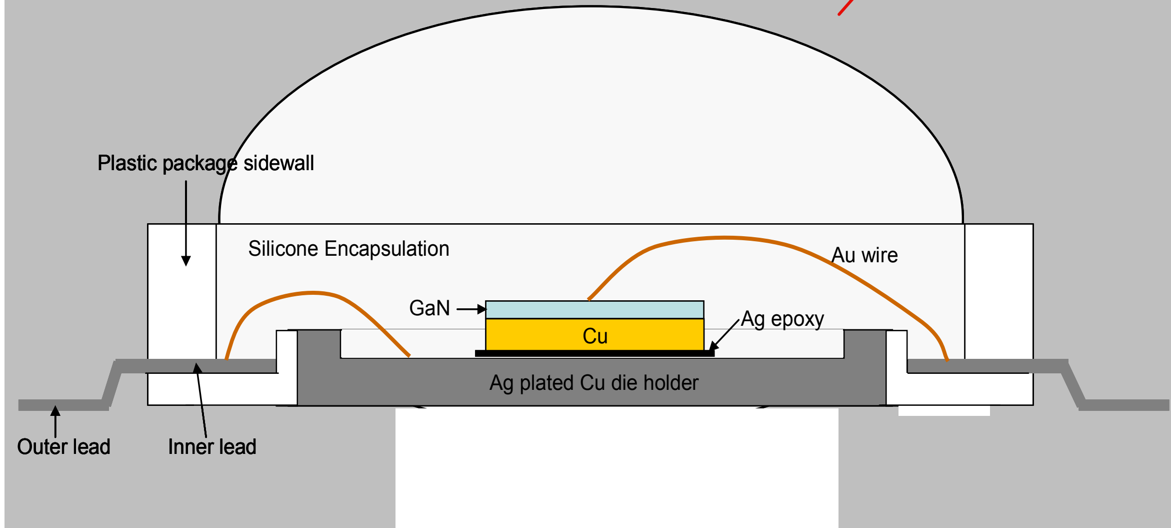
Example, Wafer No. F159

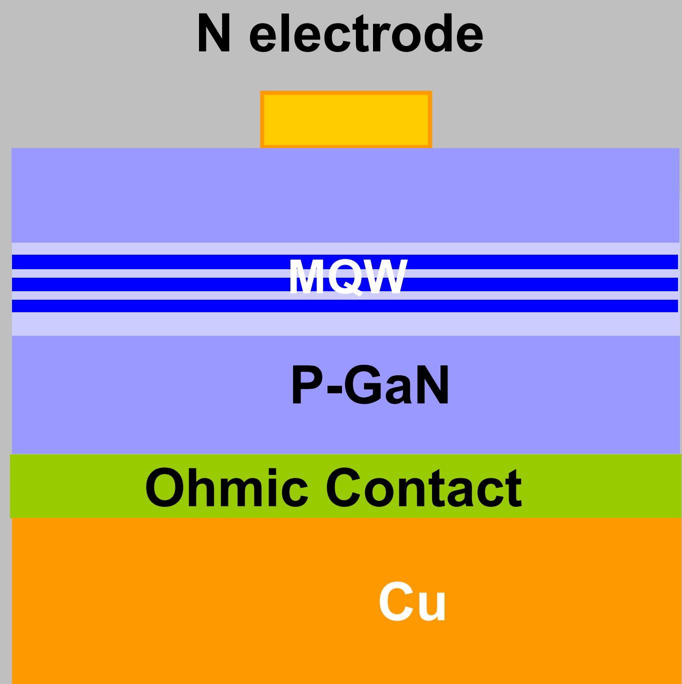
ASTRI

LEDs Made by ASTRI

