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

Dominik Eisert and Volker Härle
# Simulations in the Development Process of GaN-based LEDs and Laser Diodes

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<td>• Progress of Laser Diode Development at Osram OS</td>
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Our Activities and Locations

**San Jose**
- BU OLED
- Sales NA

**Regensburg**
- Headquarter
- Sales
- BU LED
- BU Infrared/Power Laser
- BU Lamp Modules
- Technology
- Frontend Production

**Villach**
- Silicon Waferfab (Subcon Infineon)

**Tokyo**
- Sales Japan

**Penang**
- Backend Plant
- OLED
- Frontend

**Singapore**
- Sales Asia Pacific

**Wuxi**
- Backend Plant (Subcon Infineon)

Siemens AG → OSRAM GmbH → OSRAM Opto Semiconductors GmbH
World Market by Product Segments

<table>
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<tr>
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<th>99/00</th>
<th>00/01</th>
<th>01/02</th>
<th>02/03</th>
<th>03/04</th>
<th>04/05</th>
<th>05/06</th>
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<tbody>
<tr>
<td>VIS</td>
<td>2300</td>
<td>2740</td>
<td>3540</td>
<td>4320</td>
<td>5160</td>
<td>5850</td>
<td>7000</td>
</tr>
<tr>
<td>VIS Aut</td>
<td>880</td>
<td>210</td>
<td>1180</td>
<td>1320</td>
<td>1455</td>
<td>1750</td>
<td>2000</td>
</tr>
<tr>
<td>IR/HPL</td>
<td>275</td>
<td>130</td>
<td>1060</td>
<td>1455</td>
<td>1510</td>
<td>1825</td>
<td>2255</td>
</tr>
<tr>
<td>OLED/ID</td>
<td>200</td>
<td>340</td>
<td>655</td>
<td>150</td>
<td>1510</td>
<td>260</td>
<td>305</td>
</tr>
<tr>
<td>LM</td>
<td>890</td>
<td>1050</td>
<td>660</td>
<td>130</td>
<td>2285</td>
<td>535</td>
<td>650</td>
</tr>
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Source: OSRAM OS

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Material Systems for High Brightness LEDs
Applications for GaN-LEDs

Automotive
Interior + Exterior

Mobile Applications

Marker Lights
Applications for LED Modules

Signal Lights

Illuminated Signs

Full Color Displays
Are Semiconductors the Light of the Future?

World Energy Consumption p.a.

- Energy: 1.2 x 10^4 TWh in 1980, projected to 6.9 x 10^4 TWh in 2010
- Electricity: 2.3 x 10^3 TWh in 1998
- Illumination: USA: 20% of electr., BRD: 8% of electr.

Efficiencies of Light Sources

- Incandescent: projected
- Halogen: with acceler. effort
- Fluorescent:

Source: International Energy Agency
Source: R. Haitz, Hewlett-Packard

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“White LED”

InGaN-chip generates blue light

partial conversion by a phosphore

color mixing ⇒ WHITE

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**
- Parameters: heterostructure design
- Properties To Optimize: internal QE / gain, mode control (LD), voltage control, defects
- Processes: growth kinetics, MOVPE Reactor

**Chip Processing**
- Parameters: chip geometry, contacts
- Properties To Optimize: external QE (LED), mode control (LD), voltage control, thermal management
- Processes: semiconductor processes

**Packaging**
- Parameters: housing geometry, polymer materials
- Properties To Optimize: light extraction, luminance, thermal management, mechanical properties, reliability
- Processes: molding/casting, mass production

**Module**
- Parameters: light guides, board design
- Properties To Optimize: light distribution, imaging, contrast, power drivers
- Processes: system integration
LED Development Scenario

- **Product Idea**
- **Competition**
- **Moore's Law**

**Semiconductor Development**

- **Simulation**
  - Design Concept
  - Design Verification
  - Process Development
  - Epitaxy Chip
  - Optimization

**Package Development**

- Concept
- Proof
- Process
- Logistics
- Package

**Quality Marketing**

- Reliability
- Product

**Customer**
Brightness Development of InGaN QW-LED

Sapphire technology used by competitors

power output @20mA (mW)

SiC-technology favored by Osram

wallplug efficiency

for 460nm blue LED in 5mm Radial housing

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„Dark“ Transparent Substrate?

