Simulations in the Development Process of GaN-based LEDs and Laser Diodes

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Simulations in the Development Process of GaN-based LEDs and Laser Diodes

Introduction

- Applications for InGaN high brightness LEDs

InGaN Light Emitting Diodes

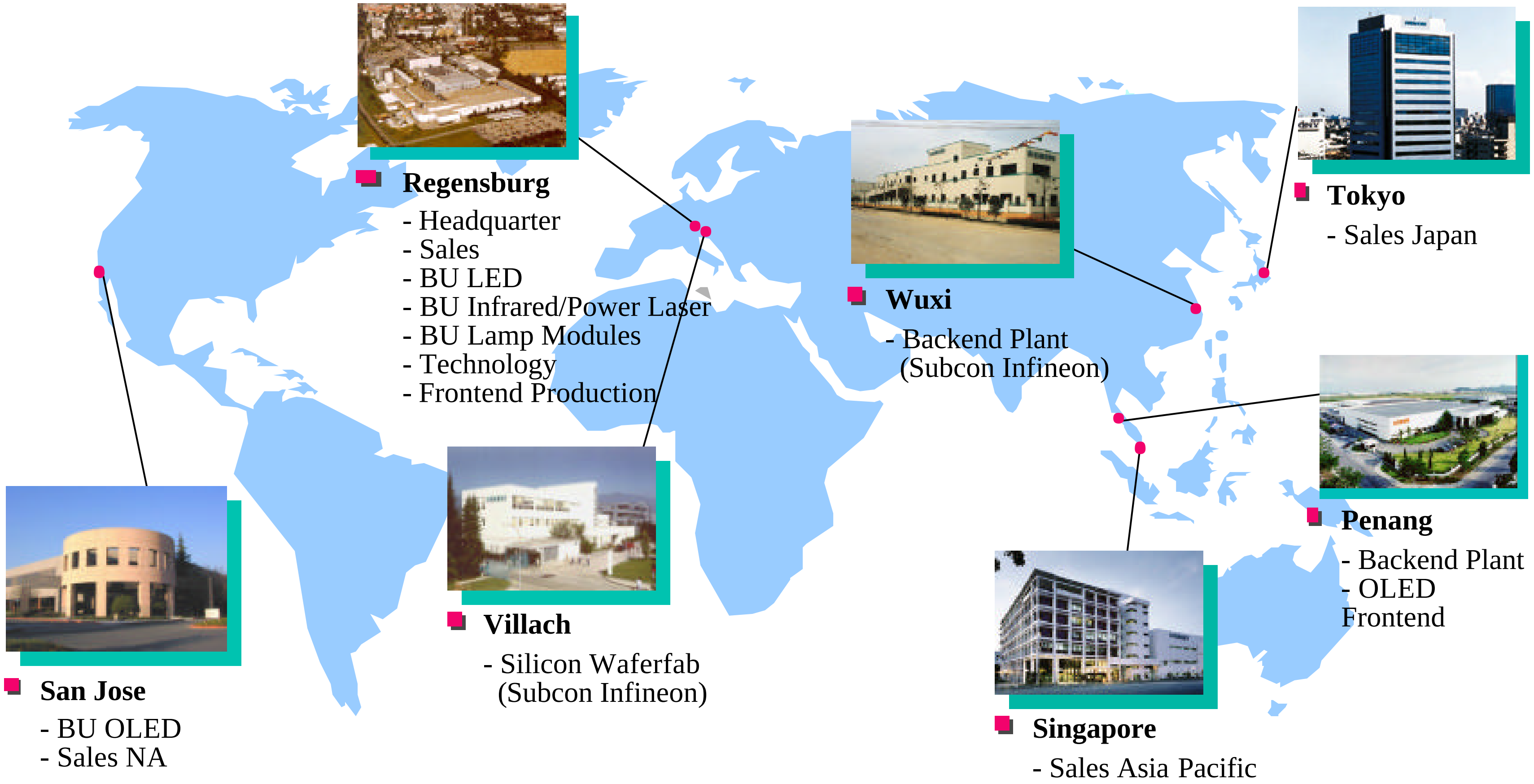
- LED development process: where can simulations be useful?
- Specific InGaN chip development project accompanied by simulations

InGaN Laser Diodes

- Progress of Laser Diode Development at Osram OS

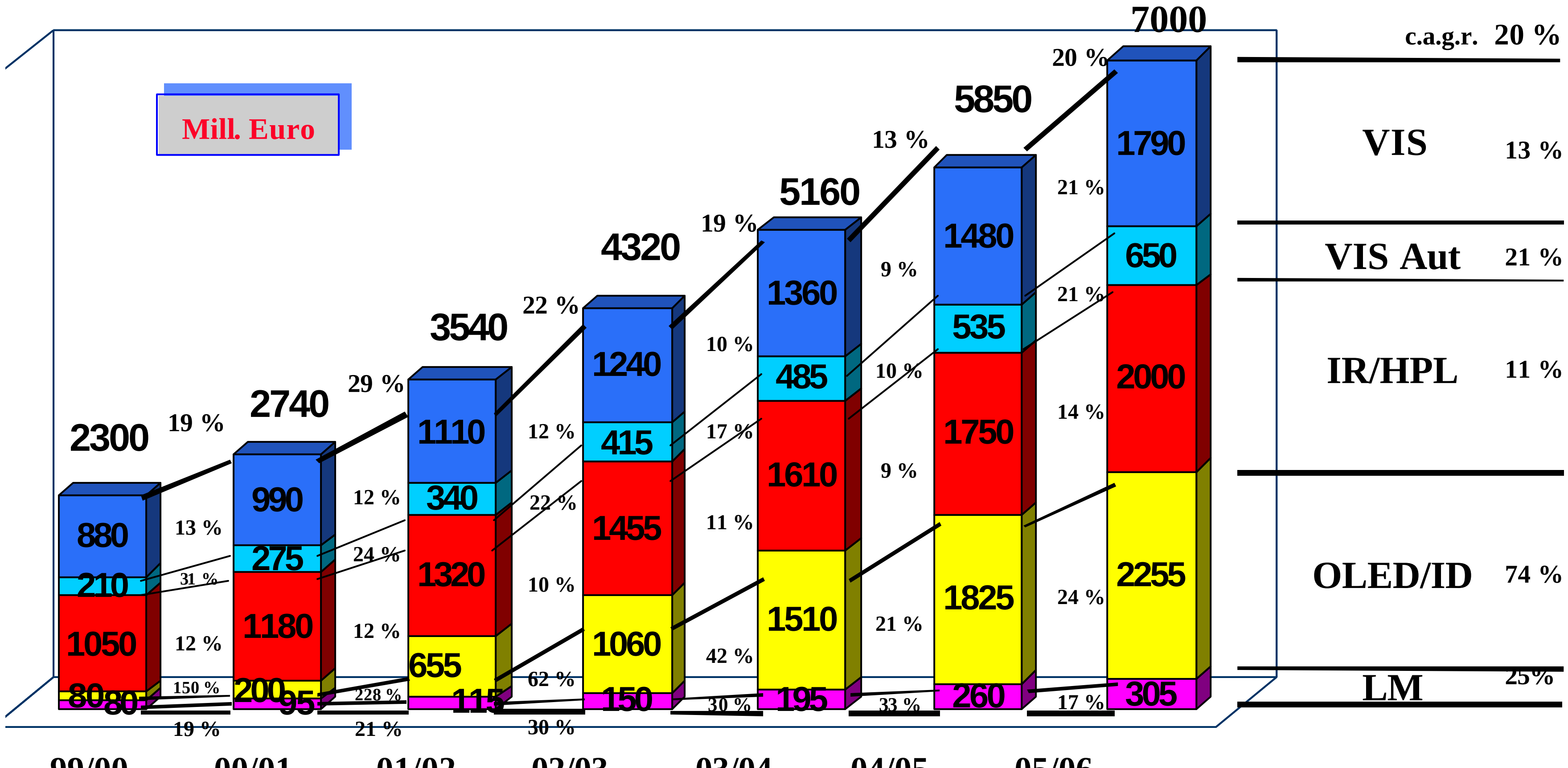
Our Activities and Locations

Siemens AG → OSRAM GmbH → OSRAM Opto Semiconductors GmbH



Opto Semiconductors OSRAM

World Market by Product Segments

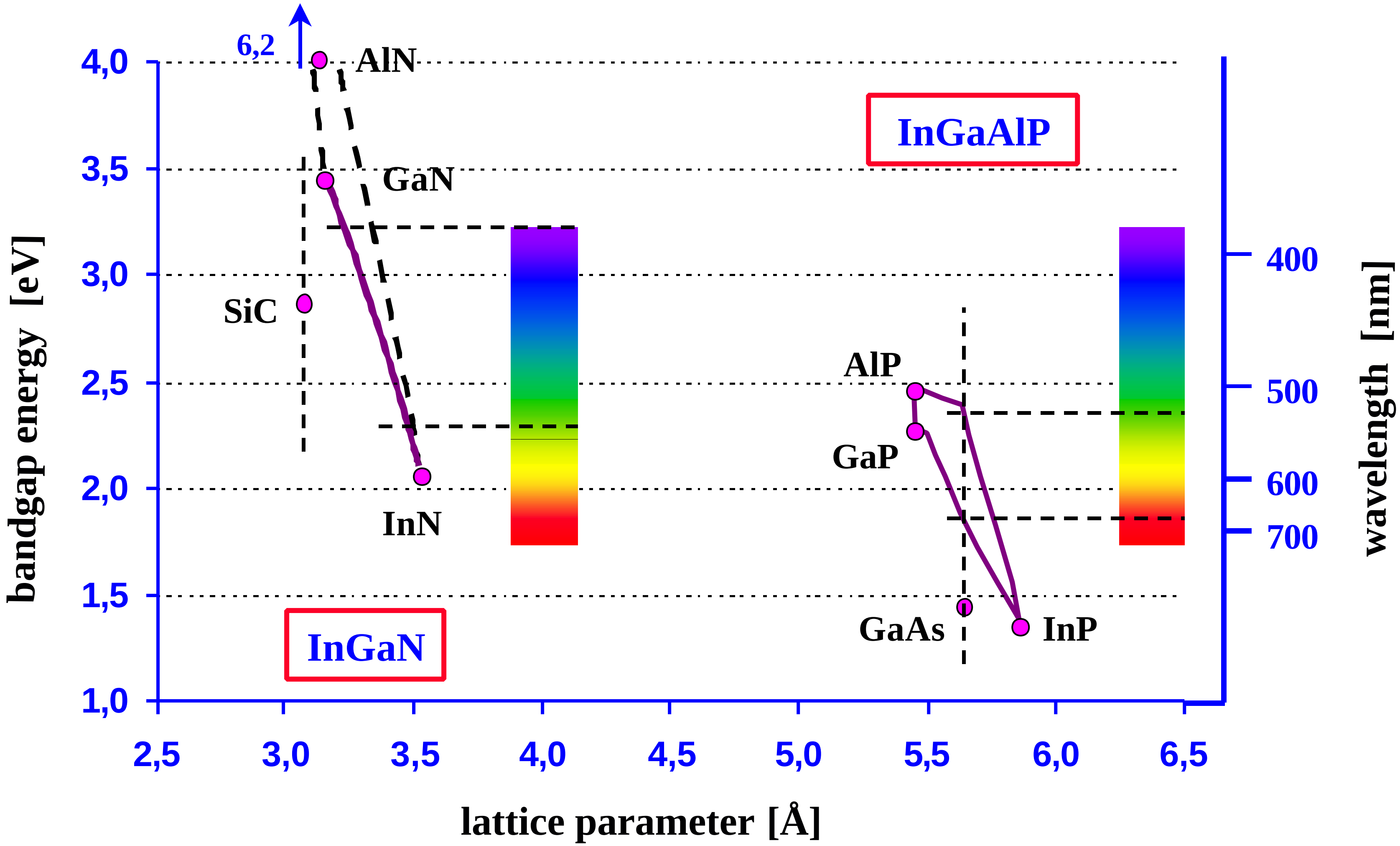


Source: OSRAM OS

Opto Semiconductors

OSRAM

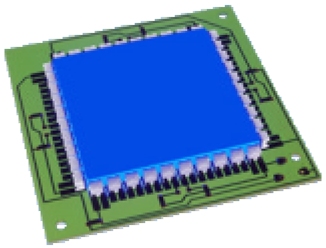
Material Systems
for High Brightness LEDs



