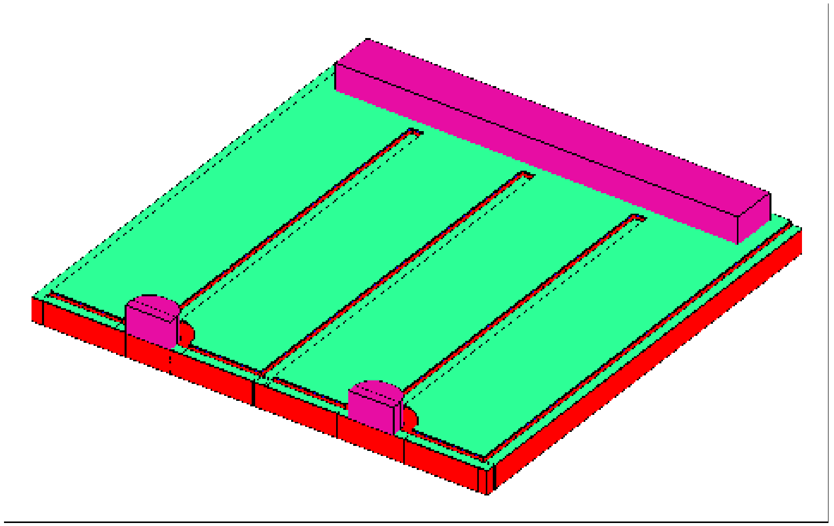
SimuLED™

Engineering software package for LED design and optimization



www.str-soft.com

Prehistory of STR:

1984: Start of the MOCVD modeling activities at Ioffe Institute, St. Petersburg, Russia

1993-1996: Group for modeling of crystal growth and epitaxy at University of Erlangen-Nuernberg, Germany

History of software development

2000: Launch of development of the first specialized software
2003: First release of commercial software package
2004: First release of the software for device engineering

STR Today:

More than 40 scientists and software engineers

STR Today

1 – Headquarter and R&D (consulting service and software development)
2 – Local offices
3 – Local distributors

Bulk crystal growth modeling (Si, Ge, SiGe, GaAs, InP, SiC, AlN, Al_2O_3, Optical Crystals)

Epitaxy and deposition modeling (Si, SiGe, SiC, AlGaAs, AlGaInP, AlGaInN, high-k oxides)

Modeling of device operation (LEDs, Laser Diodes, FETs/HEMTs Shottky diodes)

STR activity in software development and consulting service

Software & consulting services :

- Modeling of crystal growth from the melts and solutions: CGSim
- Modeling of polysilicon deposition by Siemens process: PolySim
- Modeling of bulk crystal growth of SiC, AlN, GaN: ViR
- Modeling of epitaxy of compound semiconductors: CVDSim
- Modeling of optoelectronic and electronic devices: SimuLED

Customer base:

- More than 160 companies and universities worldwide
- Top LED, LD and solar cell manufacturers
- Top sapphire, GaAs, GaP, GaN, AlN and SiC wafer manufacturers
- Top MOCVD reactor manufacturers

Multidisciplinary

- materials science
- physics of semiconductors
- heat transfer theory
- optics

Essentially nonlinear

- nonuniform voltage drop and IQE distributions over the active region
- self-heating in active region
- current crowding results in nonuniform light intensity distribution over the active region

Multidimensional and multiscale

- QW thickness is ~2-10nm
- chip size is ~300μm
- luminary size is ~10mm

	General purpose software		SimuLED™	
Simulation destination	Software is used as a tool demonstrating physical effects and test cases with simple geometry	Software is used by experts in modeling and users who have long-time experience in device modeling	Powerful fast engineering tool operating with actual devices designed by industry and developed by academia	SimuLED serves as a guidance for epitaxy engineers and LED designers in testing new ideas on device performance improvement
Getting started	Long time is necessary to start computations	Statement of the problem is complicated due to difficulties in geometry specification and specification of boundary conditions	The user can start computations in several hours after SimuLED installation	Intuitive User Interface operates in terms normally used by engineers. Layer by layer input of 2D layout for 3D geometry. Selection of predefined options typical for LEDs
General concept to LED simulation	Homogeneous app-roach for simulation of multiphysics and multiscale problem	Problems with uniform resolution of physical processes occurring at various spatial scales.	**Hybrid approach accounting for specific features of modern LED design**	Accurate resolution of key physical processes at each spatial scales
Computation time		Time consuming simulations		Extremely fast simulations
Hardware requirements		Special requirements to hardware		SimuLED operates on personal computers
Physical models implemented into the software	The software was developed initially for simulation of GaAs and Si-based devices	Conventional physical models used for a long time in modeling of semiconductor devices	SimuLED was initially developed as a tool for simulation of nitride-based LEDs	Both conventional and unique models of physical effects responsible for operation of modern LEDs
Materials properties		The data have to be collected by the user or there is a lack of data needed for computations		SimuLED is supplied with the database of materials properties and the user can start his computations immediately after the software installation
Hot-line support			Quick hot-line support, free software update within the license period	Interpretation of results upon customer request

Hybrid approach

We reject the idea of "homogeneous approach for simulation of multiphysics and multiscale problem" applied for the whole LED at all space scales

Problem of LED simulation ⇨ **In SimuLED, we replace the homogeneous model by a set of coupled submodels**

For each submodel:
- **Dominant physics**
- **Appropriate dimensionality**
- **Appropriate computational domain**

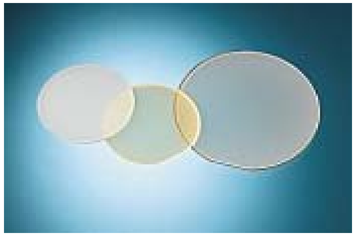
Competitive Advantage

SimuLED submodels are realized as modules:

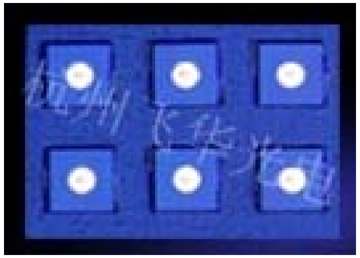
- Carrier transport through the active region: 1D + bipolar carrier transport ⇨ $j_z(U_b,T)$, $\eta_{int}(U_b,T)$, and λ
- Current spreading in LED die: 3D + unipolar carrier transport + active region replaced by nonlinear resistance ⇨ W(x,y)
- Light propagation in the LED die: 3D ⇨ EQE, P_{out}, WPE

Basic tools of SimuLED™ software package

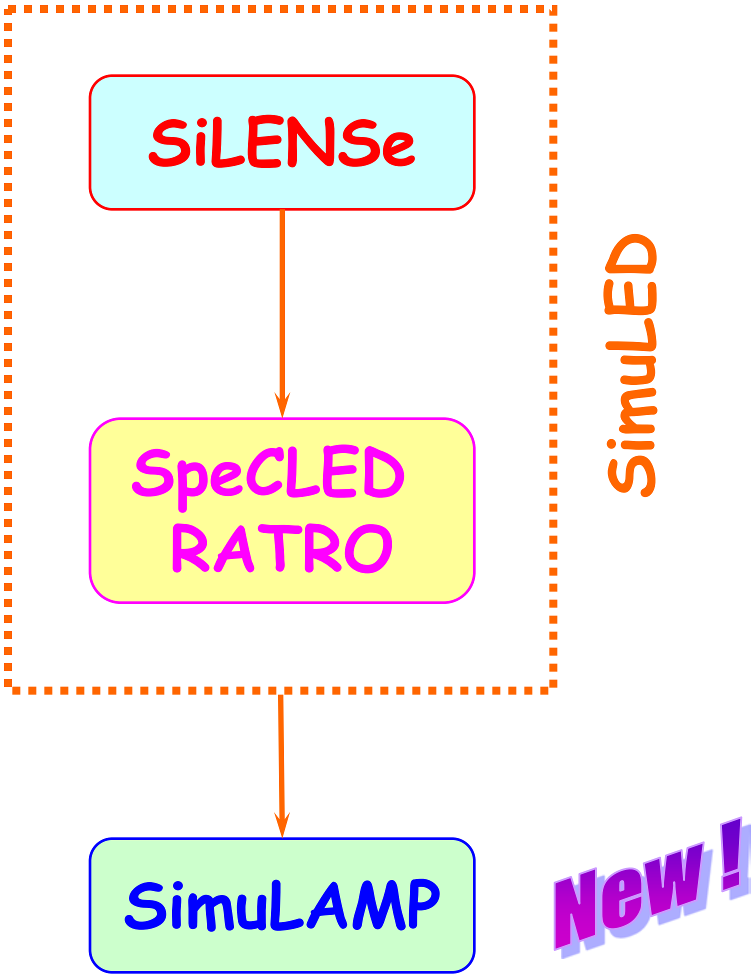
Epi level → Development & optimization of LED structures