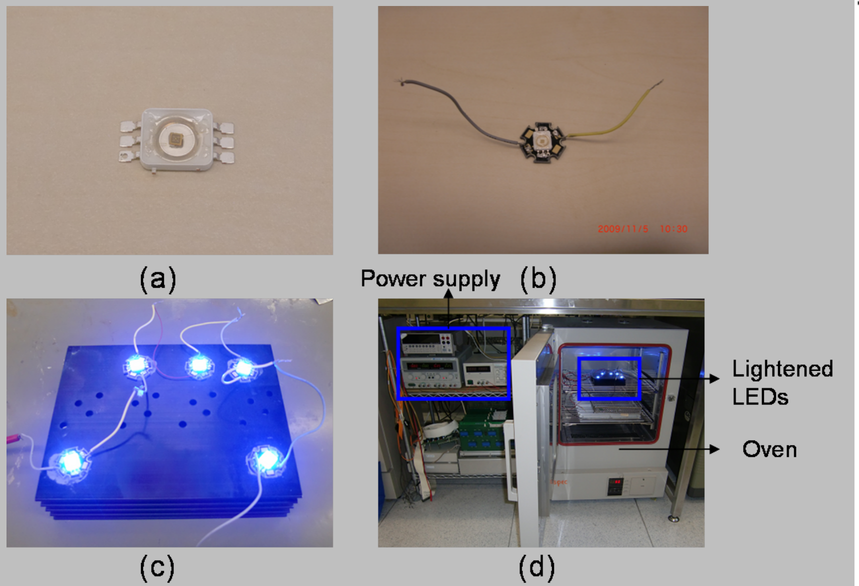




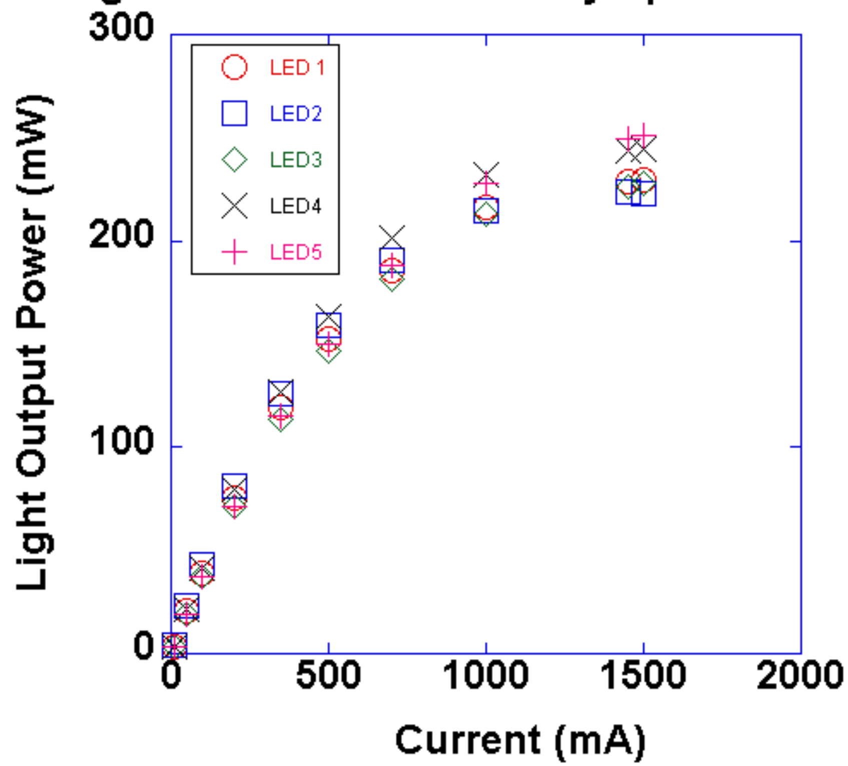




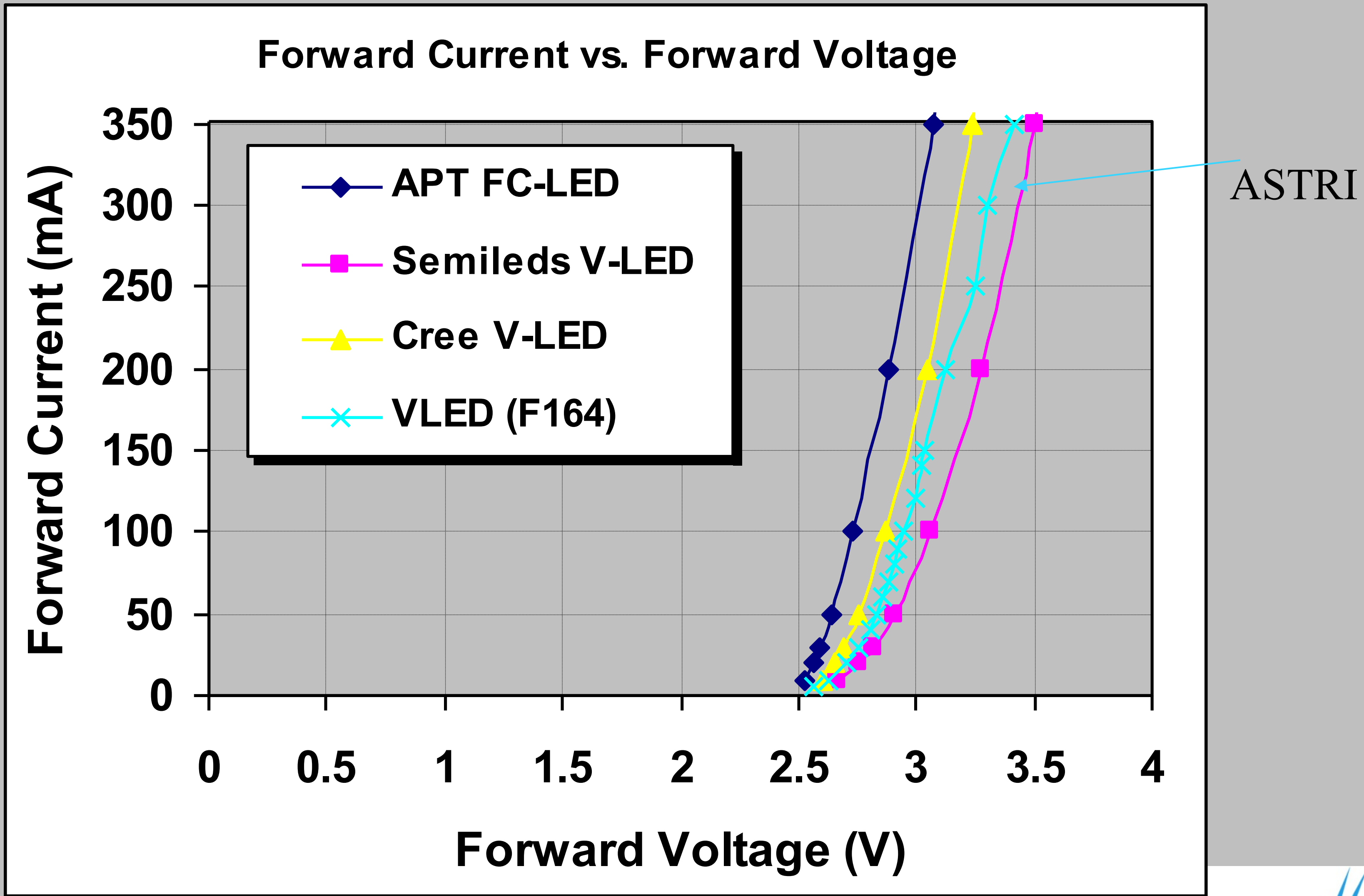
Packaged Vertical LEDs