Applications for GaN-LEDs

Automotive
Interior + Exterior

Marker Lights



Mobile Applications

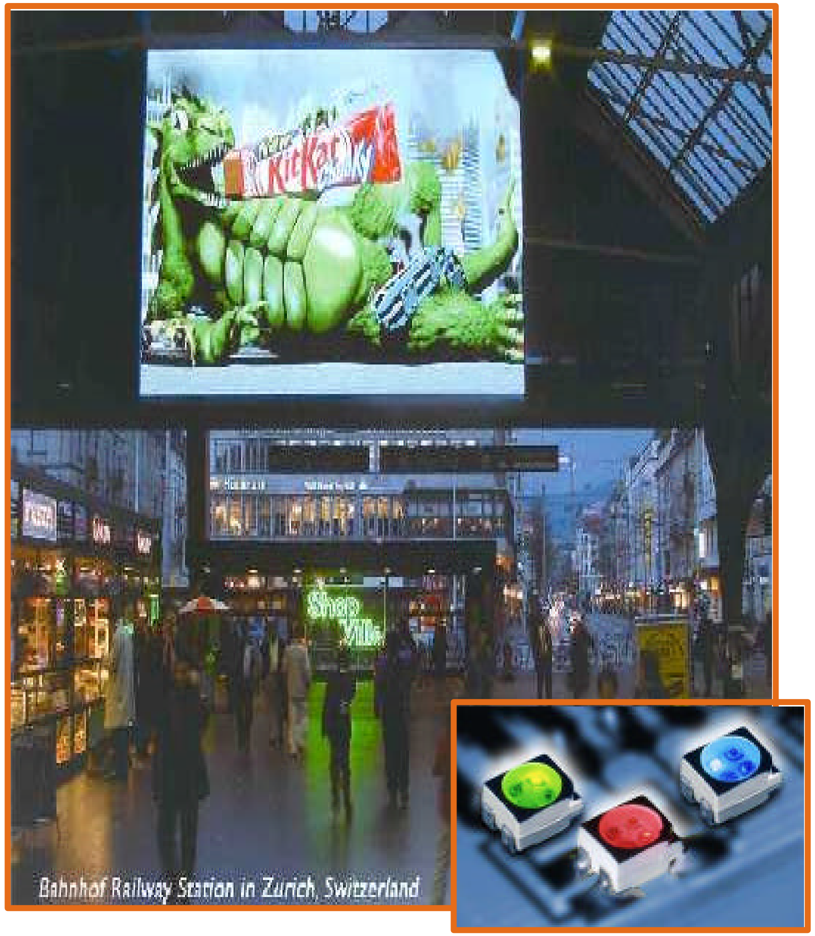
Opto Semiconductors

Applications for LED Modules

Signal Lights

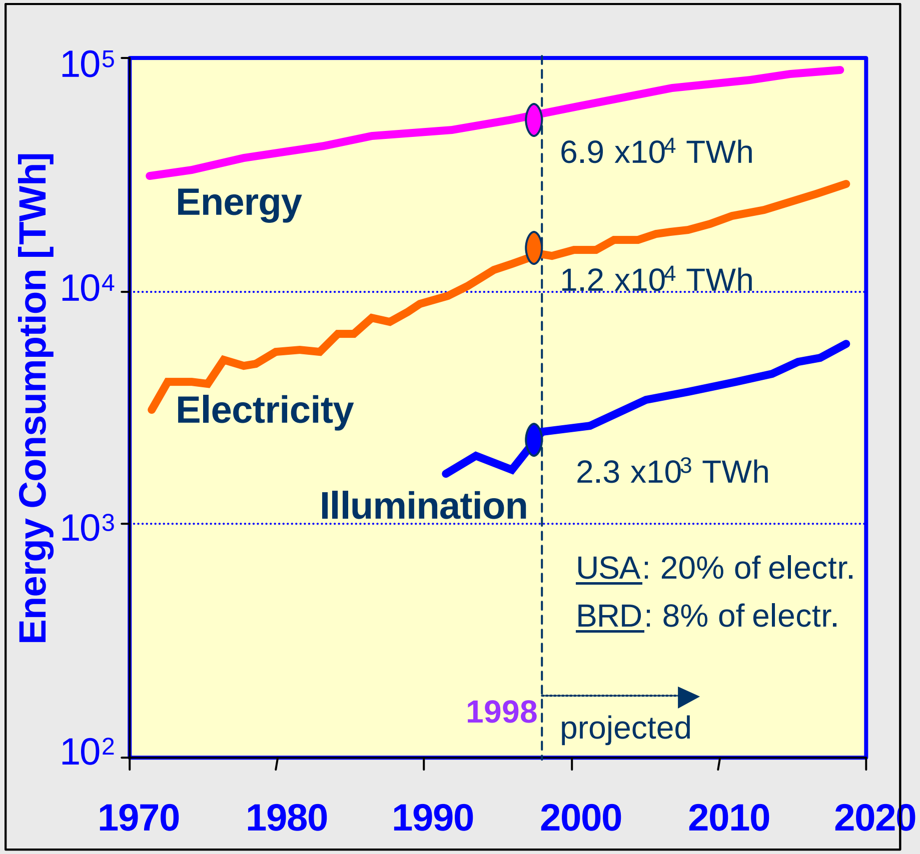
Illuminated Signs

Full Color Displays



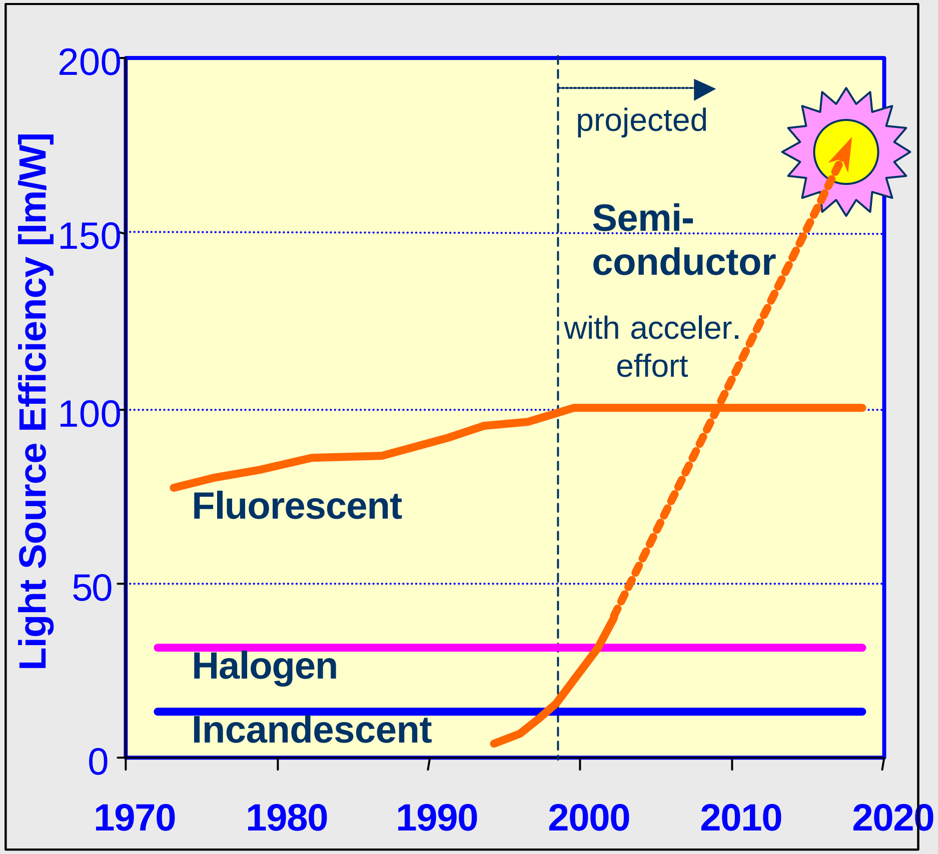
Are Semiconductors the Light of the Future?

World Energy Consumption p.a.



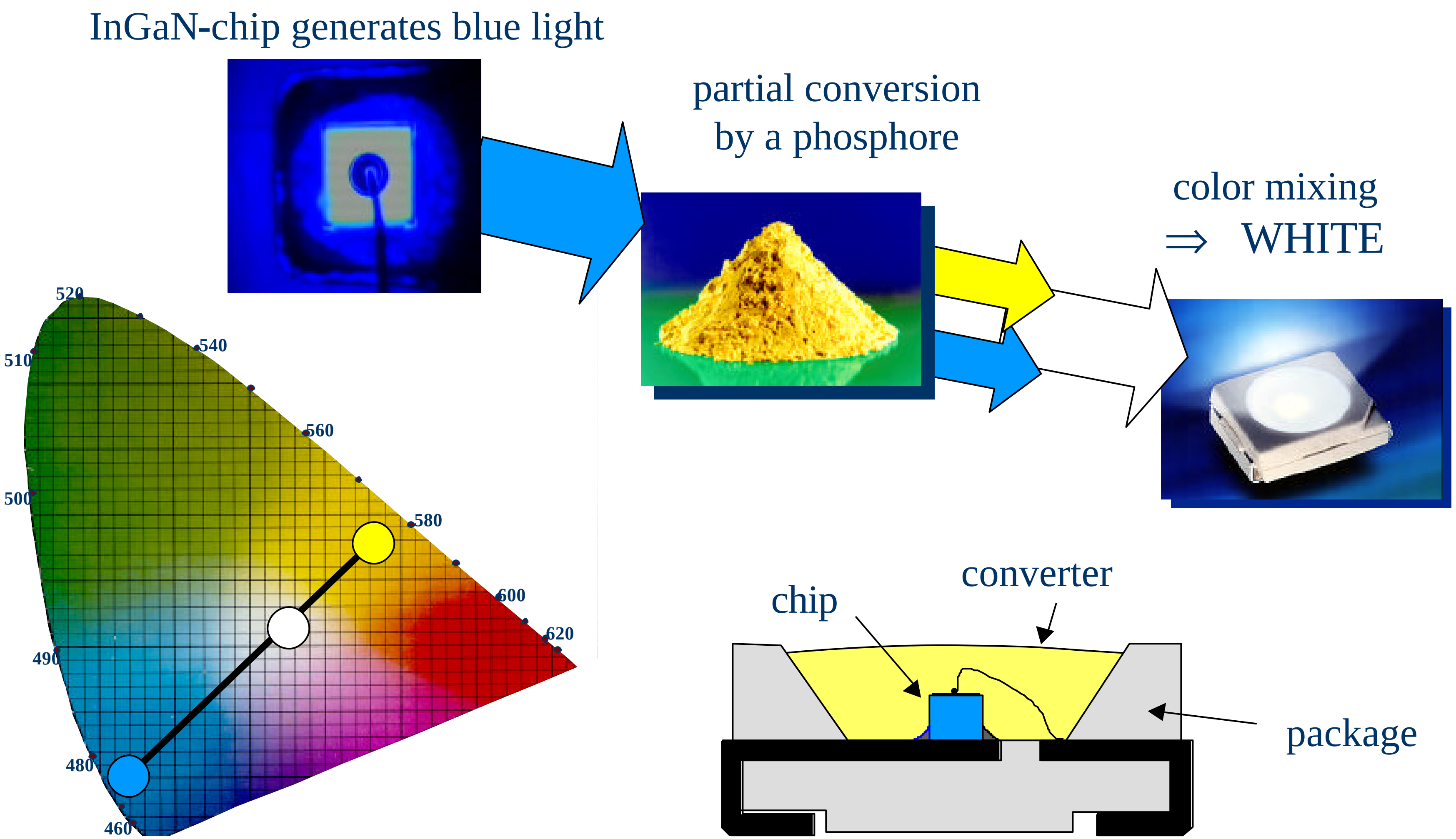
Source: International Energy Agency

Efficiencies of Light Sources



Source: R. Haitz, Hewlett-Packard

“White LED”


InGaN-chip generates blue light
partial conversion
by a phosphore
color mixing
⇒ WHITE
520
540
510
560
500
580
600
620
490
480
460
chip
converter
package