Chip level → Development & optimization of LED chips



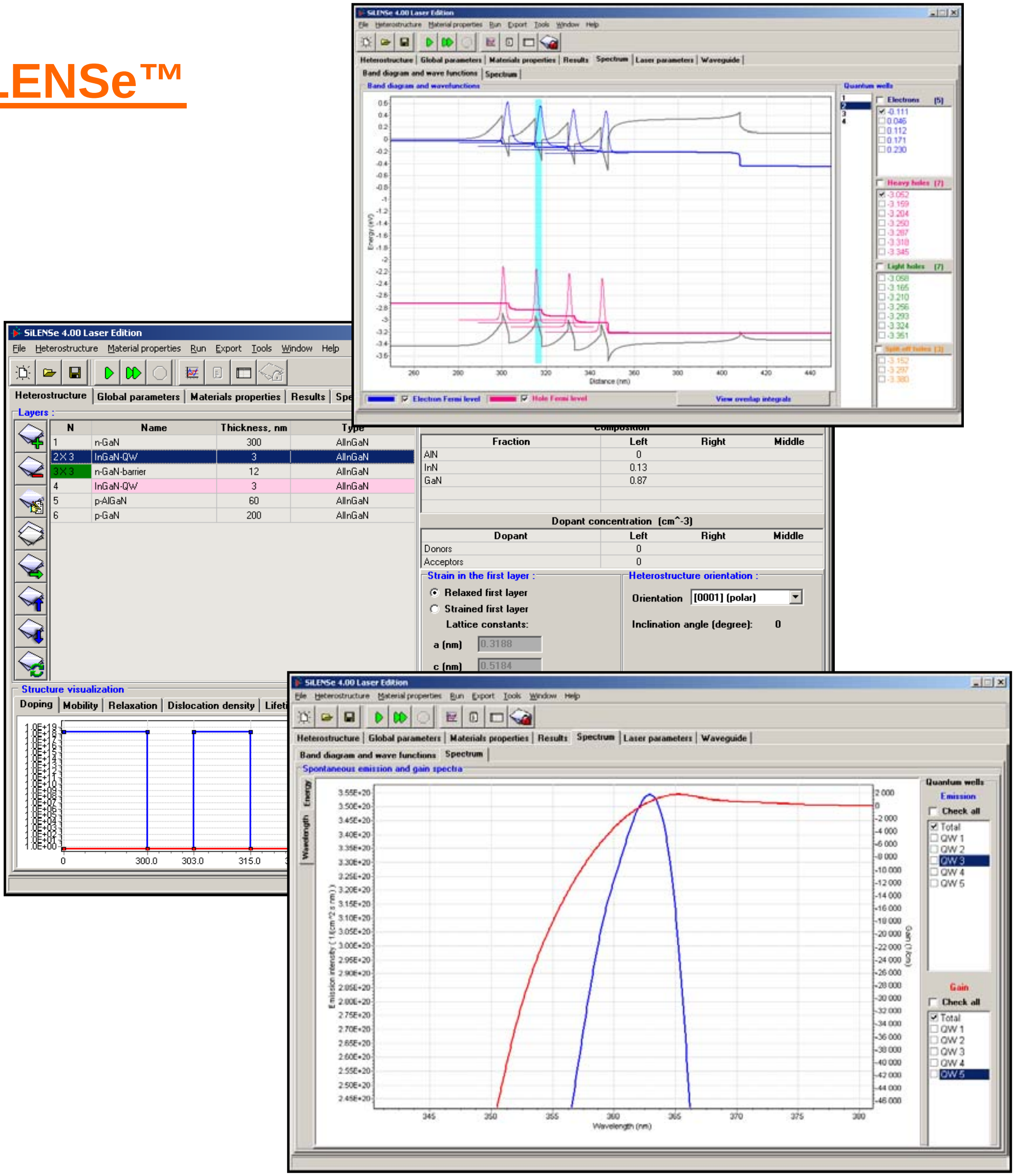
Device level → Development & optimization of LED lamps, arrays, etc.



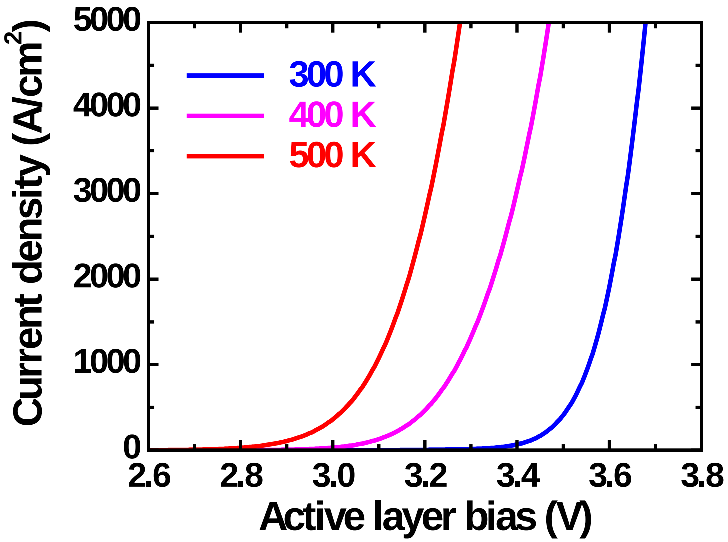
SiLENSe™: module for designing of LED/LD heterostructure

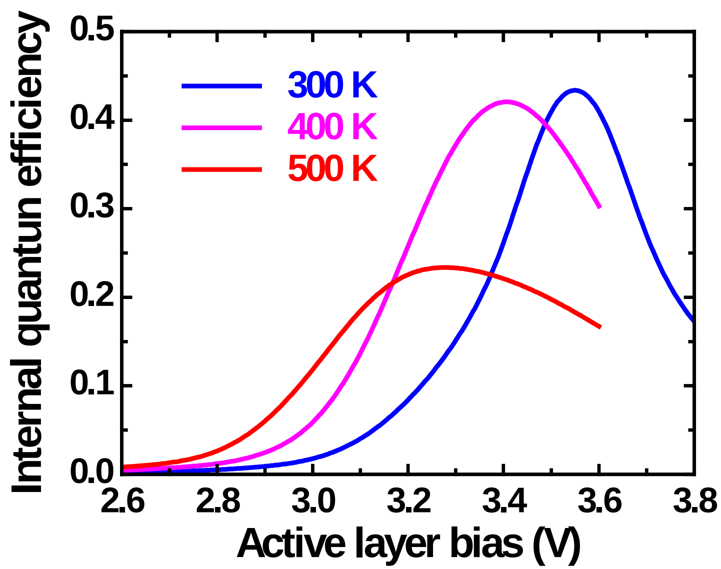
Parameters computed with SiLENSe™

- ✓ Band diagrams
- ✓ Carrier concentrations
- ✓ Electric field
- ✓ R^{rad}, R_i^{nonrad}, IQE
- ✓ Carrier fluxes and leakages
- ✓ Energy levels in QWs
- ✓ Emission and gain spectra



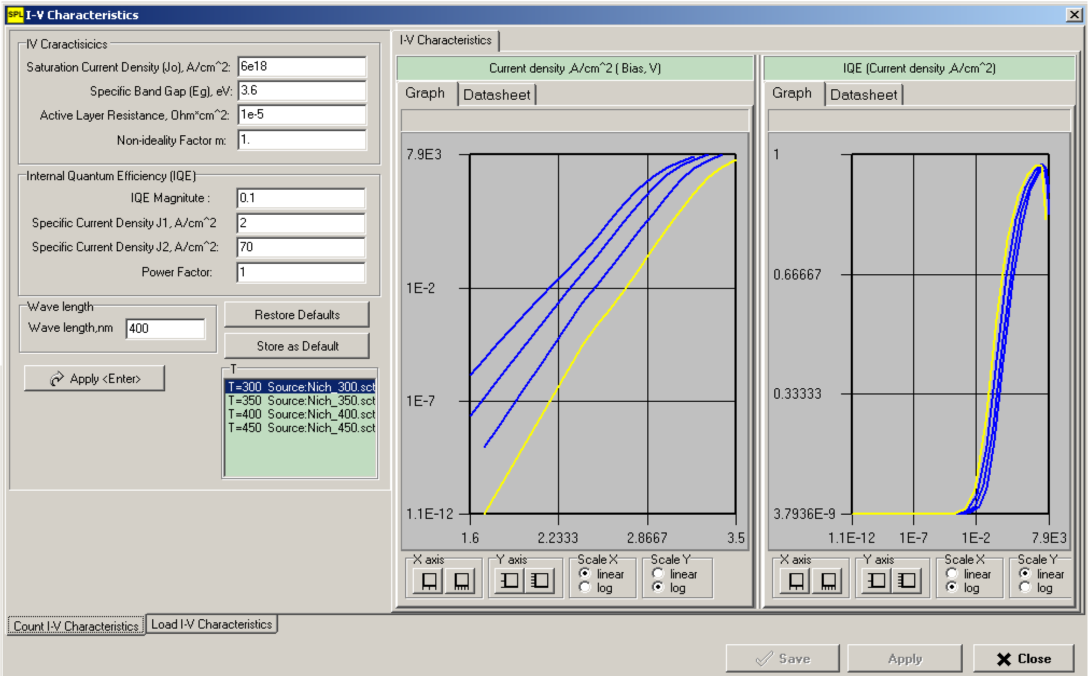
SiLENSe is supplied with the editable database of materials properties





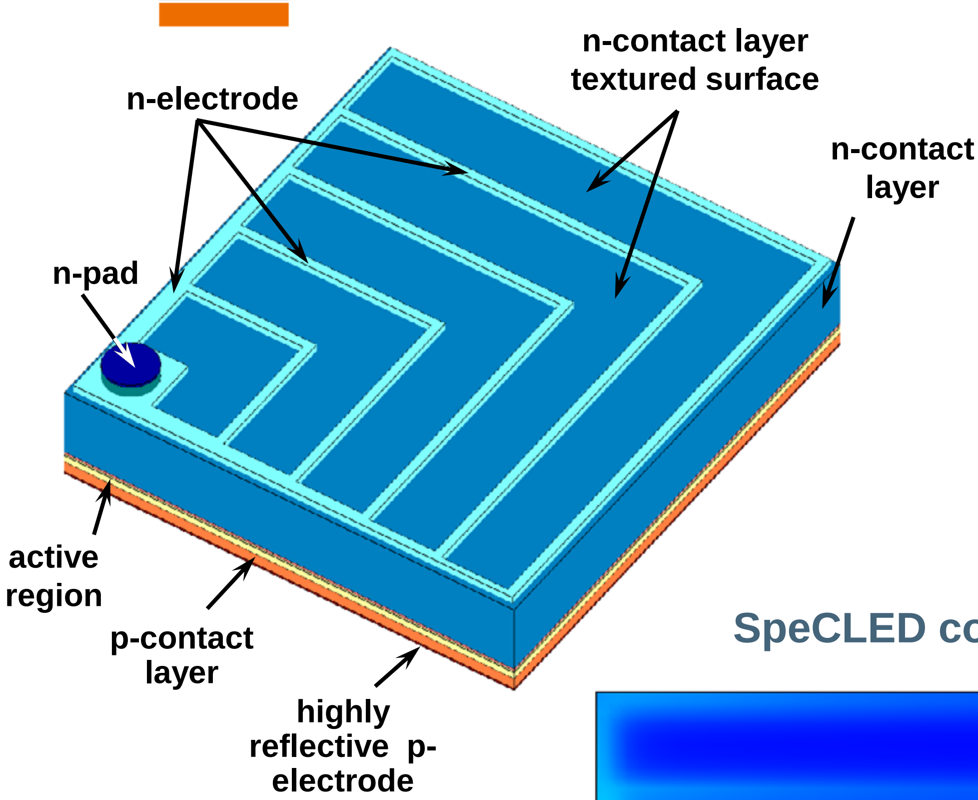
Replacement of the active region by a non-linear resistance