Though 6H-SiC is transparent for blue light: no emission from substrate observed!
Light Extraction from GaN/SiC-System

Transparent Substrate SiC ($E_g=3.03\text{eV}$)

GaN: $n=2.5$
SiC: $n=2.7$

but $n(\text{GaN}) < n(\text{SiC})$

Snell’s law
'blind‘ angle (22°)

Light Extraction from SiC:
$\theta_c=33°$
$n=1.5$
$n=2.7$

Incomplete Overlap
$\Rightarrow$ low efficiency

outcoupling angle (11°)

'blind‘ angle

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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: \( \eta = 100\% \)

first test: \( \eta = 115\% \)

'proof' of design: \( \eta = 145\% \)

accompanied by simulation

final ATON design: \( \eta = 180\% \)

Simulation:

• fewer experimental optimization cycles
• confidence in optimum performance level
Raytracing Analysis

Objective of Chip Development:
- optimize External Quantum Efficiency (EQE)
  EQE hard to assess experimentally!

Non-sequential Raytracing Analysis

⇒ 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

- optimum facet angle $\approx 30^\circ$  $\Rightarrow$ Doubling of Extraction Efficiency
- limited by ohmic heating

ATON/socket ratio

(290x290µm chip)
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

- **power output BLUE 460nm (mW)**
  - Feb 99
  - May 99
  - Aug 99
  - Nov 99
  - Feb 00
  - May 00
  - Aug 00
  - Nov 00
  - Feb 01
  - May 01
  - Aug 01
  - Nov 01
  - Feb 02
  - May 02
  - Aug 02

- **luminous flux WHITE (lm)**
  - Feb 99
  - May 99
  - Aug 99
  - Nov 99
  - Feb 00
  - May 00
  - Aug 00
  - Nov 00
  - Feb 01
  - May 01
  - Aug 01
  - Nov 01
  - Feb 02
  - May 02
  - Aug 02

- **290µm Chip in package @If=20mA**

- **ATON-Technology**
- **'Flip'-Chip reflecting p-contact**

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OSRAM
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

- $\Phi_e = 150 \text{ mW blue}$
- $\Phi_v = 33 \text{ lm white}$
- $I_i = 350 \text{ mA} / U_i = 3.9 \text{ V}$
- Chip area: $1 \text{ mm}^2$
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

- SiC-substrate
- buffer
- GaN:Mg
- AlGaN:Mg
- GaN:Mg
- GaInN/GaN MQW
- GaN:Si
- AlGaN:Si
- wave guide active zone
- n-doped cladding
- p-doped cladding
- contact layer

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 $5 \times 10^9 \text{cm}^2$
Minimize Threshold Current Density

quantum well parameters

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

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Influence of Mounting

- 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

Puls
$I_{th} = 89 \text{ mA}$
$J_{th} = 5.4 \text{ kA/cm}^2$
$\eta = 240 \text{ mW/A}$
$U_{th} = 5.8 \text{ V}$
$\Delta T = 10 \text{ K}$
$R_{th} = 18 \text{ K/W}$

CW
$I_{th} = 96 \text{ mA}$
$J_{th} = 5.8 \text{ kA/cm}^2$
$\eta = 191 \text{ mW/A}$
$U_{th} = 6.0 \text{ V}$

cw-Kennldaten
$I_{th} = 193 \text{ mA}$
$J_{th} = 11.7 \text{ kA/cm}^2$
$\eta = 340 \text{ mW/A}$
$U_{th} = 7.4 \text{ V}$

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
- $I_{th}$: 96mA
- $U_{th}$: 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

- Sony (on sapphire) - EPD: $3 \times 10^{8}$ cm$^{-2}$
- Sony (on ELO-GaN) - EPD: $1 \times 10^{5}$ cm$^{-2}$
- Nichia (HVPE) - EPD: $5 \times 10^{7}$ cm$^{-2}$
- Nichia (ELO) - EPD: $1 \times 10^{6}$ cm$^{-2}$
- Nichia (HVPE & ELO) - EPD: $7 \times 10^{5}$ cm$^{-2}$
- OSRAM OS (on SiC) - EPD: $3 \times 10^{9}$ cm$^{-2}$

Influence of reduced dislocation density

Lifetime limiting factor:

- $P_{el} > 1$ W: $P_{el}$
- $P_{el} < 1$ W: Defect density

Lifetime $>10000$ h:

- $P_{el} < 0.4$ W: Defect density $\leq 1 \times 10^{6}$ cm$^{-2}$
Simulations in the Development Process of GaN-based LEDs and Laser Diodes

| ATON LED-Technology | • 80% brightness improvement  
|                     | • makes SiC-technology highly competitive  
|                    | • extensive use of Raytracing Simulations  
|                     | • chip optimization, emission patterns, ...  
|                    | • 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