Lamp Modules Applications: General Lighting

LED Modules for general lighting

- information and orientation lighting
- effect lighting
- ambient lighting

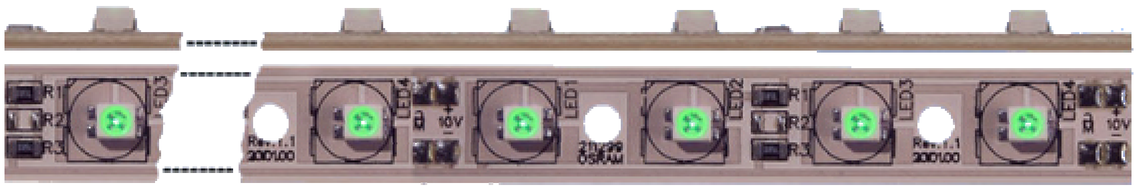
LED Modules offers

creative design possibilities

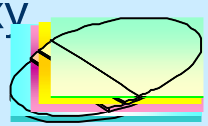
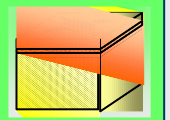
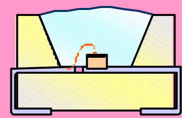
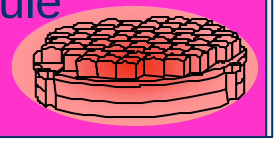
extremely low-profile light solutions

high light output ratio

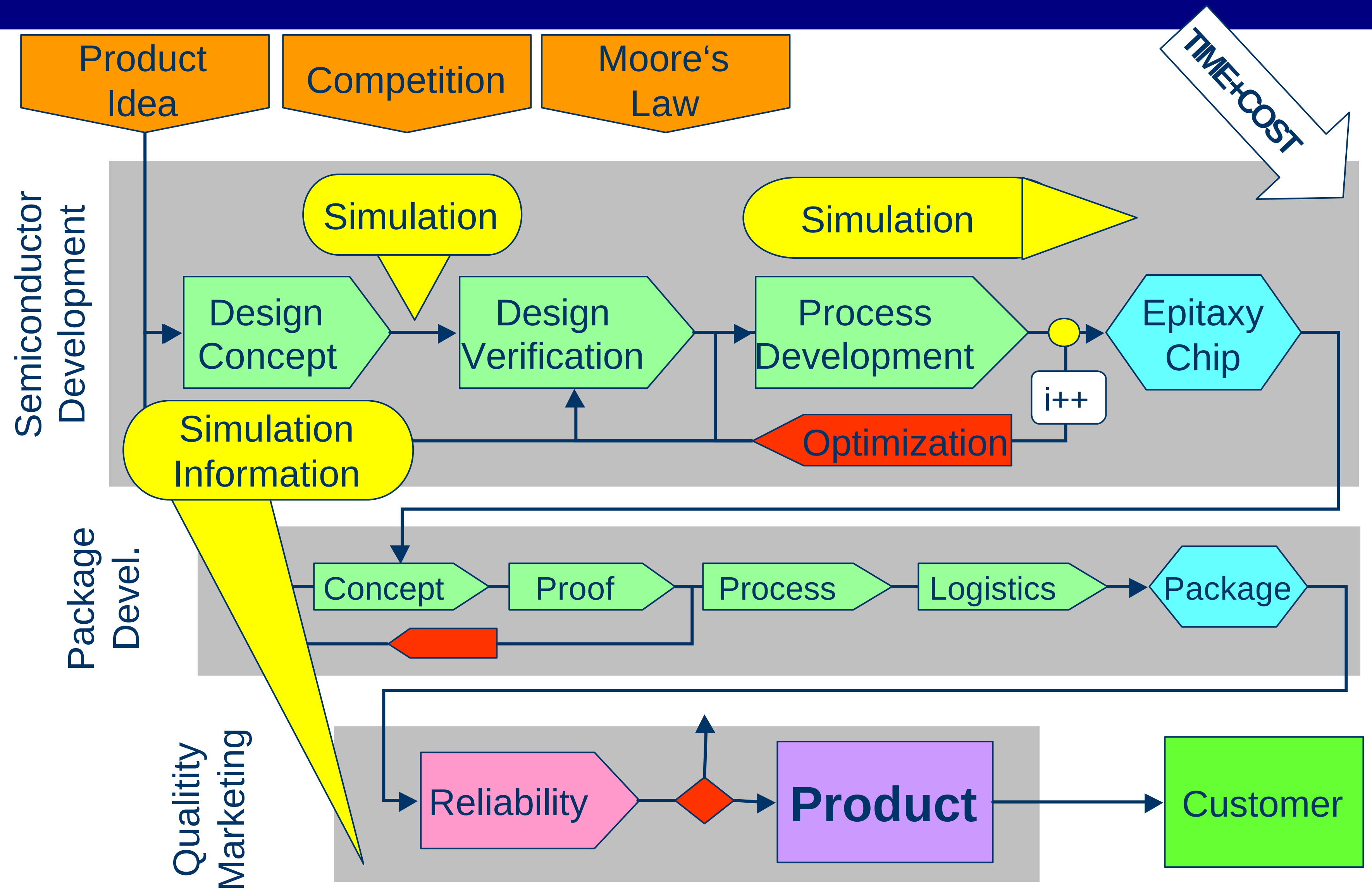
reduced maintenance costs



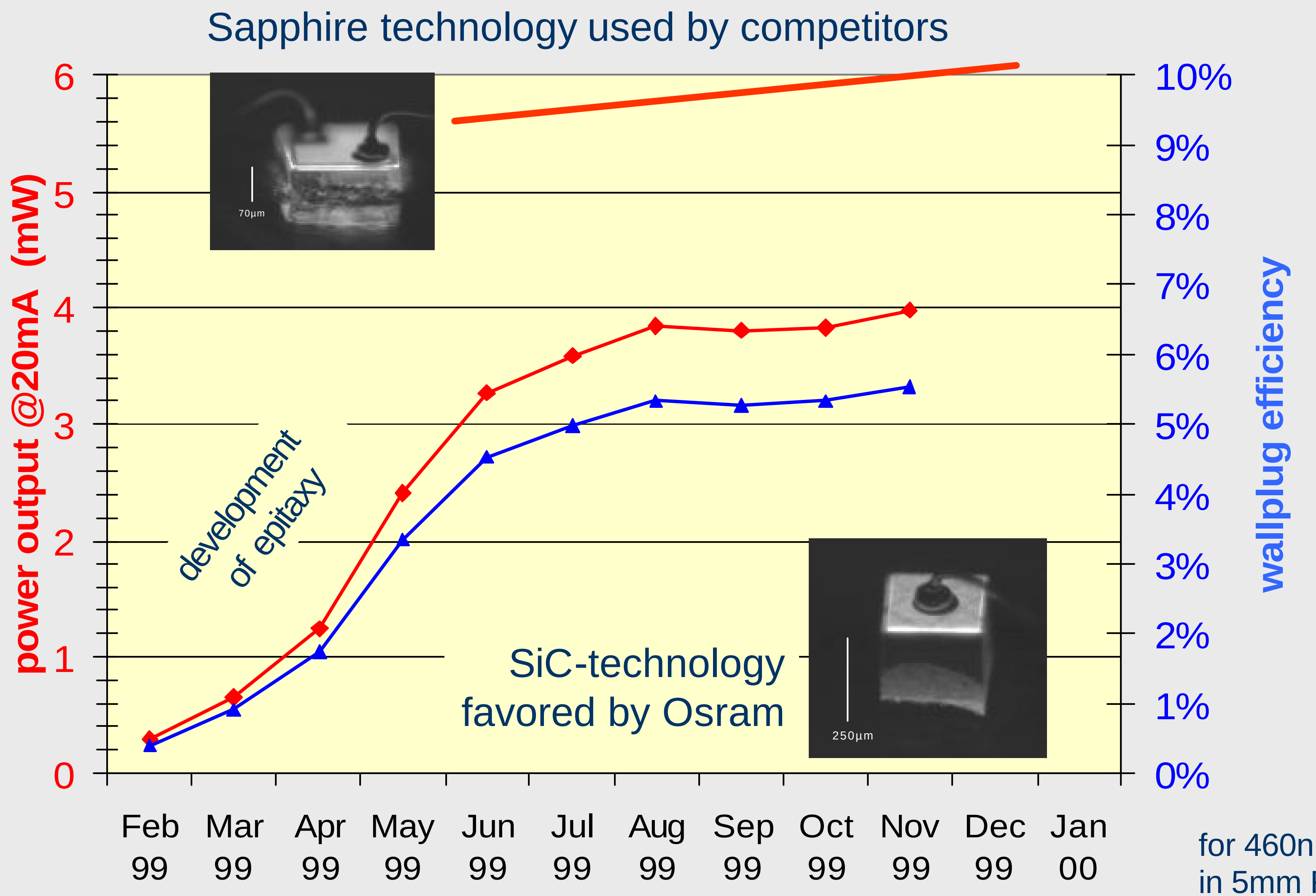
Complexity of LED Production

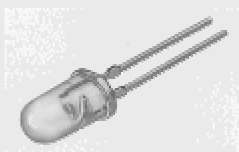
Epitaxy 	Chip Processing 	Packaging 	Module 
Parameters			
heterostructure design	chip geometry contacts	housing geometry polymer materials	light guides board design
Properties To Optimize			
internal QE / gain mode control (LD) voltage control defects	external QE (LED) mode control (LD) voltage control thermal management	light extraction luminance thermal management mechanical properties reliability	light distribution imaging contrast power drivers
Processes			
growth kinetics MOVPE Reactor	semiconductor processes	molding/casting mass production	system integration

LED Development Scenario



Brightness Development of InGaN QW-LED

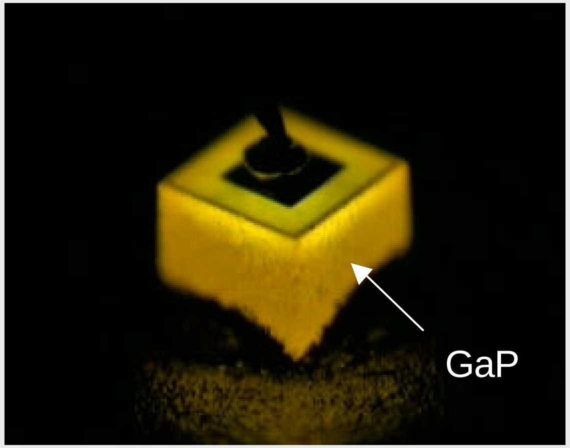




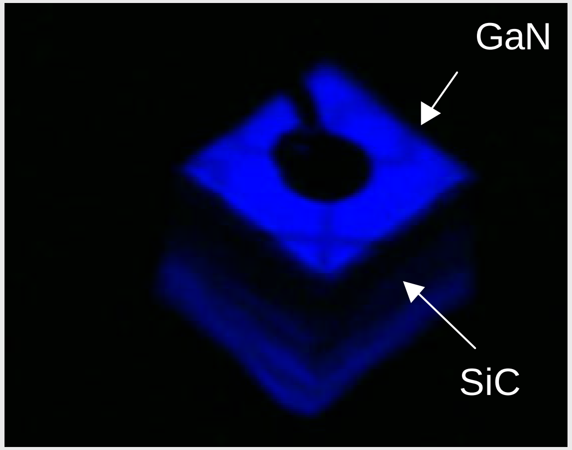
for 460nm blue LED
in 5mm Radial housing

„Dark“ Transparent Substrate?

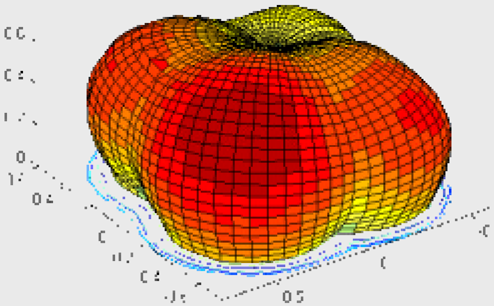
GaP-based chip

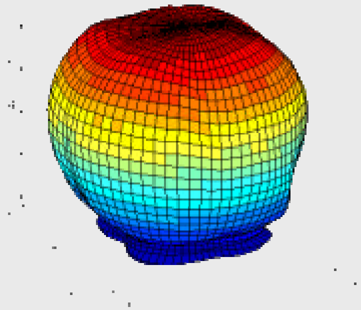


GaN on SiC



angular distribution





Though 6H-SiC is transparent for blue light:

no emission from substrate observed!