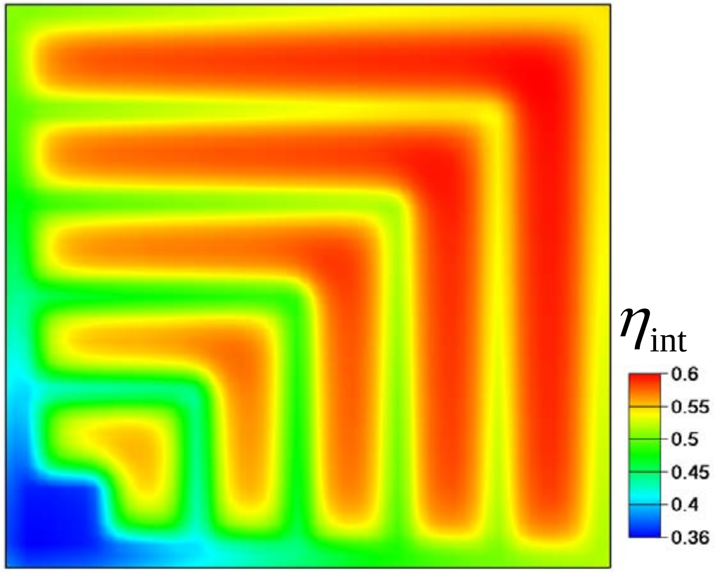
$$Q(x,y,z) = \frac{j^2(x,y,z)}{\sigma(x,y,z)}$$



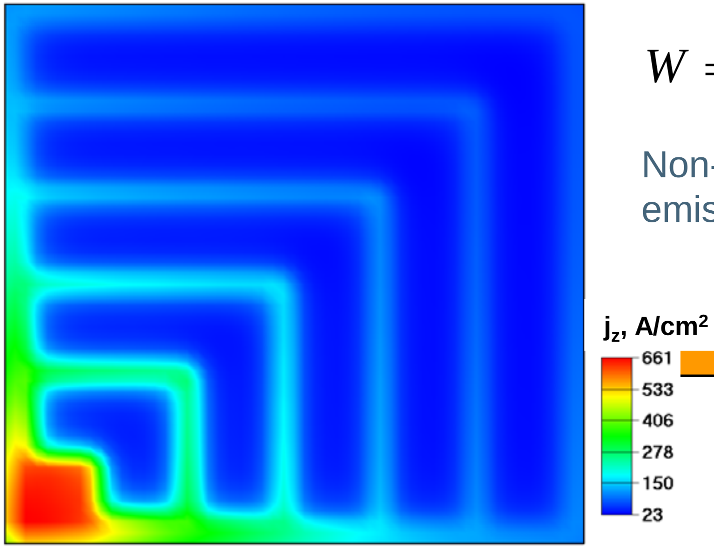
$$q_0(x,y) = j_z(x,y)\cdot U_b(x,y) - \frac{j_z(x,y)}{q}\cdot\hbar\omega\cdot\eta_{\mathrm{int}}(x,y)\cdot\eta_{ext}$$

SimuLED hybrid approach: SpeCLED/RATRO coupling





SpeCLED computations



$$W = \frac{j_z(x,y)}{q}\cdot\hbar\omega\cdot\eta_{int}(x,y)$$

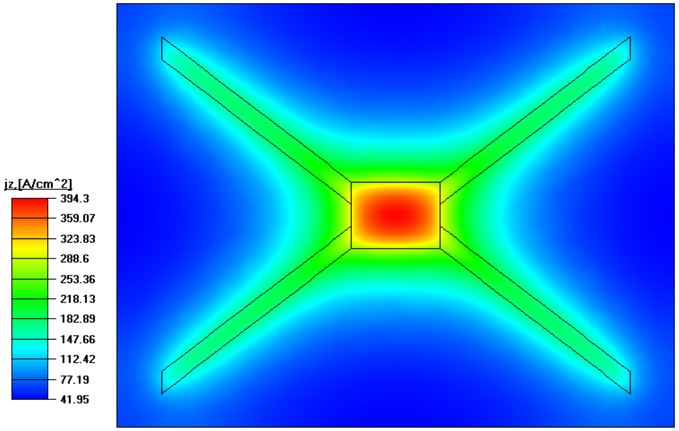
Non-uniform distribution of light emission from the active region

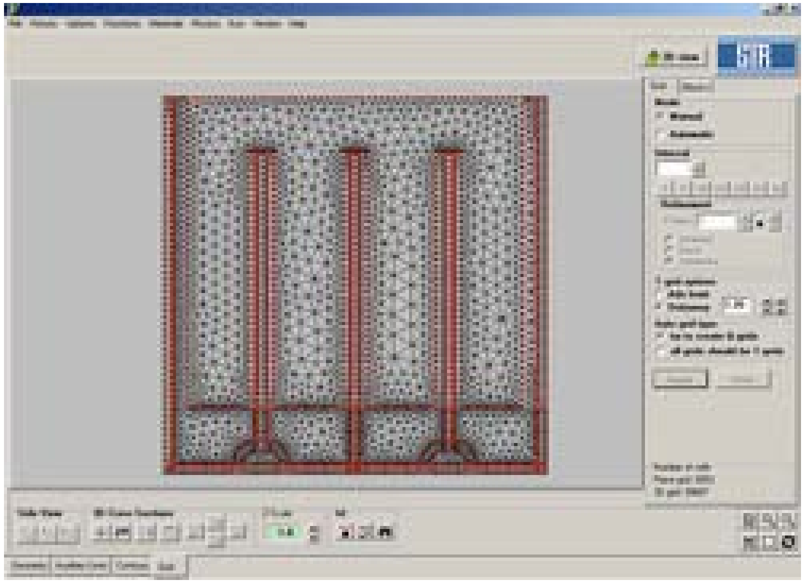
RATRO

SpeCLED™: Current Spreading and Heat Transfer in LED dice

Parameters computed with SpeCLED™

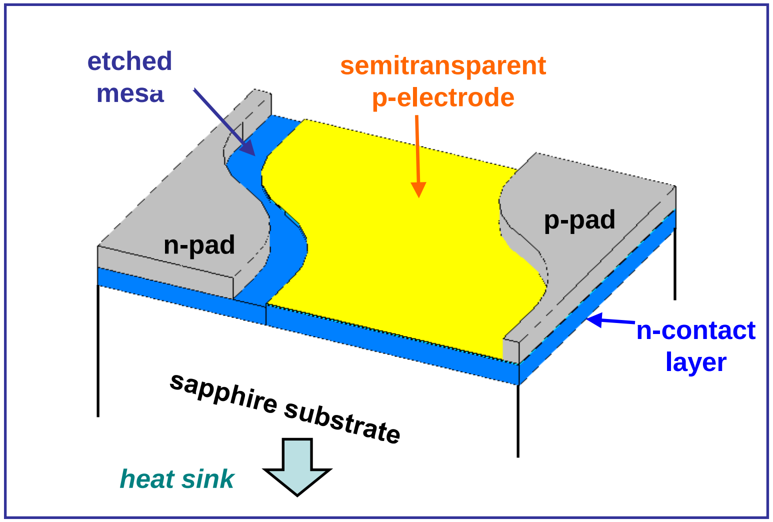
- ✓ 3D distributions of the electric potential, current density, and temperature in the whole die
- ✓ 2D distributions of the p-n junction bias, current density, IQE, and temperature in the active region plane
- ✓ I-V characteristic
- ✓ Series resistance
- ✓ EQE and WPE





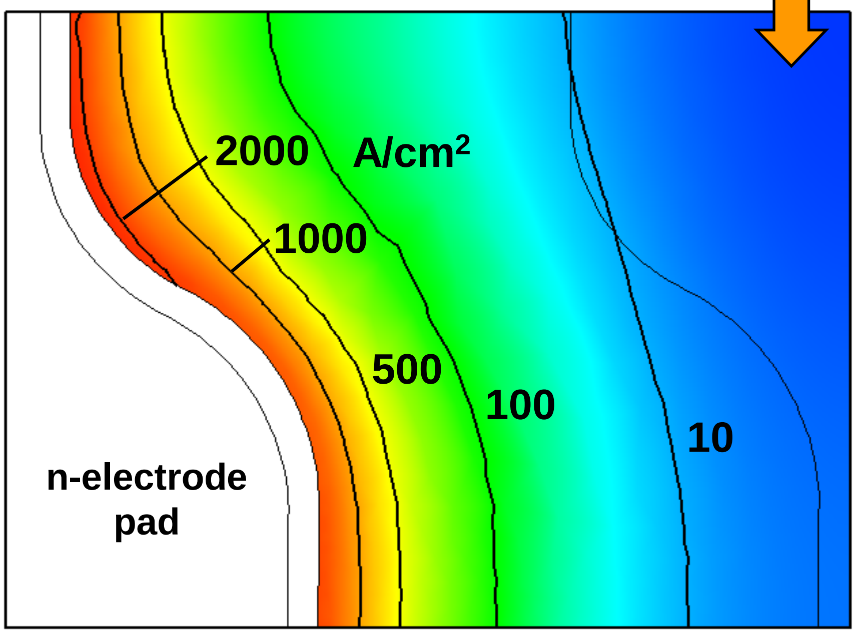
Planar chip design typical for LEDs fabricated on sapphire substrate

Conventional LED
A = 0.0466 mm^2 ;
substrate-down
mounting

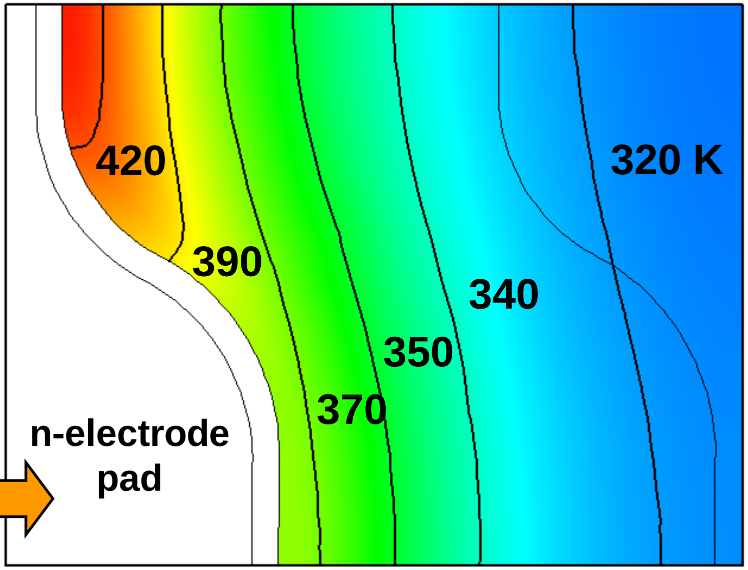


Current crowding and in-plane temperature non-uniformity

Current crowding occurring at the electrode edge (I = 80 mA) produces a very non-uniform in-plane EL intensity distribution