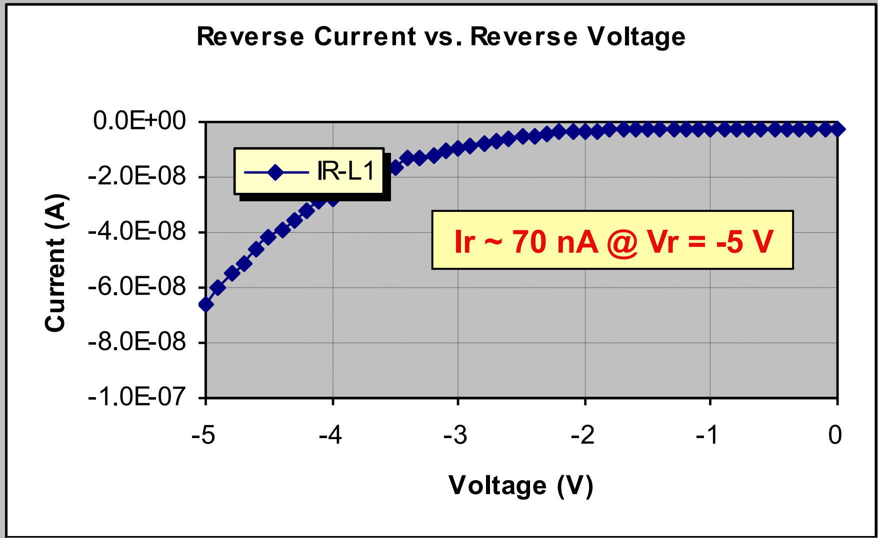
Example of LED power versus injection current, from LEDs made from Wafer No. F140, packaged and tested at Century Epitech.