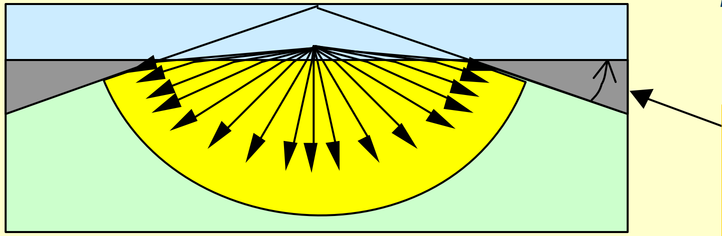
Light Extraction from GaN/SiC-System

Transparent Substrate SiC (E_g=3.03eV)

but
n(GaN) < n(SiC)

GaN: n=2.5

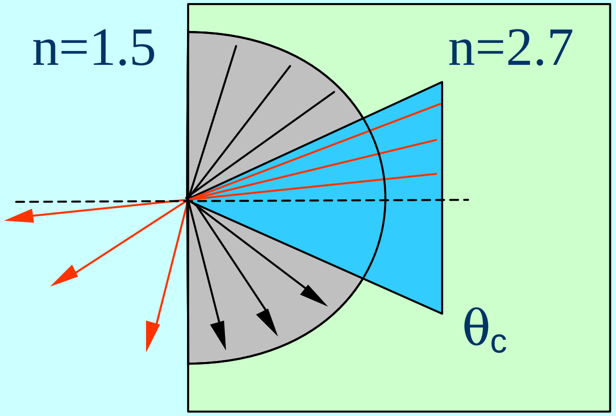
SiC: n=2.7



ß

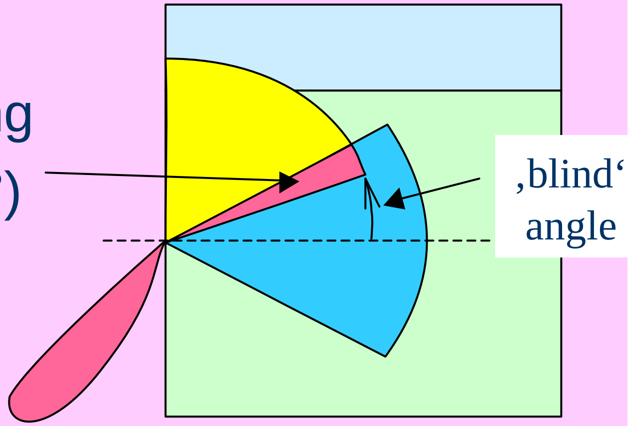
Snell‘s law
‚blind‘ angle (22°)

Light Extraction from SiC:
θ_c=33°



Incomplete Overlap
⇒ low efficiency

outcoupling
angle (11°)



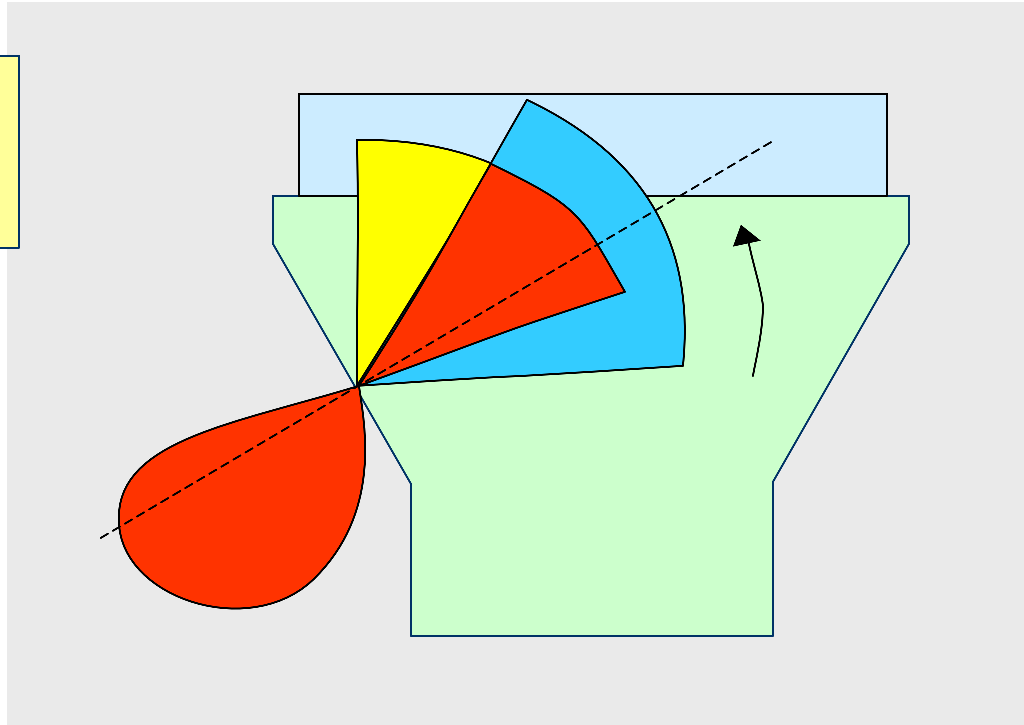
How can the Efficiency be Improved

improved light extraction:

Increase overlap of incident rays with outcoupling cone

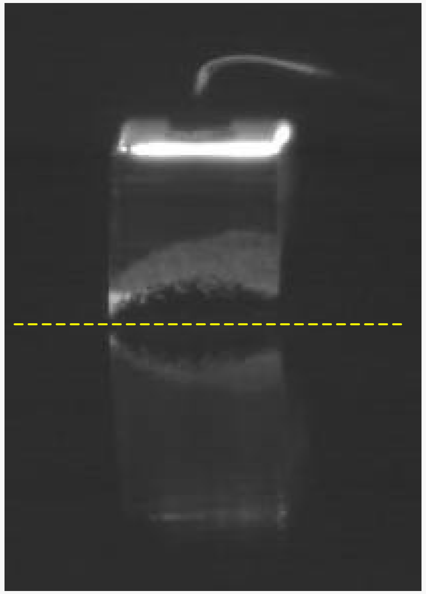
Inclined substrate facets

- optimized use of outcoupling cone
- light extraction on first incidence

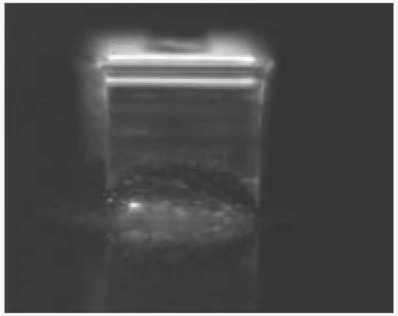


Steps towards Realization of ATON-Technology

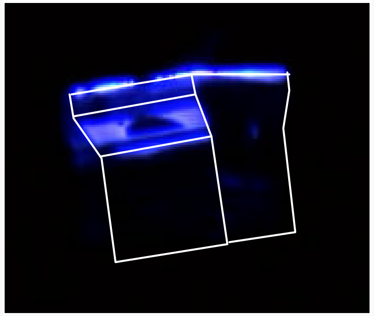
dicing process modification: transfer of inclined facet design into SiC-substrate



standard cube:
η=100%

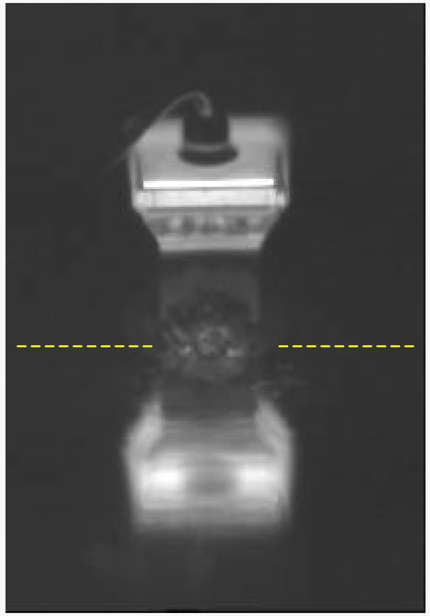


first test:
η=115%



‚proof' of design:
η=145%

accompanied by simulation



final **ATON** design:
η=180%

Simulation:

- fewer experimental optimization cycles
- confidence in optimum performance level

Raytracing Analysis

Objectivel of Chip Development:

- optimize External Quantum Efficiency (EQE)

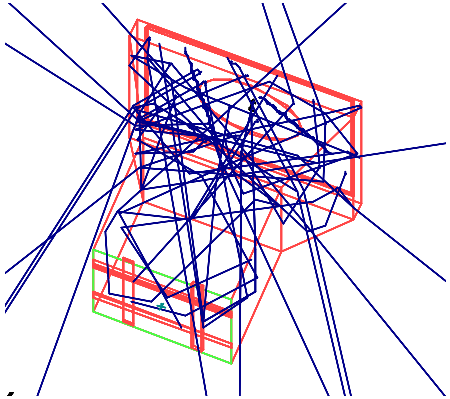
EQE hard to assess experimentally!

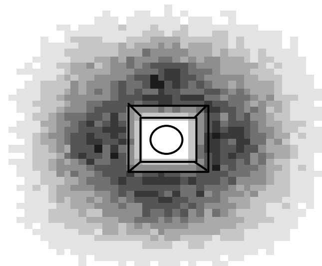
<u>Non-sequential Raytracing Analysis</u>

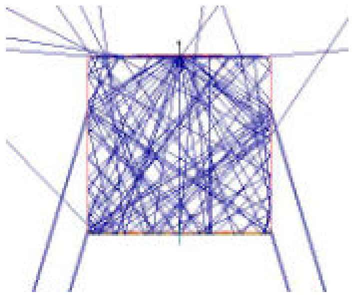
Þ EQE + intensity distribution

- + complete geometrical 3D chip model
- + transparent + absorbing elements
- + scattering
- + interface to package development