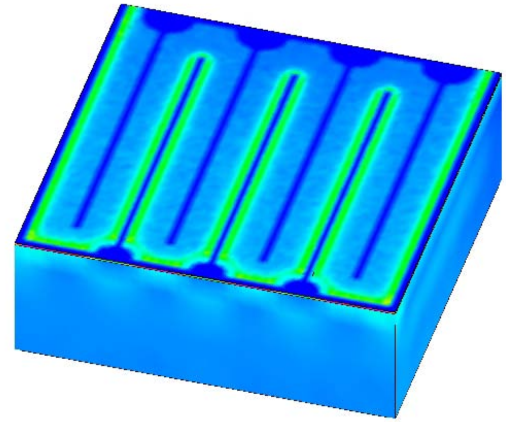
A local overheating depends on the current density and die confi-guration

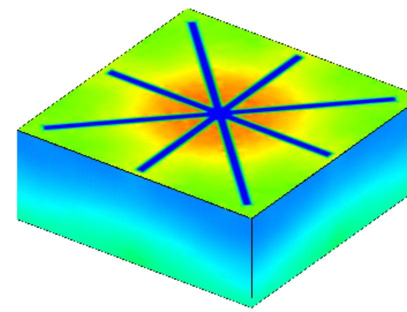


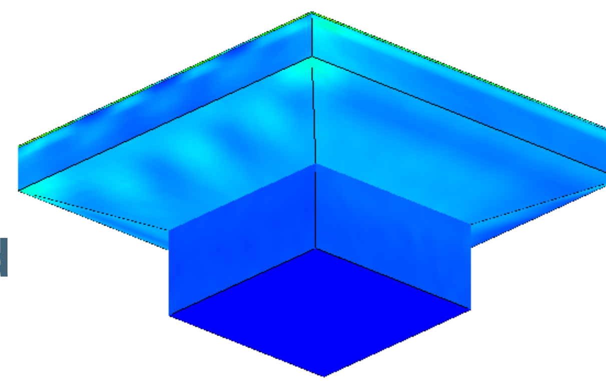
RATRO™: 3D ray-tracing analysis of optical characteristics of LED dice

Parameters computed with RATRO™

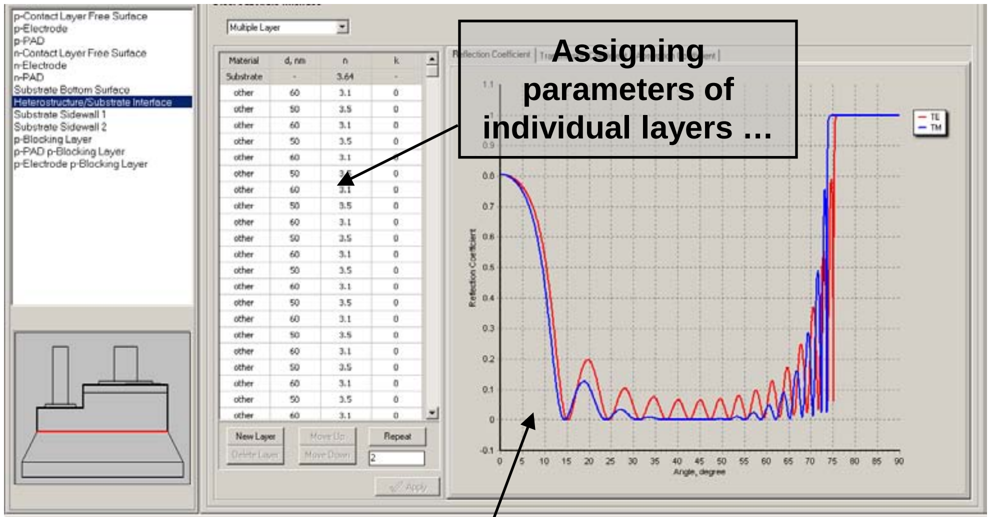
- ✓ Light extraction efficiency from an LED die
- ✓ Far- and near-field emission patterns
- ✓ Light polarization distribution **new**
- ✓ Consideration of non-uniform electroluminescence intensity distribution in the active region plane
- ✓ Various die configurations, including shaped substrate are supported







RATRO™ : Advanced physical models implemented into the tool



Assigning parameters of individual layers …

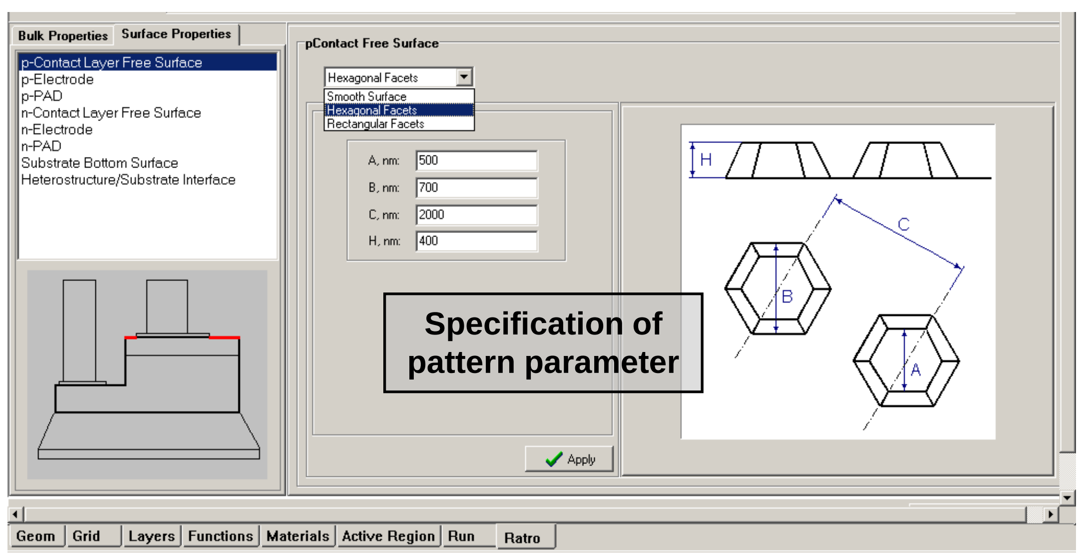
… the user obtains angle-dependent reflection, transmission, and absorption coefficients of DBR surface

Model of light transmission through semitransparent multilayer metallic electrodes

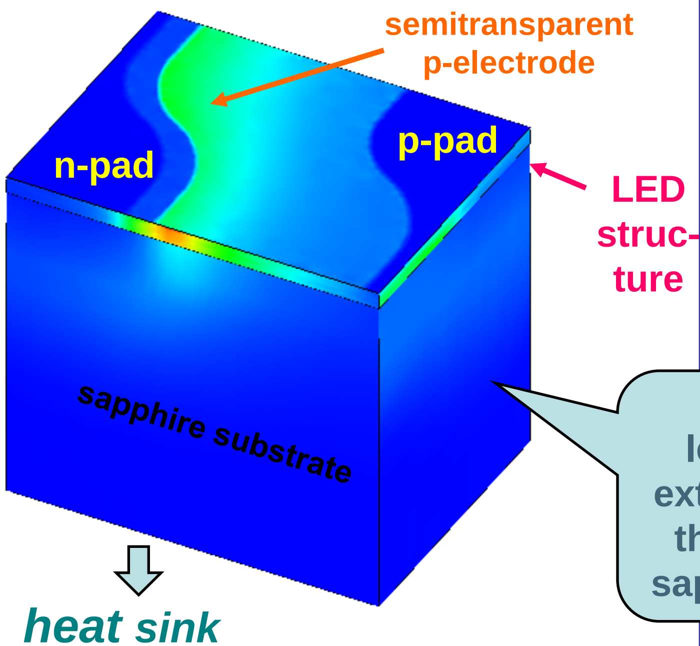
Competitive Advantage

Competitive Advantage

Original model was developed to describe light interaction with surfaces patterned with regular array of hexagonal or rectangular pyramids or holes

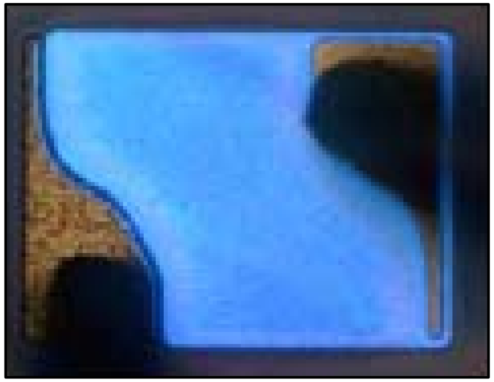


Specification of pattern parameter



Output light intensity

Waveguiding leading to light extraction through the side walls of sapphire substrate

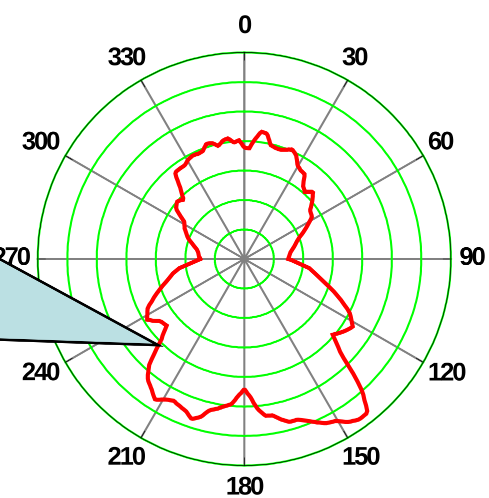


Lumileds low-power chip

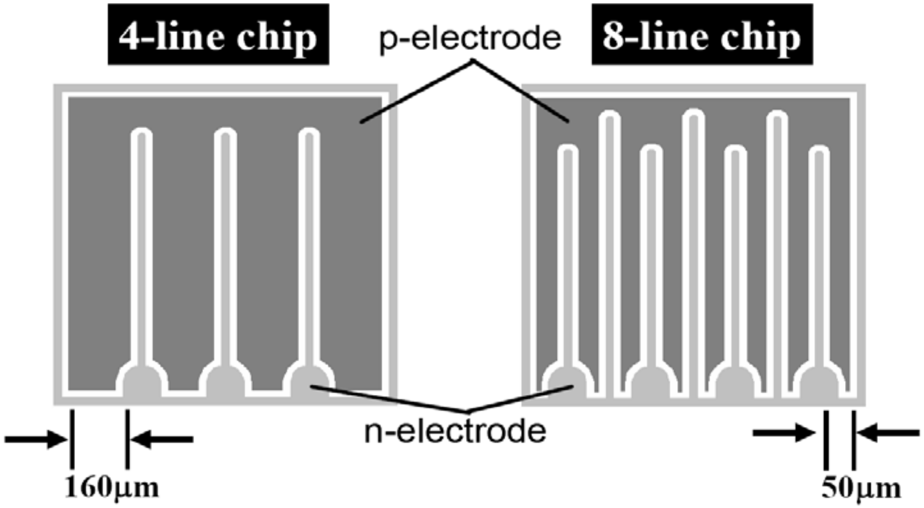
Radiation far-field pattern of planar LED die