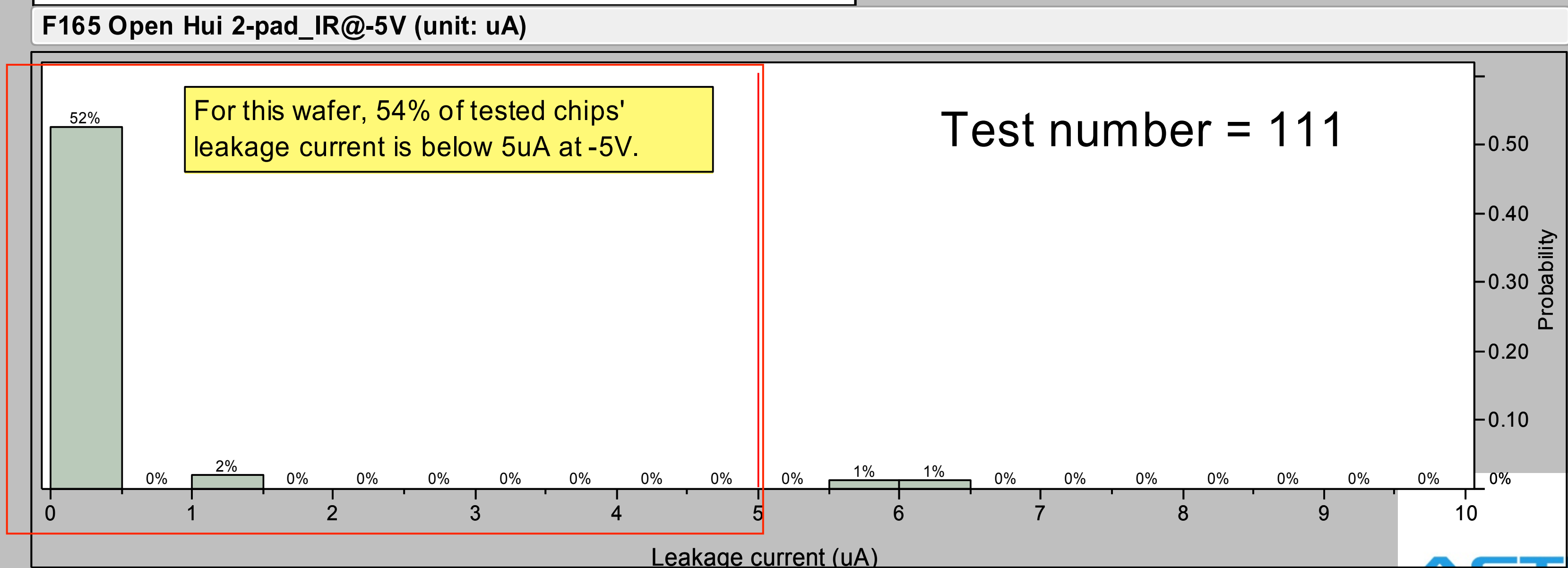
Electrical Characteristics



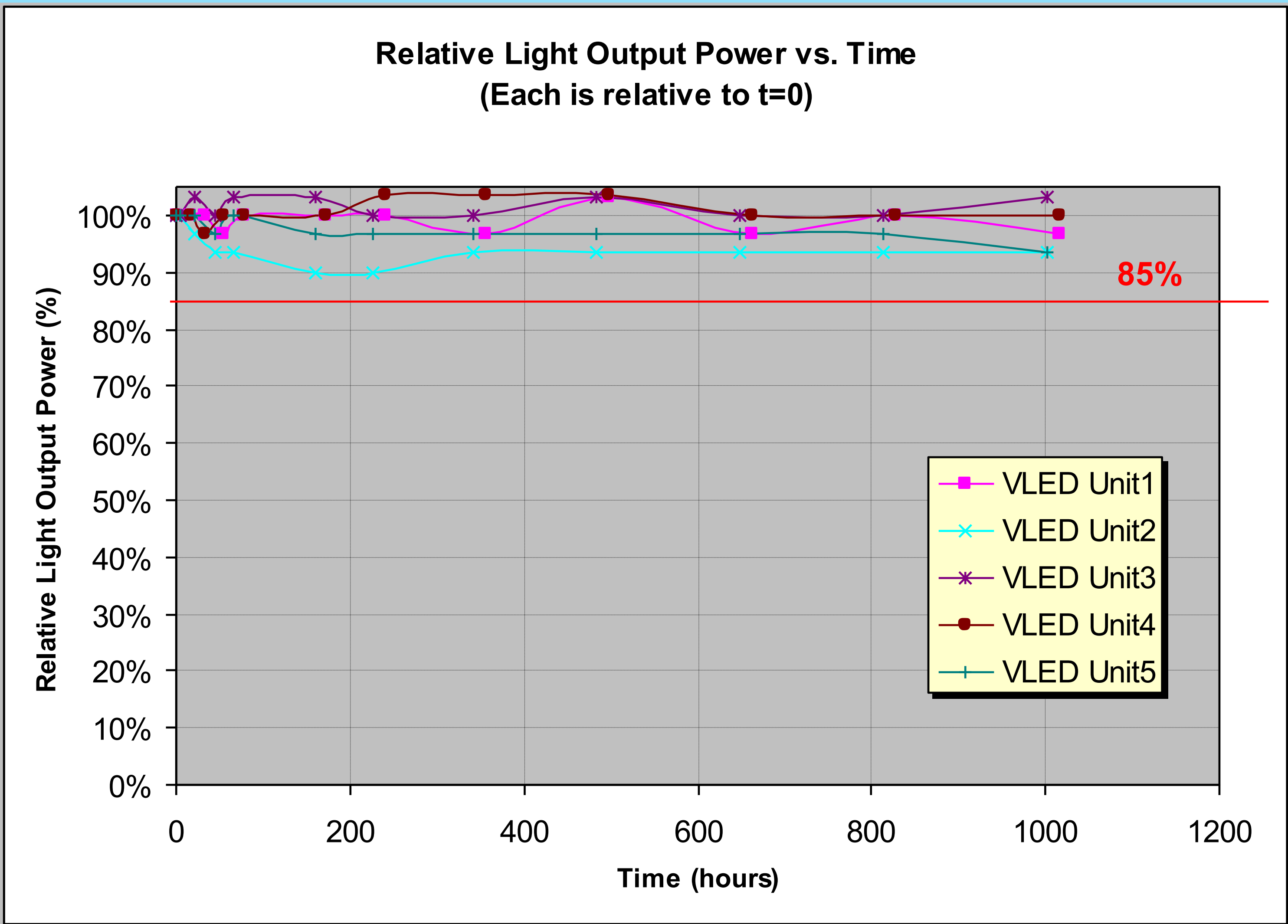
LEDs Made by ASTRI Method



Example of current – voltage characteristics of LEDs (data from LEDs made from Wafer No. 165)