- \- wave effects
- \- electrical/thermal properties

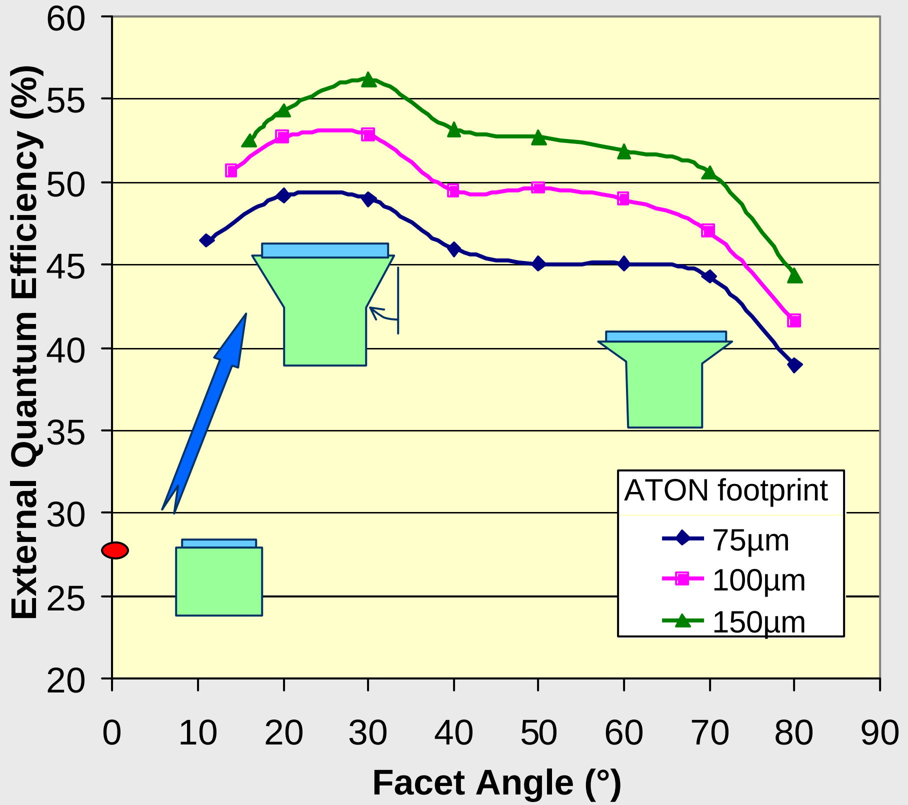






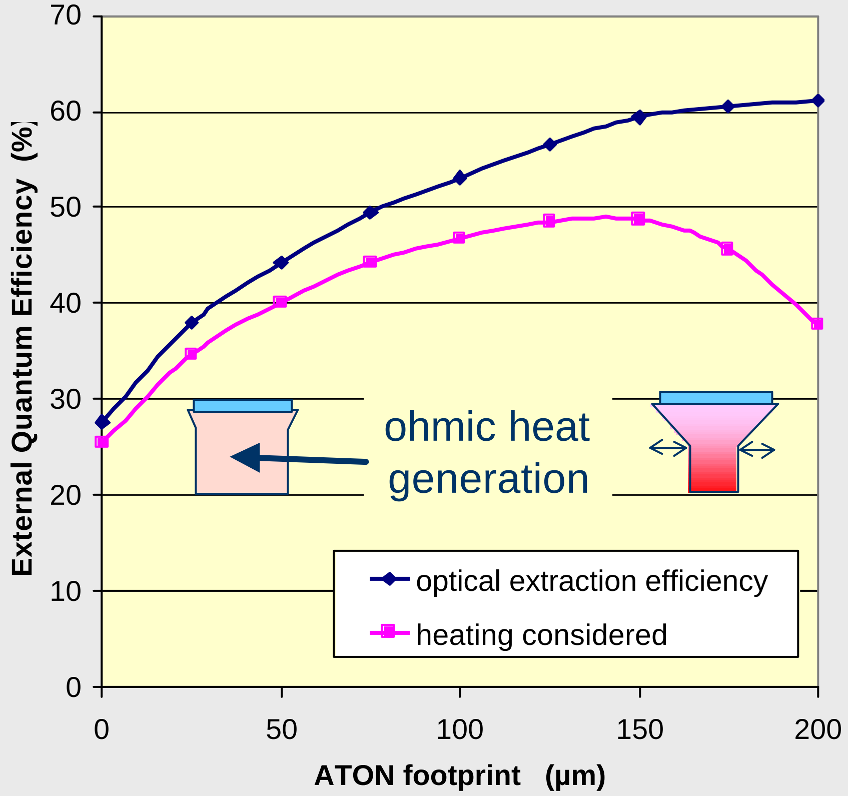
Optimization of Chip Shape

Facet Angle



ATON/socket ratio

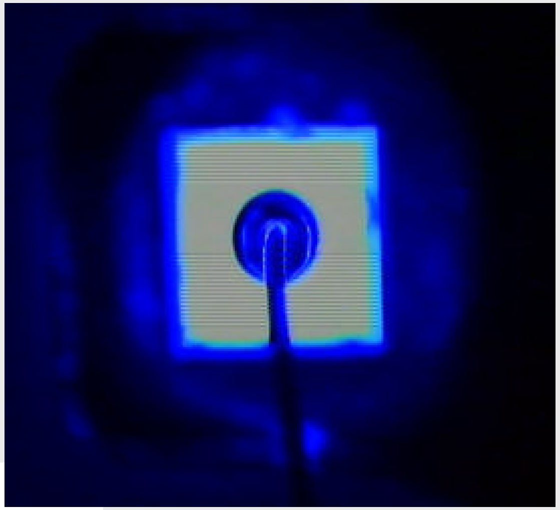
(290x290µm chip)

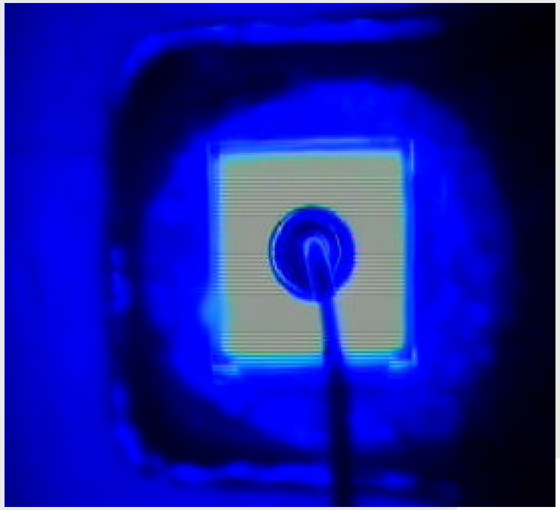


- optimum facet angle ≈30° ⇒ **Doubling of Extraction Efficiency**
- limited by ohmic heating

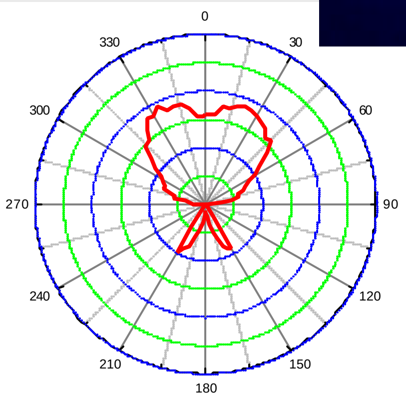
ATON in TOPLED - Package

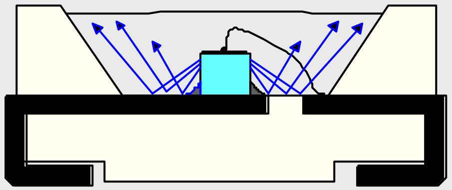
Standard Chip

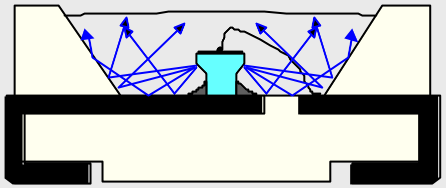


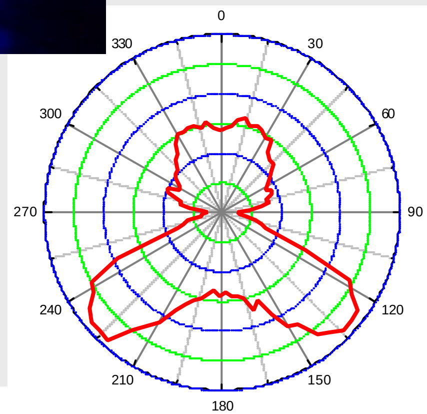


ATON Chip









brightness gain from backwards directed radiation

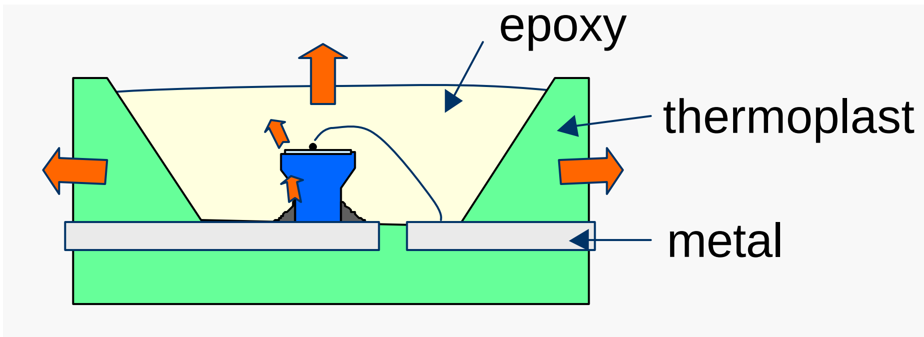
⇒ **REFLECTOR** is essential!

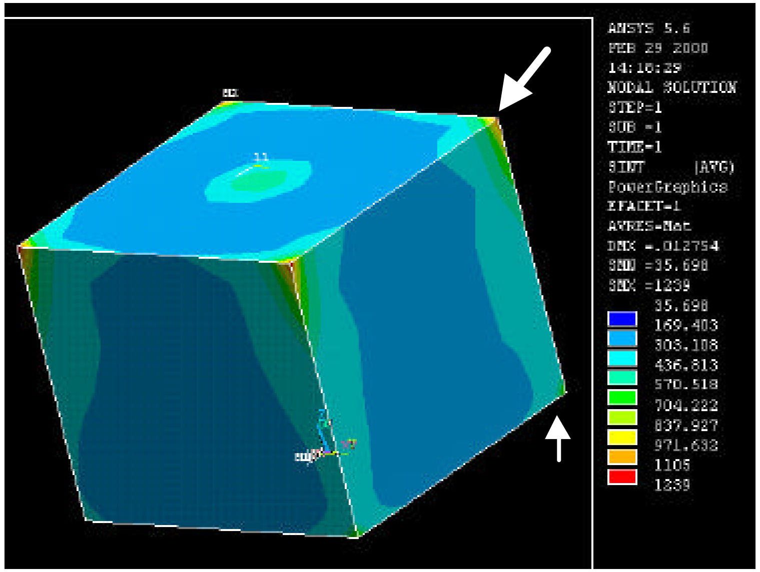
Reliability of ATON Chip in Package: Mechanical Stresses

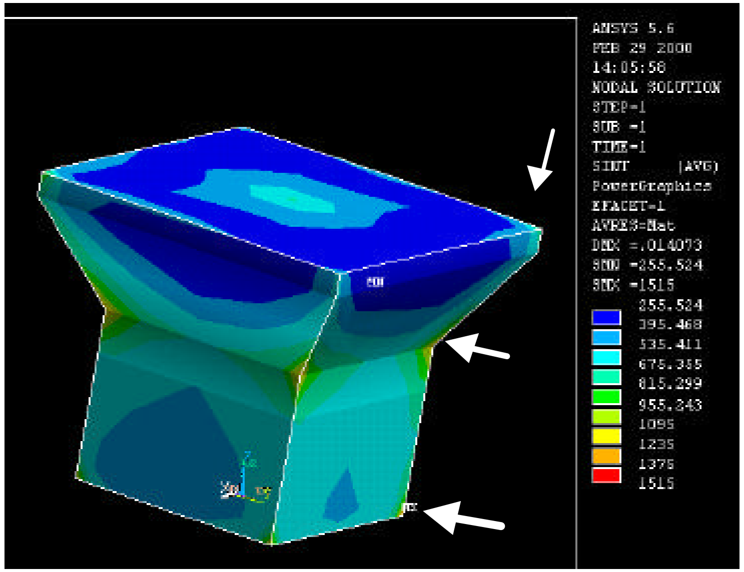
LED-Package:

materials with largely differing thermal expansion coefficients

⇒ Delamination?