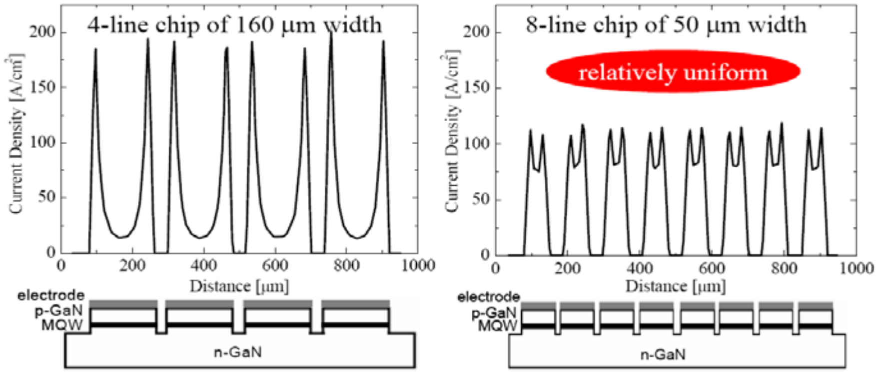
Predicted Extraction Efficiency through top surface is 8.8% and correlates well with fitting results obtained for Lumileds low-power chip

Bottom emission occurs largely through the side walls of sapphire substrate, providing two-peak angular dependence

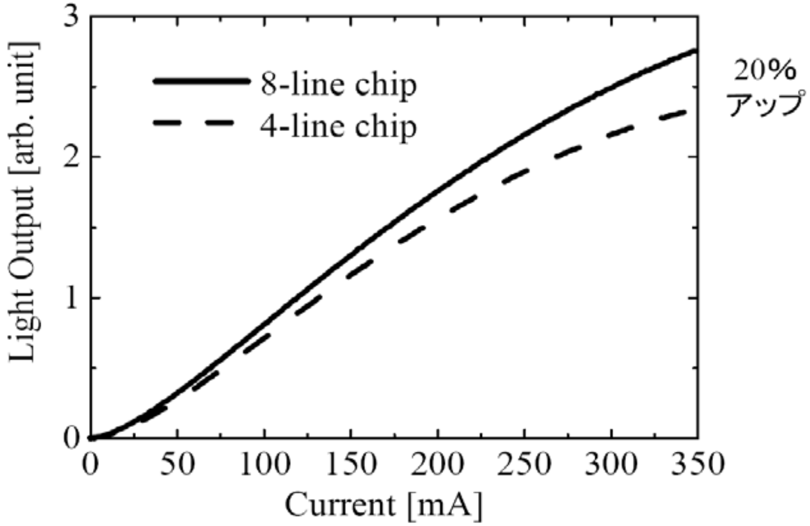


Optimization of electrode configuration to suppress current crowding





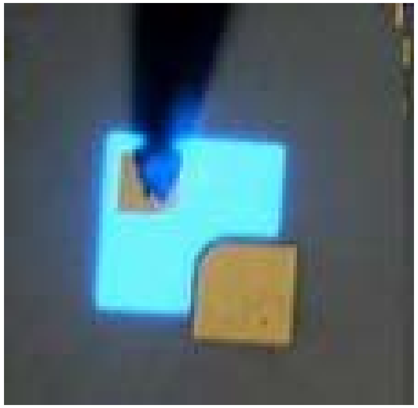
シミュレーションでは，350mA時10%アップ



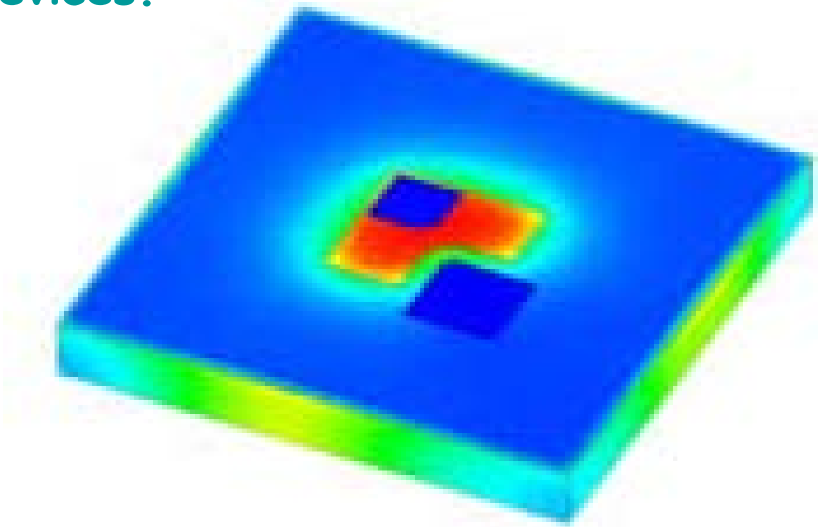
improvement of LED performance due to appropriate chip design http://www.sle.sharp.co.uk/research/advanced_optoelectronics/blue_leds.php

Modeling software such as SpeCLED is used to optimize the LED chip design in order to improve operating voltage, light extraction efficiency and junction temperature.

Other tools such as SiLENSe are also available to model band diagrams and to understand fundamental theoretical work, such as the piezoelectric effect in nitride-based devices.



Electroluminesence from blue LED chip



LED chip design using SpeCLED

Enhancement of light extraction in ultraviolet light-emitting diodes using nanopixel contact design with Al reflector

N. Lobo,[1,a)] H. Rodriguez,[2] A. Knauer,[2] M. Hoppe,[2] S. Einfeldt,[2] P. Vogt,[1] M. Weyers,[2] and M. Kneissl[1,2]
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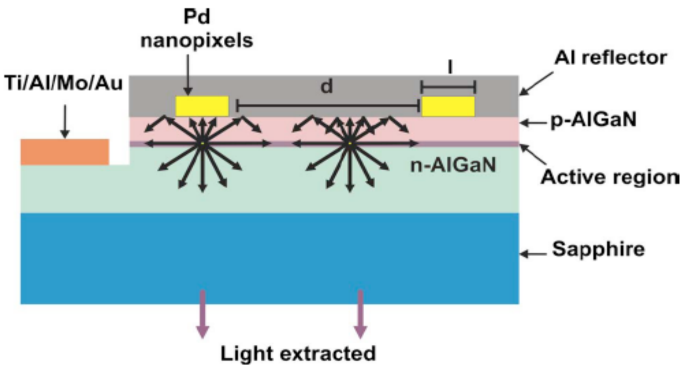
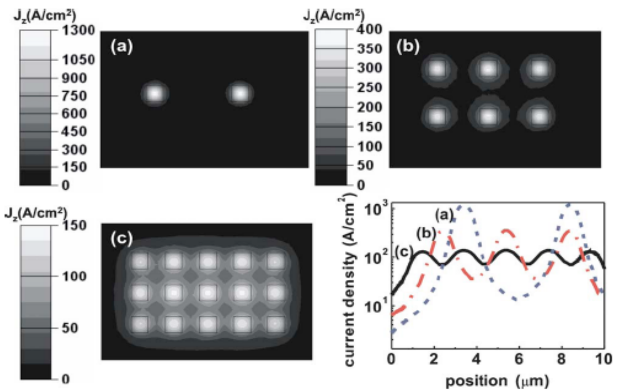
We report on a nanopixel contact design for nitride-based ultraviolet light-emitting diodes to enhance light extraction. The structure consists of arrays of Pd ohmic contact pixels and an overlying Al reflector layer. Based on this design a twofold increase in the light output, compared to large area Pd square contacts is demonstrated. Theoretical calculations and experiments reveal that a nanopixel spacing of 1 μm or less is required to enable current overlap in the region between the nanopixels due to current spreading in the p-GaN layer and to ensure current injection into the entire active region. Light emitted in the region between the nanopixels will be reflected by the Al layer enhancing the light output. The dependence of the light extraction on the nanopixel size and spacing is investigated. © *2010 American Institute of Physics*. [doi:10.1063/1.3334721]

Schematic cross-sectional view of nitride-based nanopixel UV LED with Pd contacts and Al reflector layer





Simulation of the current injection in the active region for nanopixel AlInGaN LEDs with nanopixel size 1x1 μm2 and nanopixel spacing (a) 4 μm, (b) 2 μm, and (c) 1 μm. The total current is constant. In the graph the injection current density as a function of the position along a line through the center of the nanopixels is shown for the different structures.

<u>A nanopixel LED design with an Al reflector</u> was developed resulting in enhanced light extraction in UV LEDs.

Optimization of electrode configuration to suppress current crowding

Optimization of electrode configuration in large GaInN light-emitting diodes

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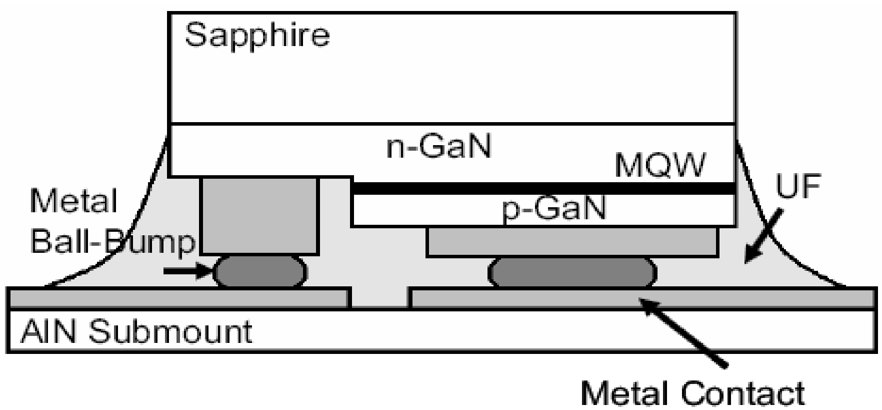