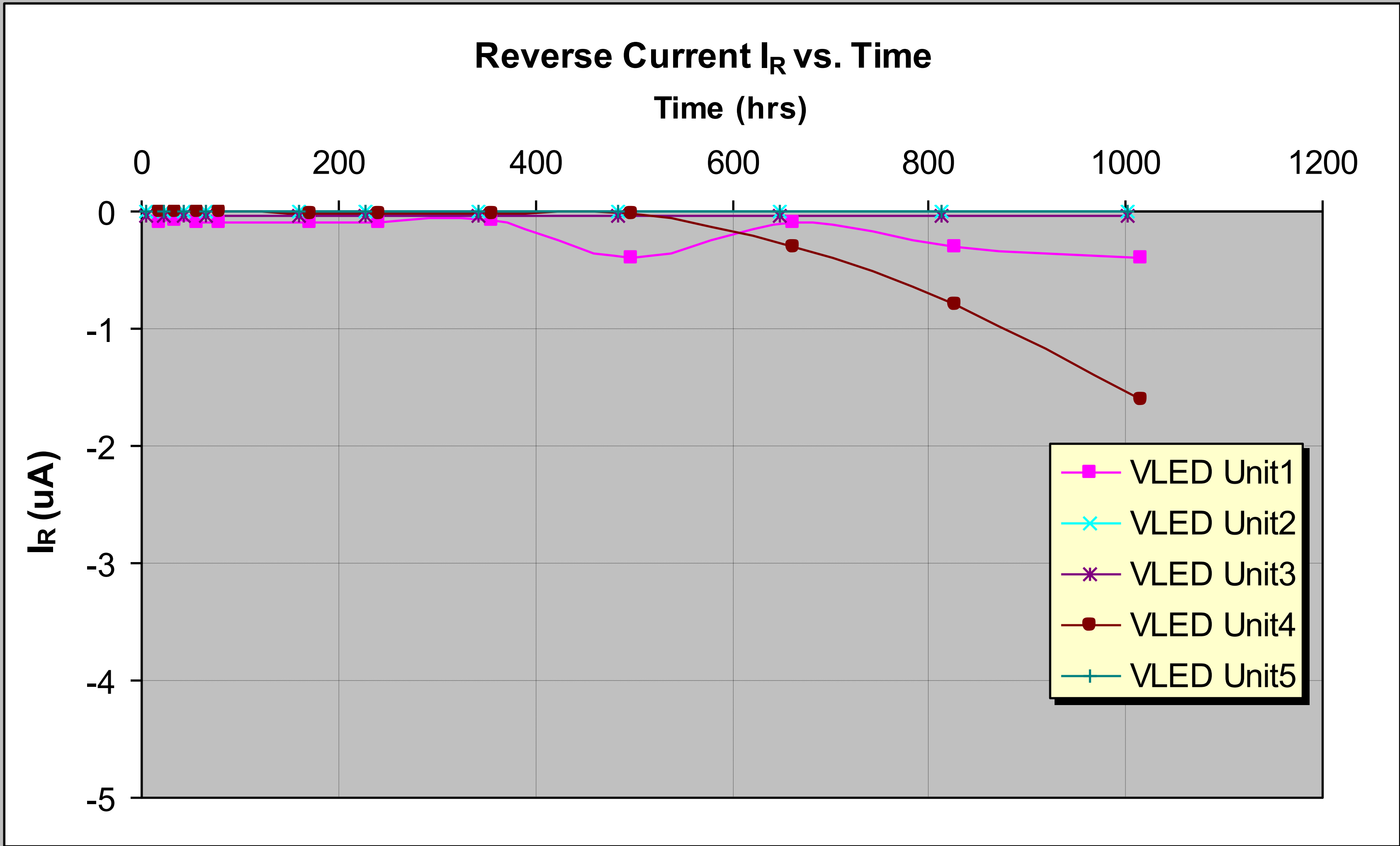


LEDs Made by ASTRI Method: Relability



Test conditions: 350 mA, 50° C

LEDs Made by ASTRI Method: Relability



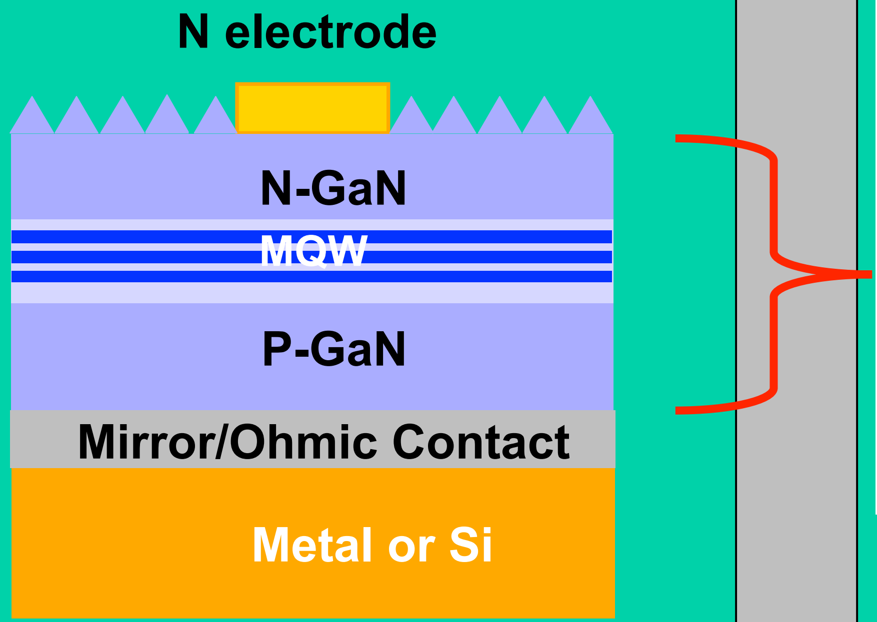
Test conditions: 350 mA, 50° C

ASTRI Power LED Chip Projects

5 patents filed, licensed to Epistar and Century Epitech

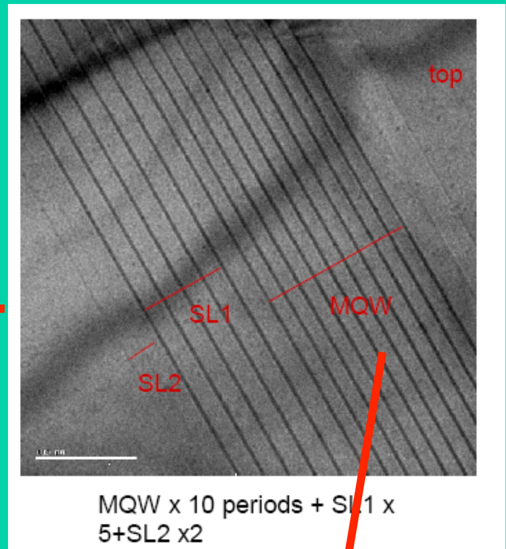
Finished Project (2/2008 – 9/2009)

Chip Design and Fabrication



New Project (1/2010 – 6/2011)

Epitaxial Structure Design + Chip Design and Fabrication



MQW: Multiple Quantum Wells

SL: Superlattice

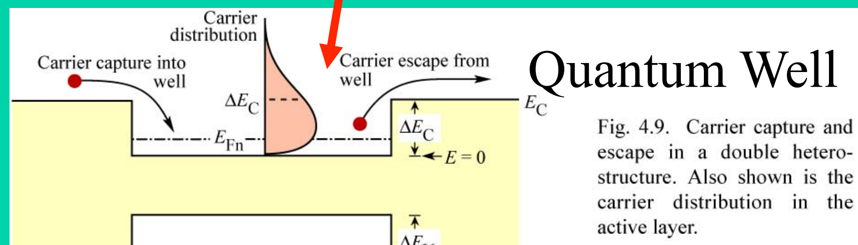


Fig. 4.9. Carrier capture and escape in a double heterostructure. Also shown is the carrier distribution in the active layer.

E. F. Schubert *Light-Emitting Diodes* (Cambridge Univ. Press) www.LightEmittingDiodes.org

Conclusions

1. GaN-related materials are academically and commercially important materials.

2. For GaN LEDs, the current trend is towards power LEDs for solid-state lighting etc.

3. Removal of the substrate and replacing it is inevitable for power devices.

4. ASTRI has developed a core technology platform for making power GaN LED chips. The technology has been licensed to 2 major chip makers. We are racing to commercialize it in coming years.

Thank you !!