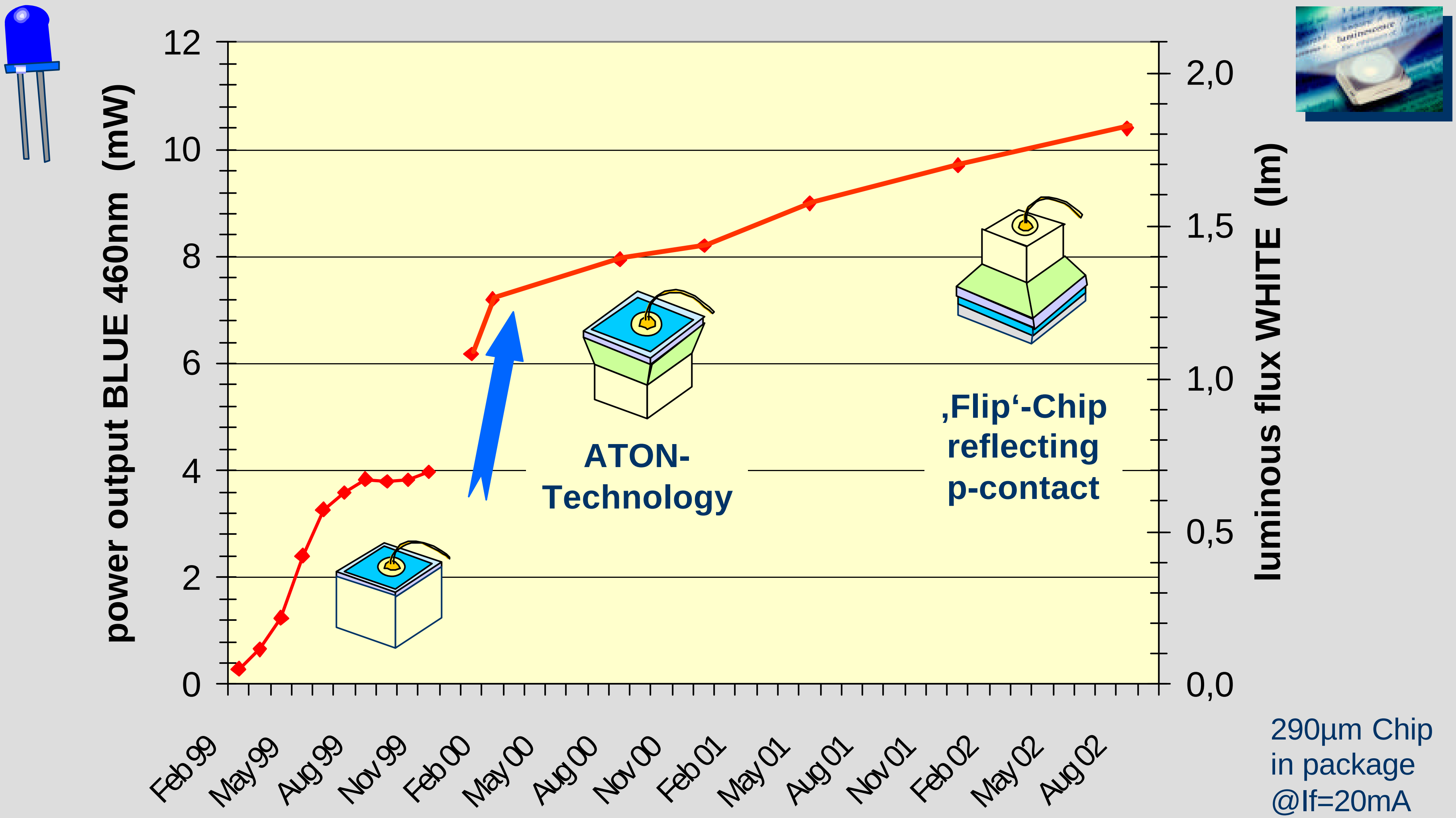






FEA shows no increased delamination risks for pyramidal chip

Brightness Development of InGaN-LED



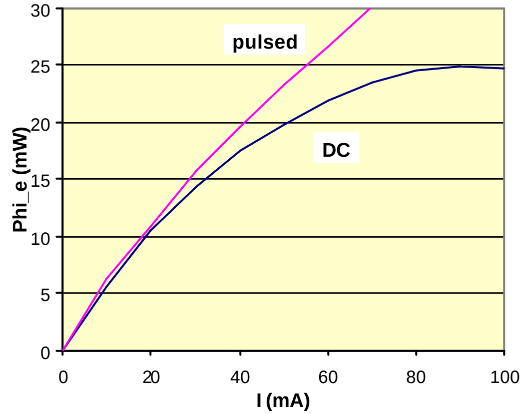
290µm Chip
in package
@If=20mA

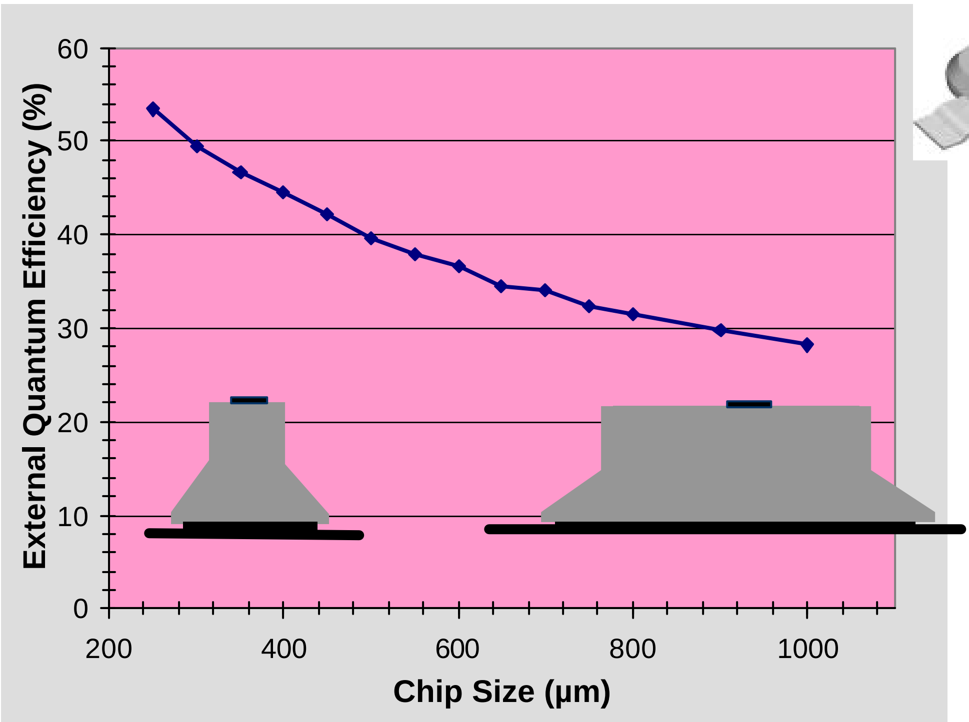
LEDs for POWER Applications

Applications like e.g. Headlamps

- LEDs with high luminous flux

⇒ go to high operation currents (350mA, 1W)



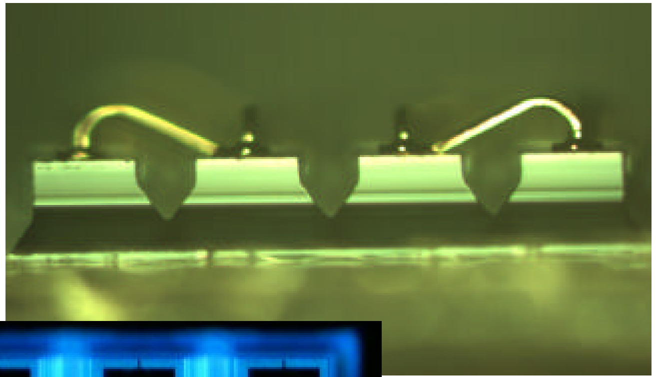


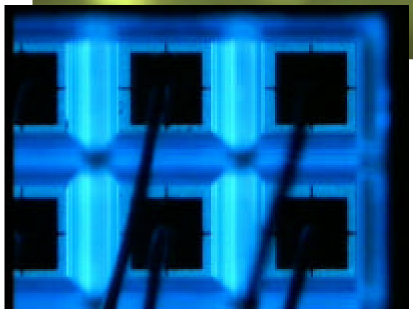
- new low R_{th} package
- increase chip size to minimize heating

Simulation shows:
efficiency decreases with chip size!

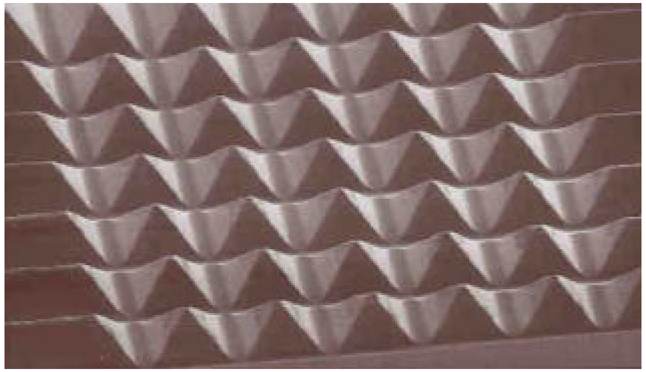
High flux LED on SiC:
Options for Scalability

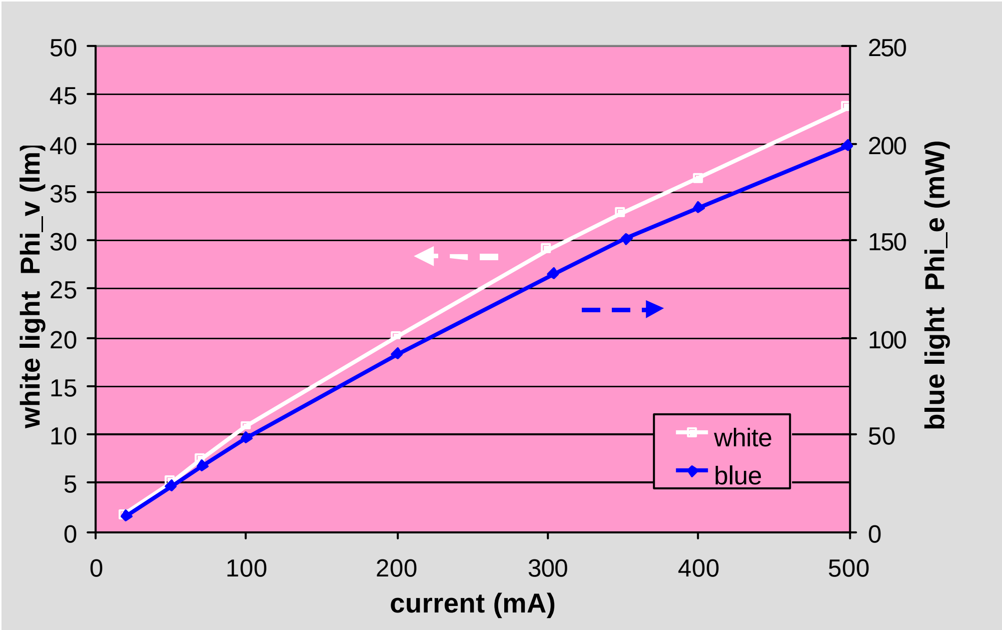
Multiple inner grooves





Surface texturing

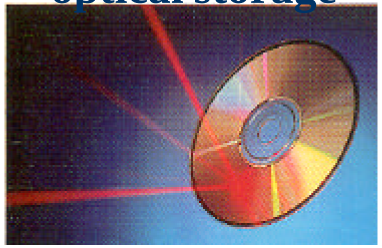




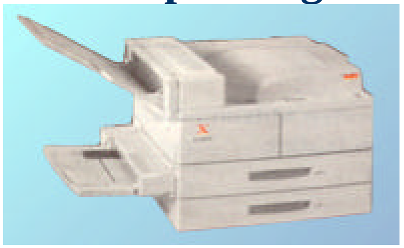
- Φ_e= 150 mW blue
  Φ_v= 33 lm white
- I_f=350 mA / U_f=3,9 V
- Chip area: 1 mm^2

Potential Market Segments for Blue Laser Diodes

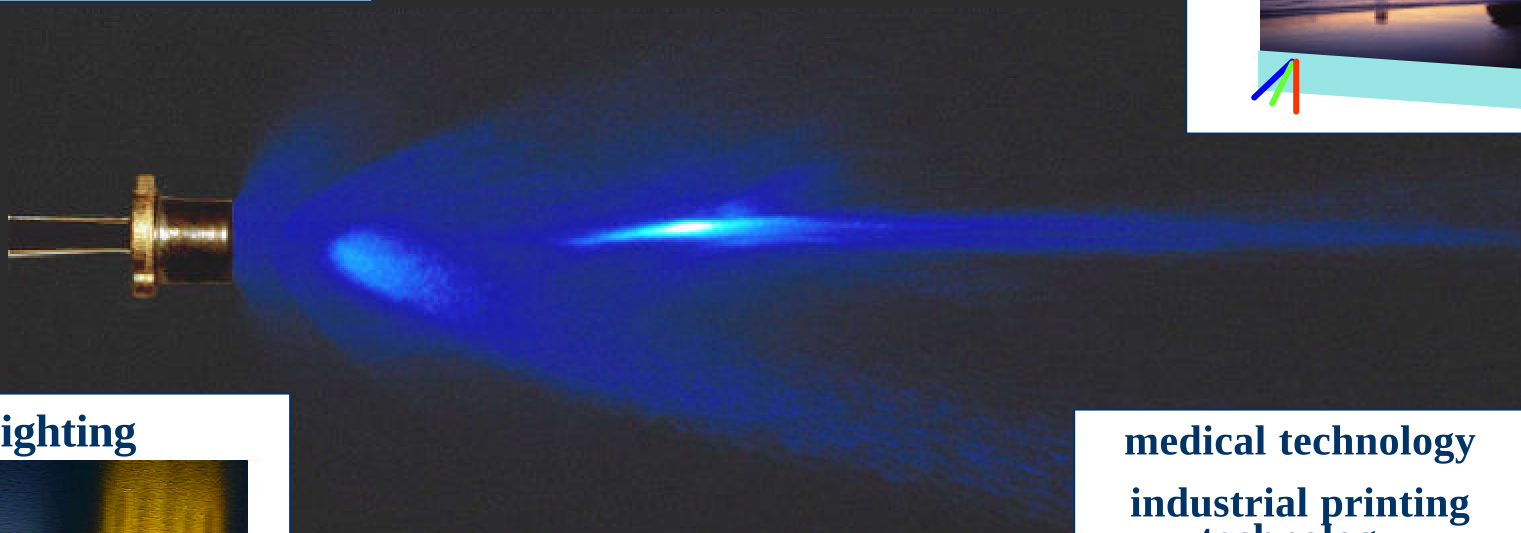
optical storage



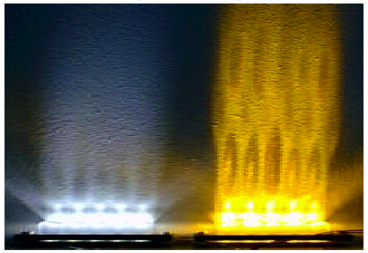
laser printing



projection - displays



lighting



medical technology

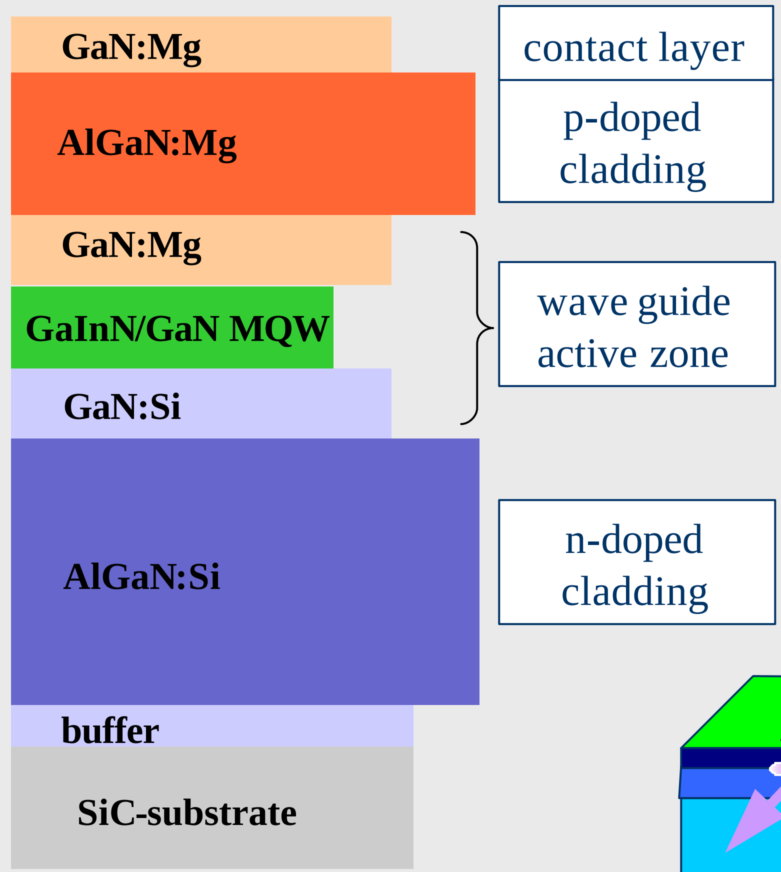
industrial printing technology

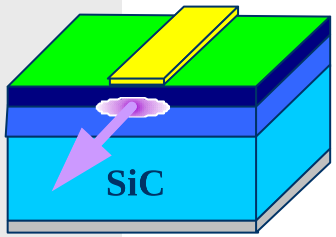
spectroscopy

...