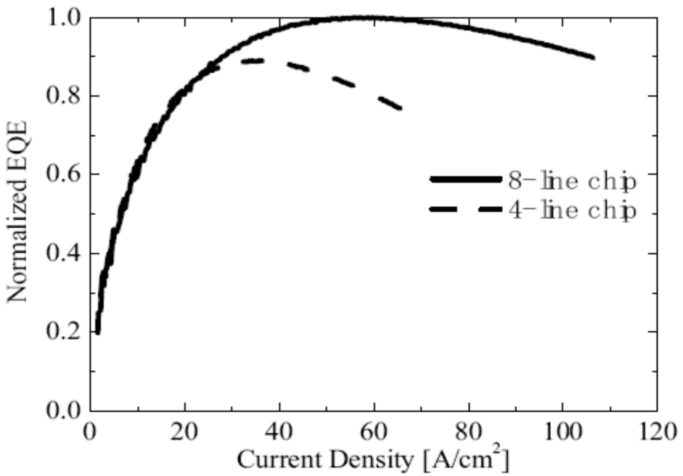


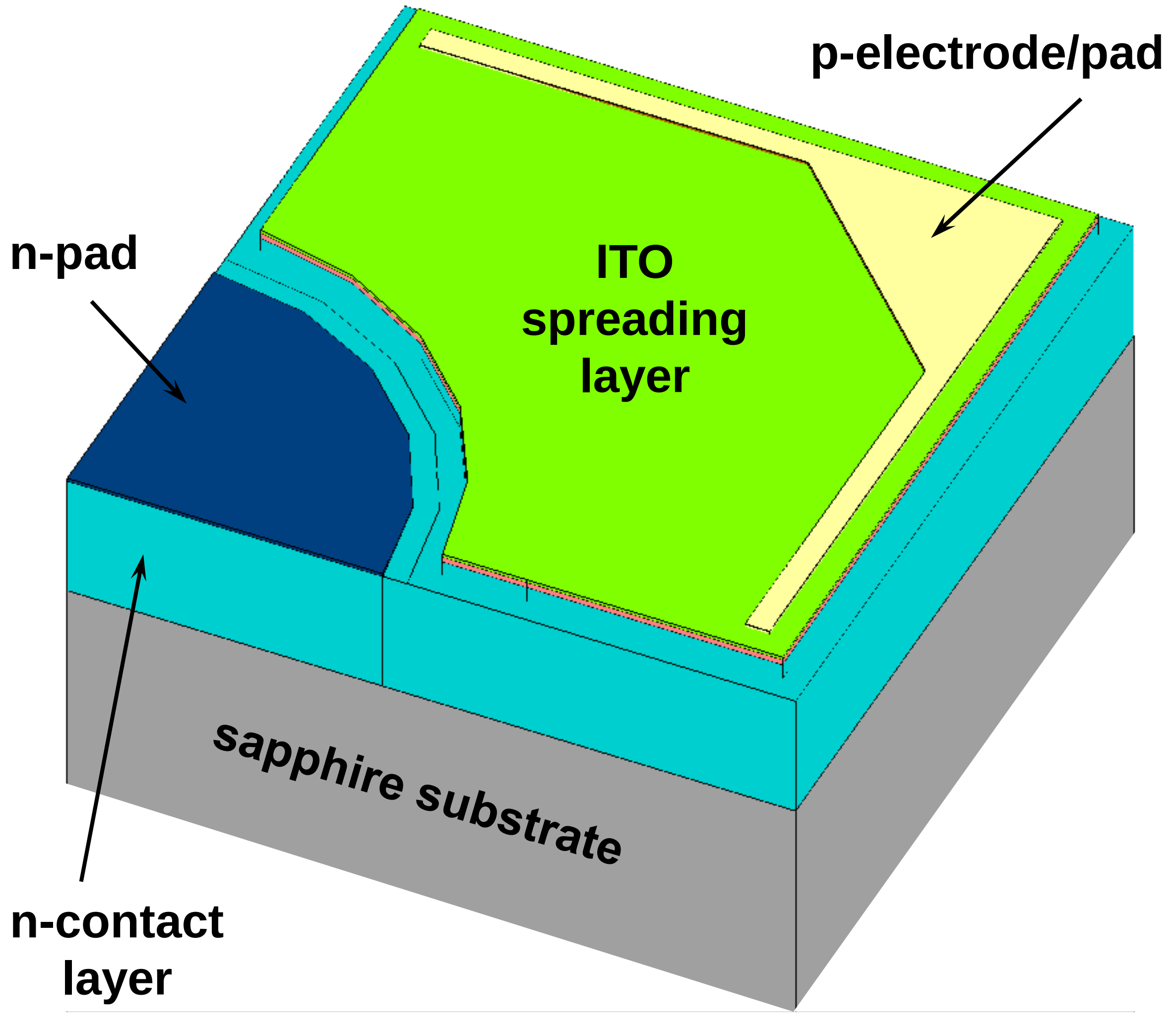
Figure 5 Normalized EQE versus current density of actual devices.

simulations allowed authors to design electrode configuration for a uniform current injection in a large GaInN LED chip and demonstrated an increase in output power in an optimized device.

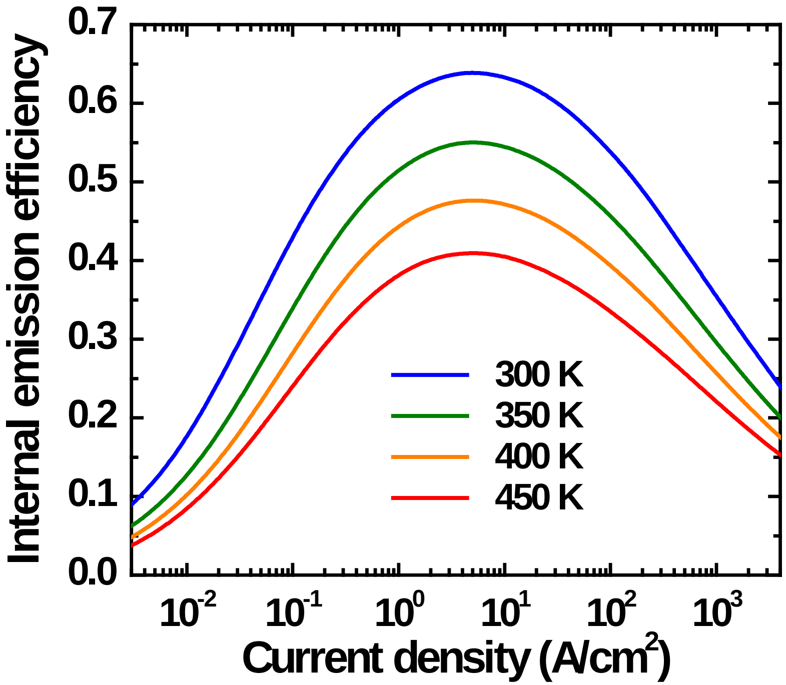
3. Operation of modern light emitters

A. Use of ITO spreading layer for improvement of LED performance

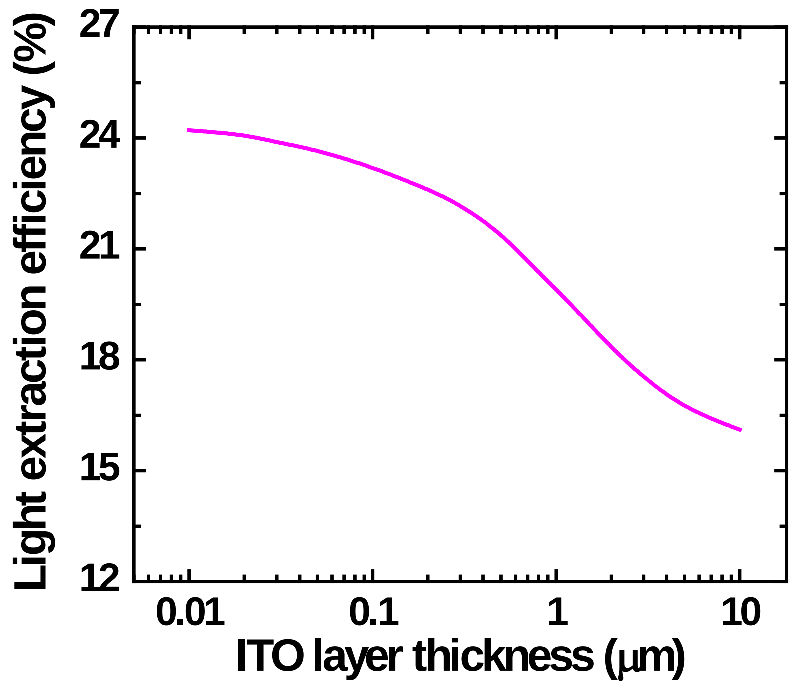
General 300×300 μm^2 LED die design utilizing ITO spreading layer



Factors affecting the overall LED efficiency



IQE of the MQW LED structure depends on both current density and temperature



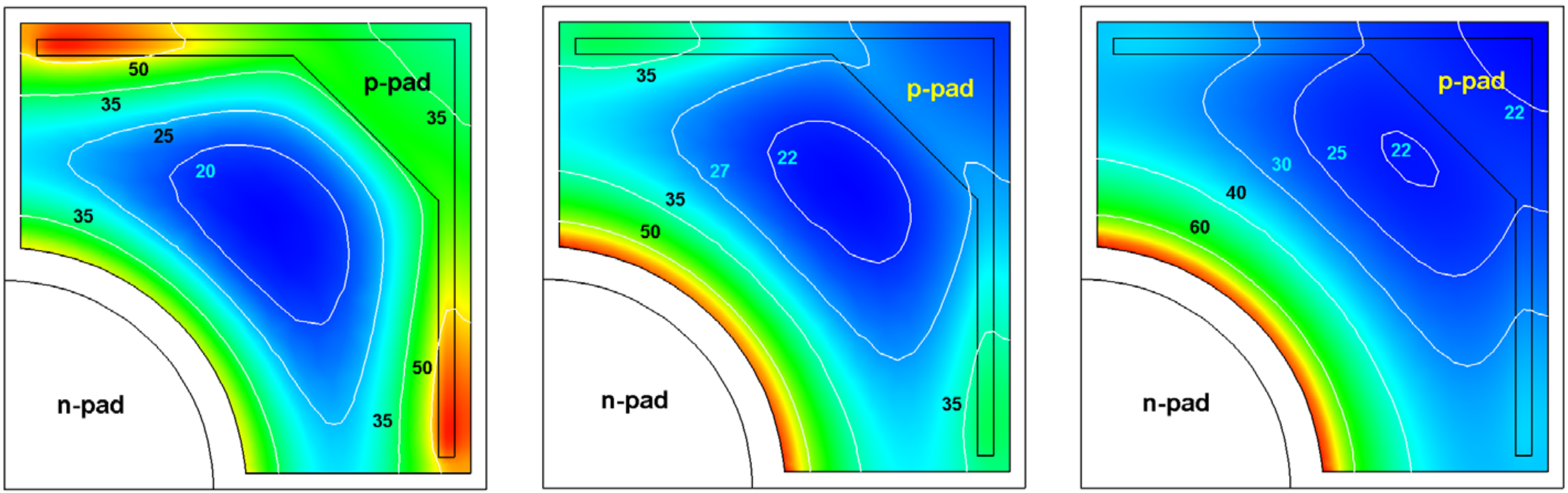
Light extraction efficiency (LEE) computations <u>accounting for interference in the ITO layer</u> and depends on the ITO layer thickness

Competitive Advantage

NB!