Structure of InGaN Laser Diode on SiC

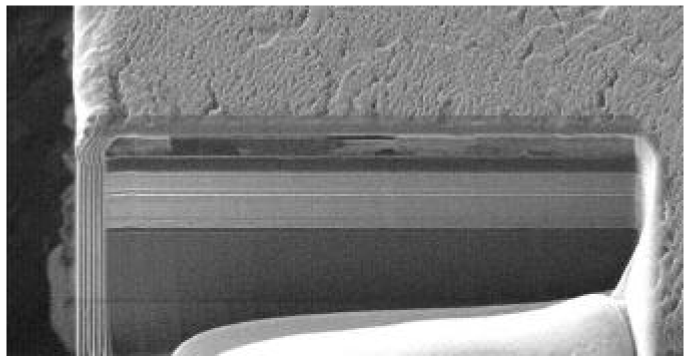
Vertical Structure





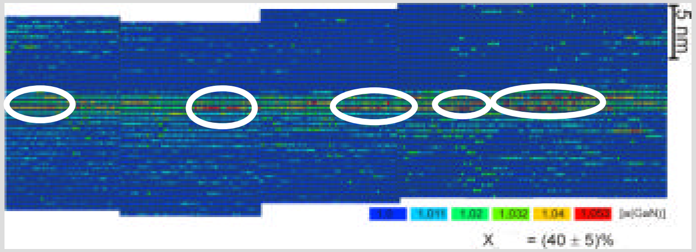
InGaN SCH-Laser Diode

- SiC substrate
- vertical current flow
- ridge wave guide
- cleaved facets
- dielectric mirror coating



Work Packages with GaN Lasers on SiC

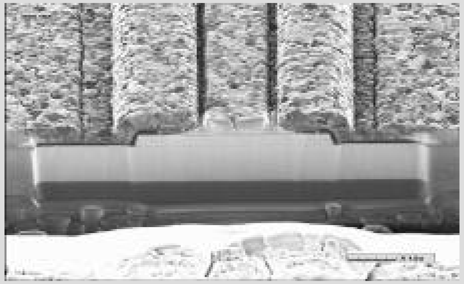
Indium fluctuations

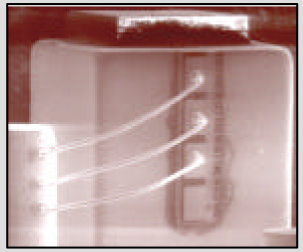


epitaxial growth parameters

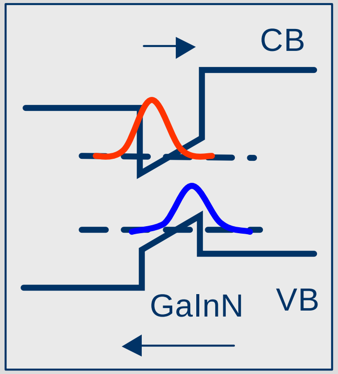
Reduction of Losses

- p-contact
- laser facets
- index guiding
- laser mounting



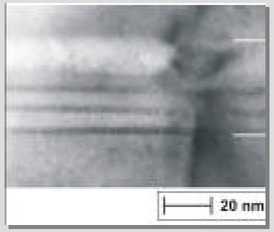


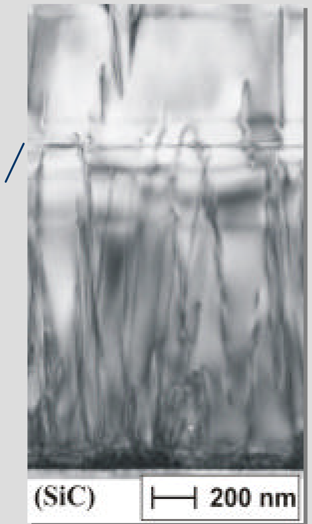
Heterostructure design



- number and depth of quantum wells
- piezoelectric effect
- wave guides

Dislocations



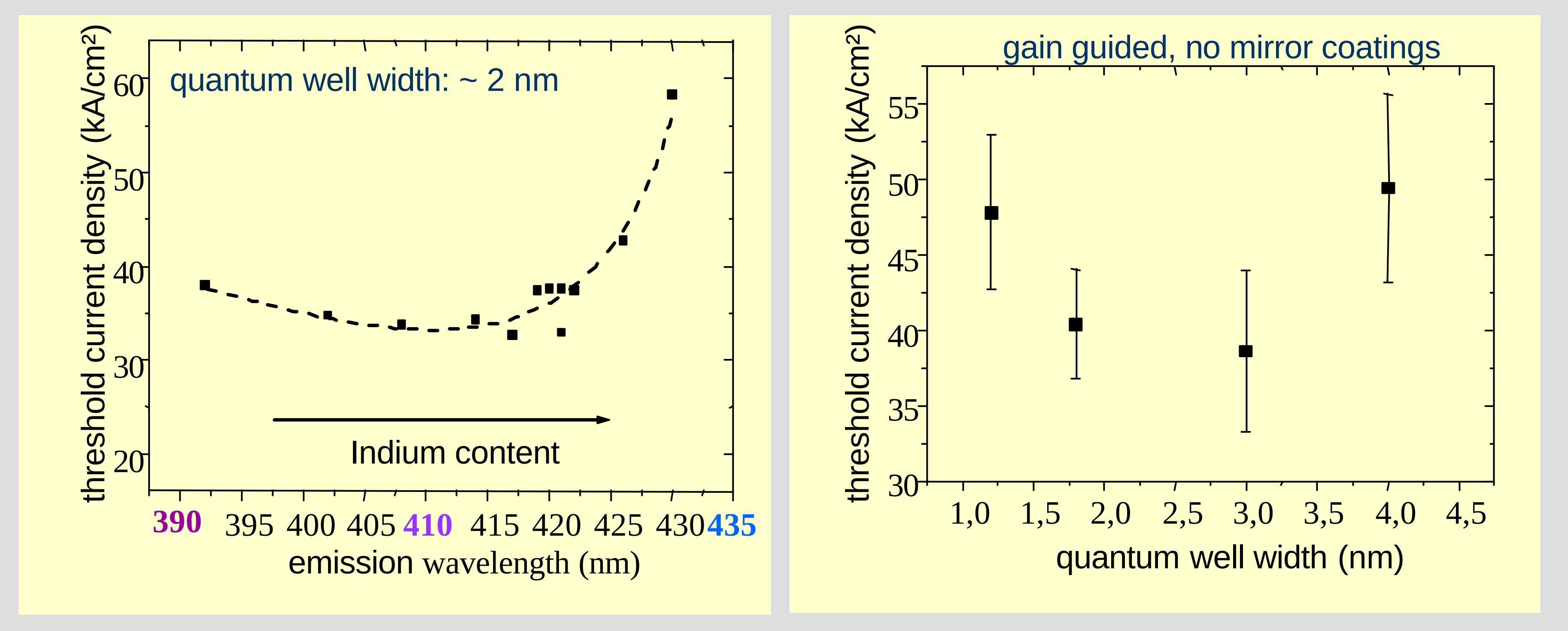


lattice mismatch
GaN/SiC 3.4%

disloc. dens. up to $5x10^9 cm^2$

Minimize Threshold Current Density

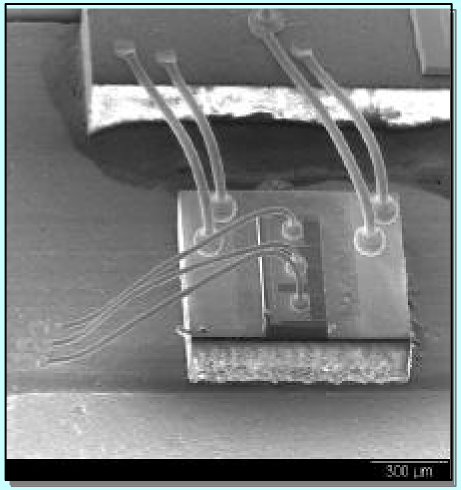
quantum well parameters



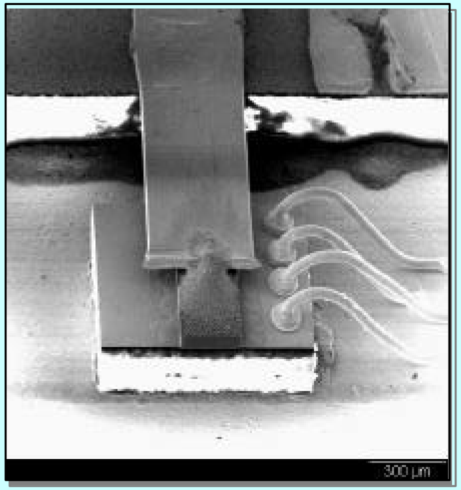
- optimum number of quantum wells: 2-3
- electrical confinement vs. - piezoelectric effect
  - Indium phase separation

Influence of Mounting

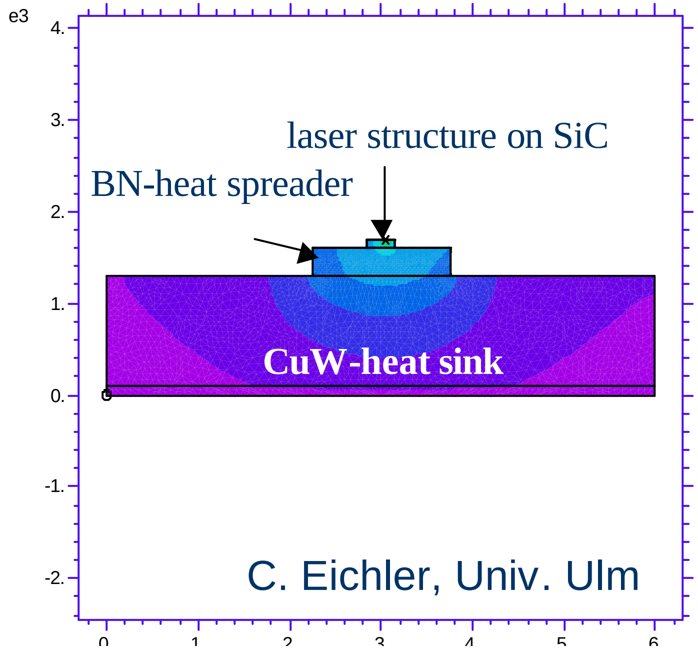
Mounting Technology



epi-side-up



epi-side-down

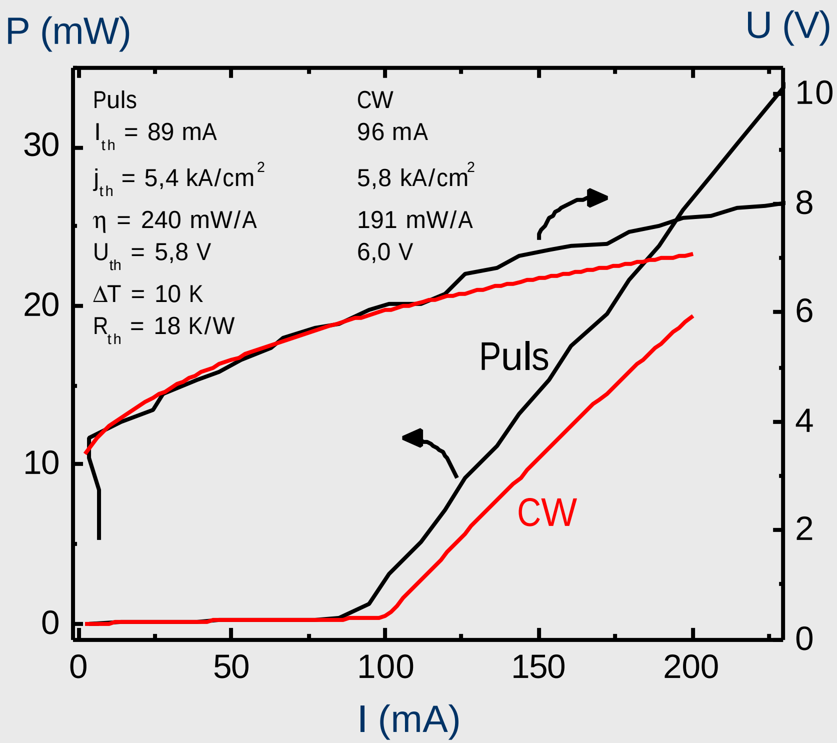


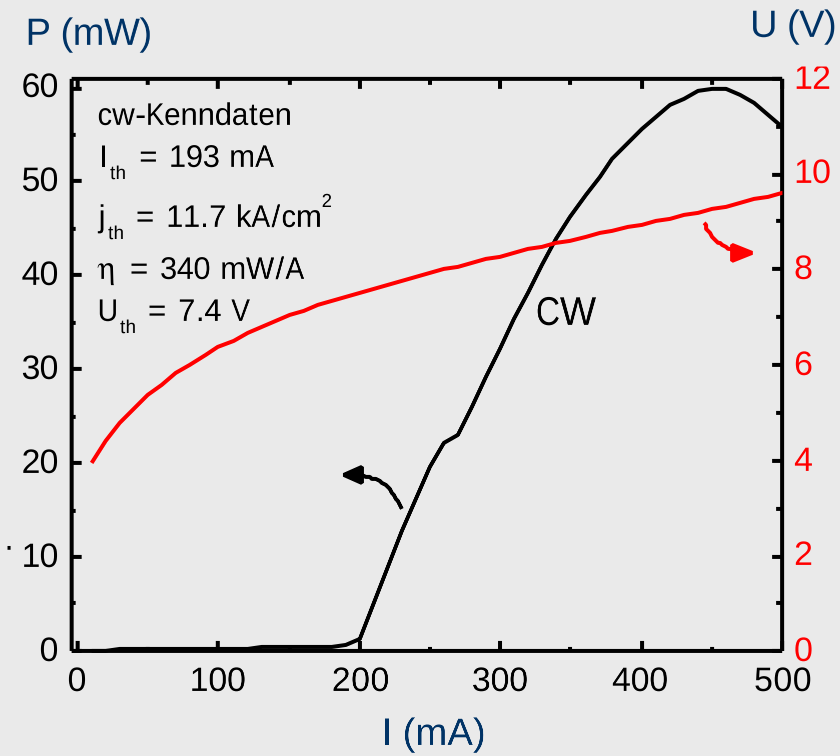
- 3 µm ridge, heatspreader c-BN
- calculated thermal resistance R_{th} = 22.8 K/W

Direction of mounting:

→ not critical due to high thermal conductivity of SiC (=Cu)

Lasing Characteristics





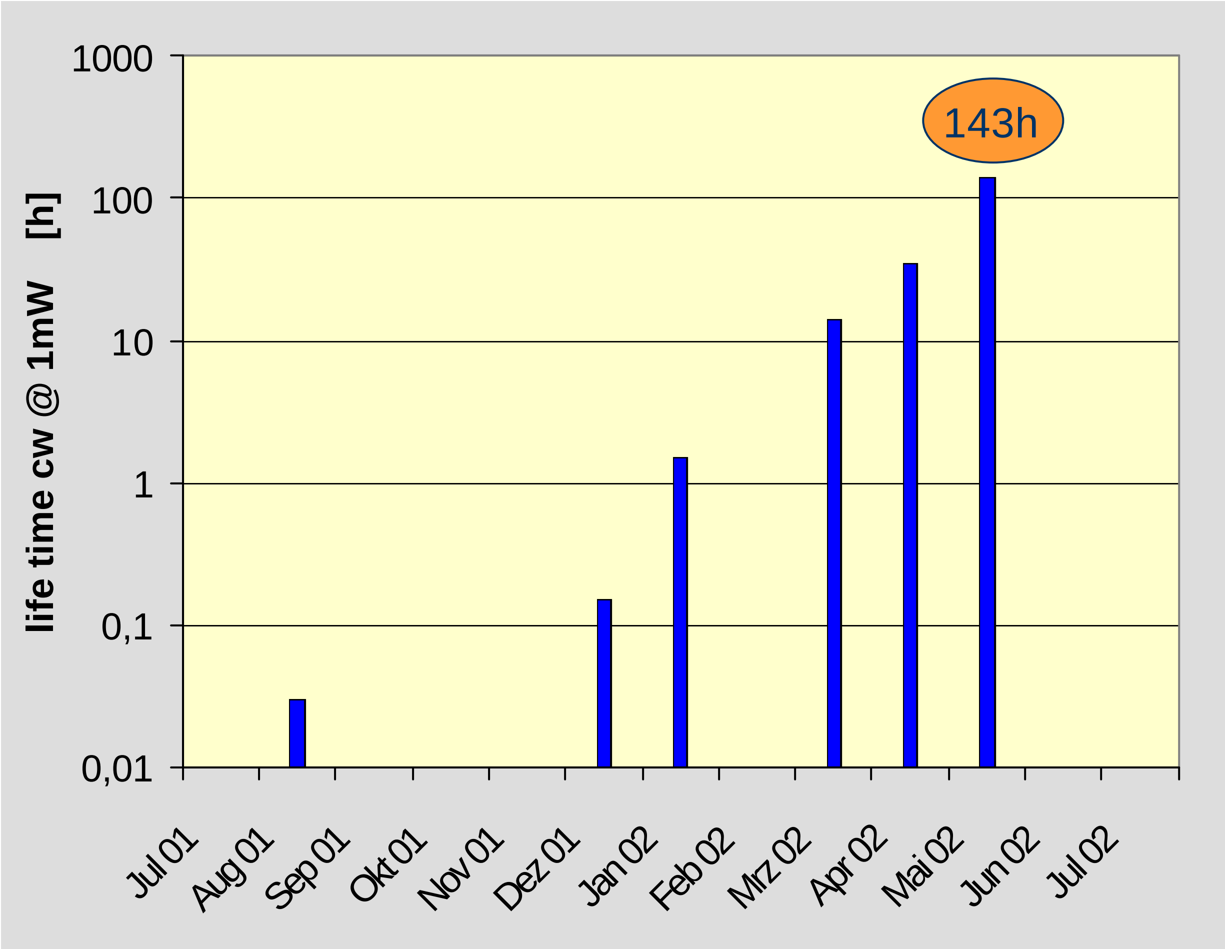
facet reflectivity 70% - 98%

threshold current 96mA

facet reflectivity 16% - 98%

output power of 60mW

Lifetime Development



Actual values

life time
143 h @ 1mW
54h @10mW

ridge: 2.7x600µm

R_{th}: 18K/W

I_{thr}: 96mA

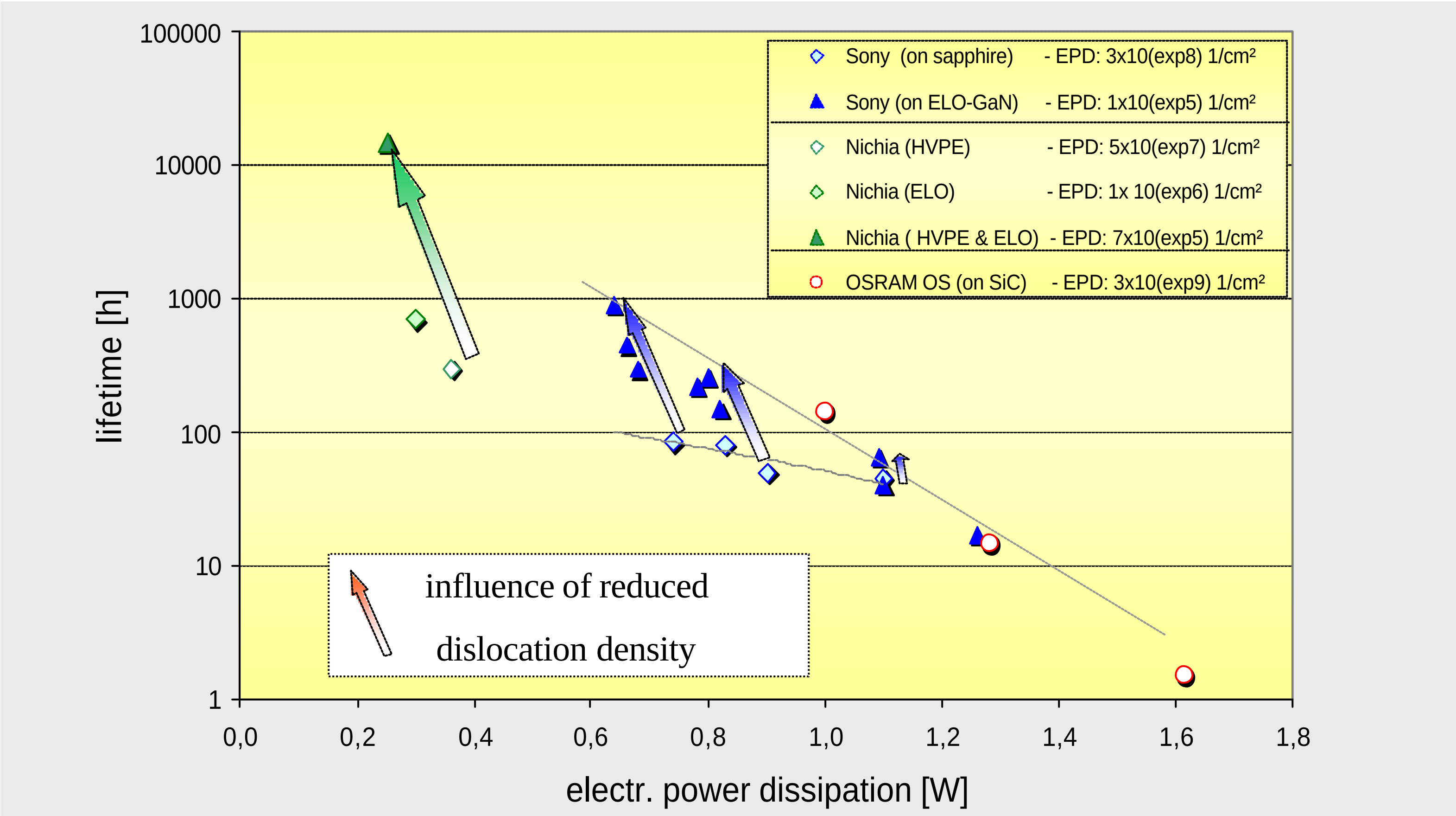
U_{thr}: 6V

P_{el}: 0.6W

T_{pn}: 35°C

(first pulsed LD: 07/99 first cw LD: 03/01)

Lifetime of GaN Laser Diodes: Defect Density and Pump Power



lifetime limiting factor: **P_{el} > 1W**: P_{el} **P_{el} < 1W**: defect density

lifetime >10000h: P_{el} < 0.4W defect density £ **$1x10^6$ cm^{-2}**

Opto Semiconductors OSRAM

Simulations in the Development Process of GaN-based LEDs and Laser Diodes

ATON LED-Technology

- 80% brightness improvement
- makes SiC-technology highly competitive

Simulations in Development

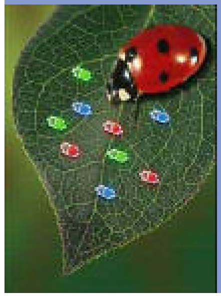
- extensive use of Raytracing Simulations
  chip optimization, emission patterns, ...

Benefit of Simulations

- fast and linear progress
- know-how basis for future projects

InGaN Laser Diodes

- life time of 143h optimizing GaN on SiC technology
- next objective must be defect reduction



Thanks

InGaN LED/LD devel. team, Process devel. group
Package devel. group, External partners