Current crowding in LED dice with various ITO thickness at 20 mA

Current density distribution across the LED active region, A/cm^2



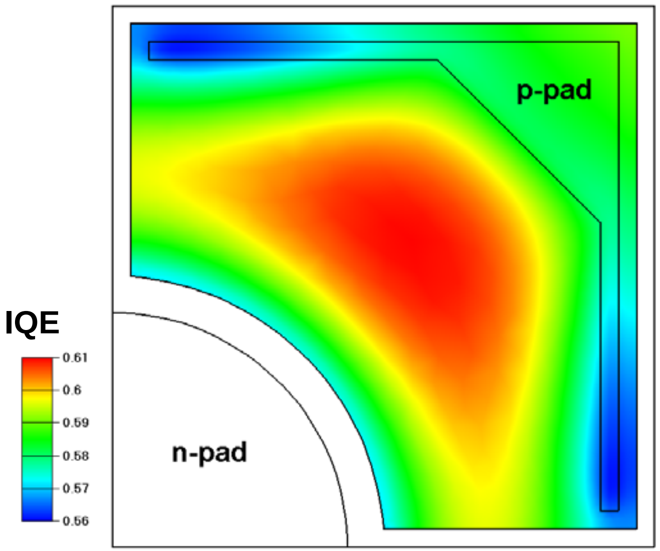
20 nm   50 nm   100 nm

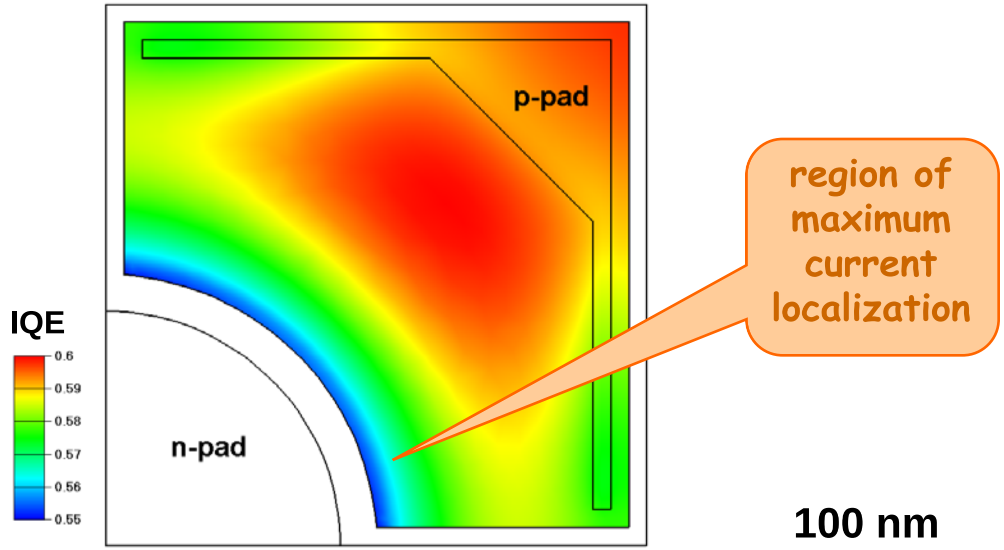
increasing ITO layer thickness (electrical sheet conductivity) results in redistribution of the current density but does not avoid the current crowding; moreover, the higher the sheet conductivity, the stronger becomes current crowding near the n-electrode edge !!

NB!

IQE distribution in the LED die at 20 mA

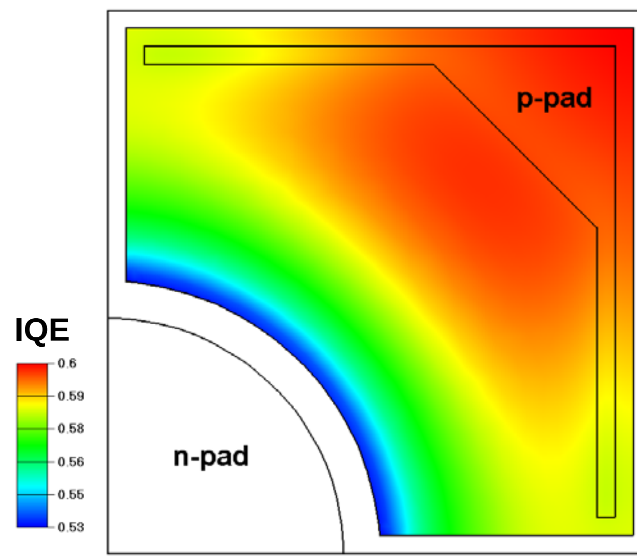
20 nm





50 nm

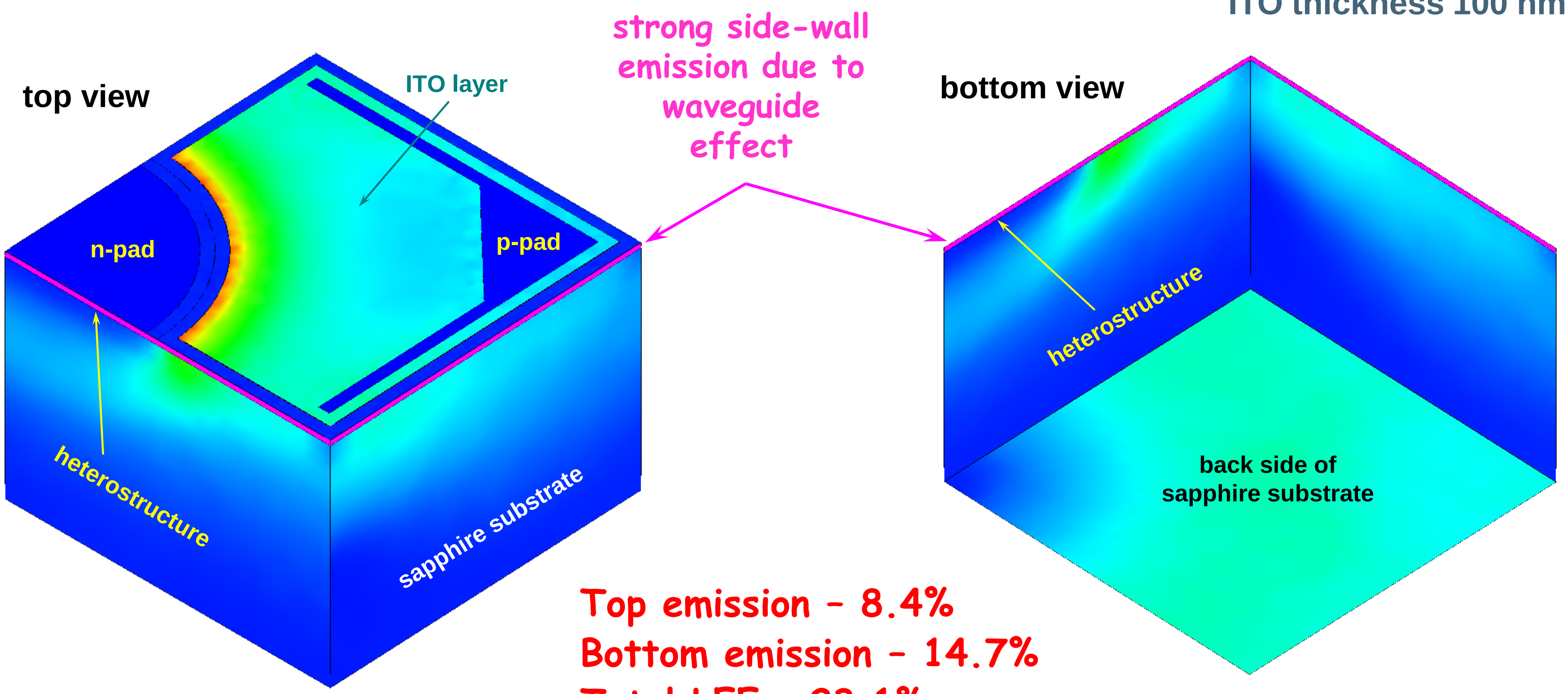
100 nm



because of high current density, the region of maximum current localization has the lowest IQE, which is caused by non-radiative Auger recombination

Near-field emission intensity distribution at 20 mA

ITO thickness 100 nm



Top emission – 8.4%
Bottom emission – 14.7%
Total LEE – 23.1%

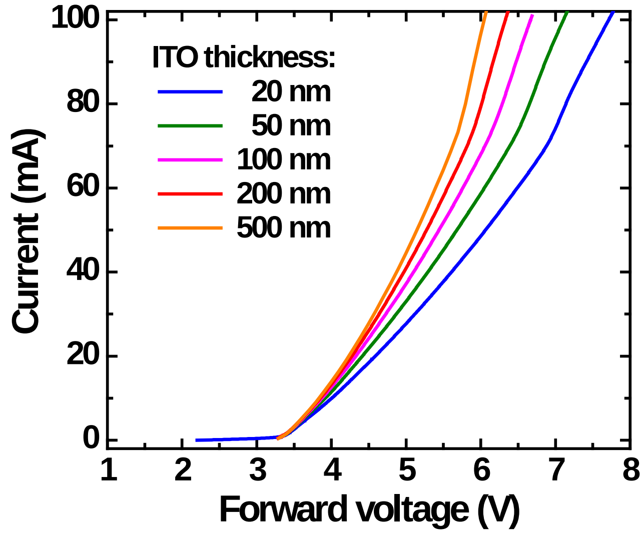
Total LEE is ~1.5-2.0 time higher than in the LED with metallic p-electrode

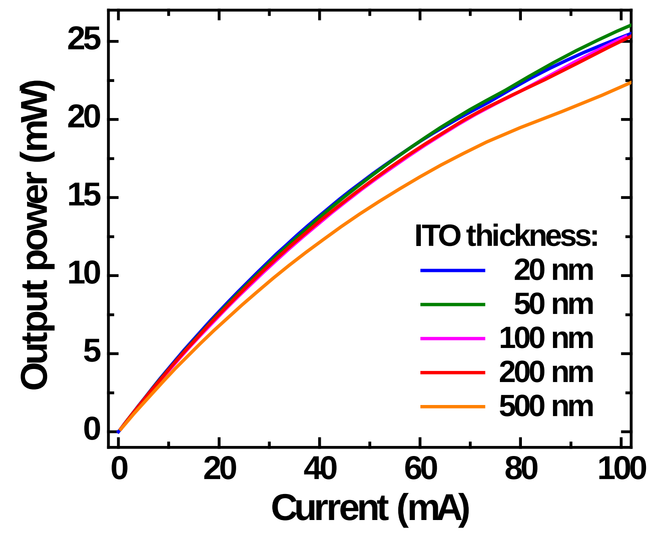
NB!

Characteristics of basic Thin-Film LED die

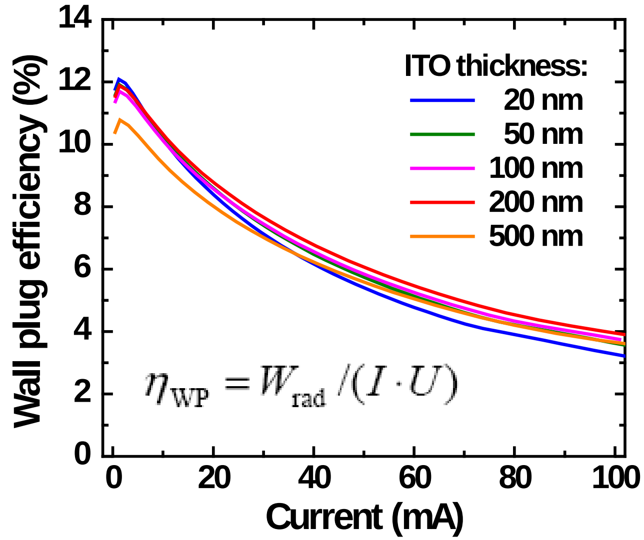
optimization of output power and operating voltage require quite different thicknesses of the ITO layer

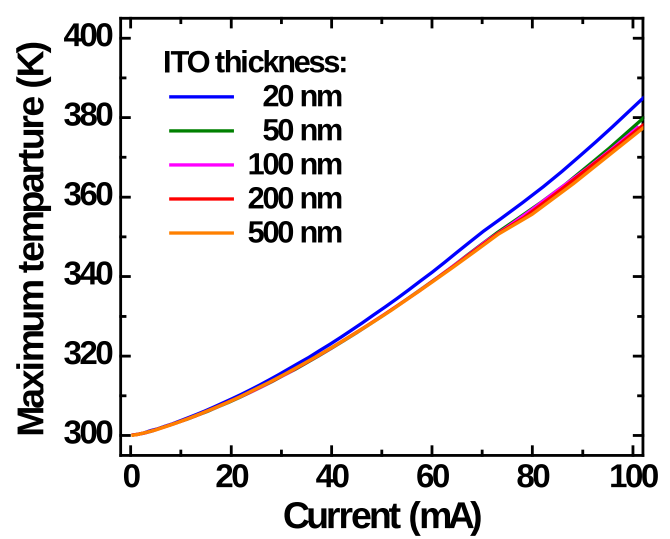
NB!





maximum WPE is attained at the ITO thickness of ~100-200 nm (at the electric conductivity of 2000 S/cm)

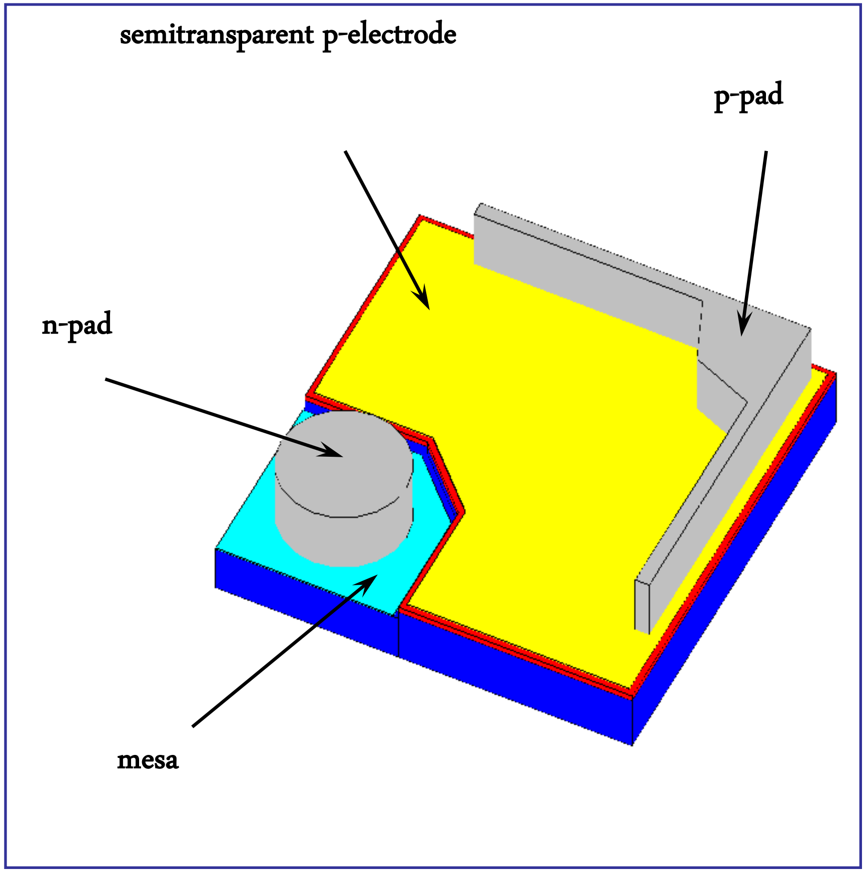




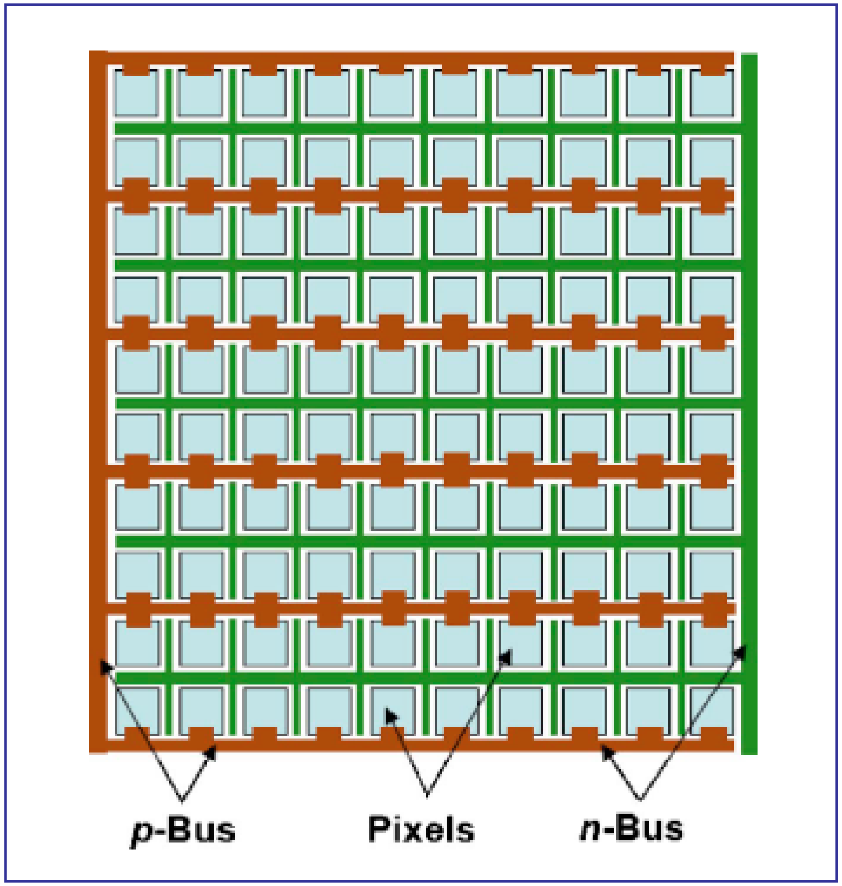
B. Operation of Interdigitated multi-pixel array (IMPA)

Design of LED array was suggested by A. Chakraborty et al. (UCSB), Appl.Phys.Lett 88 (2006) 181120

Comparison of LEDs with IMPA and conventional square chip designs



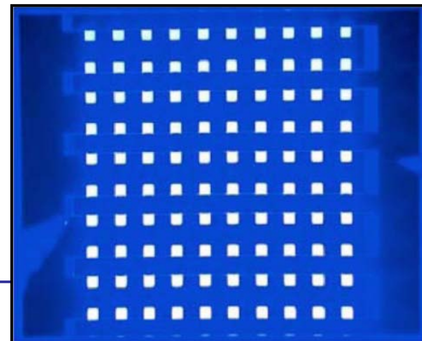
300×300 μm² square LED



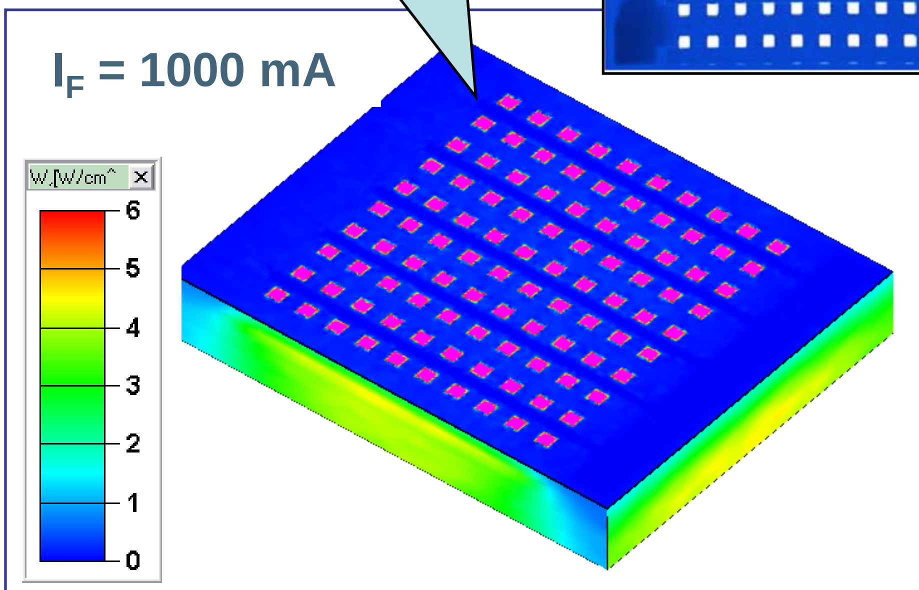
Interdigitated multi-pixel array (IMPA) containing a hundred of 30×30 μm² pixels

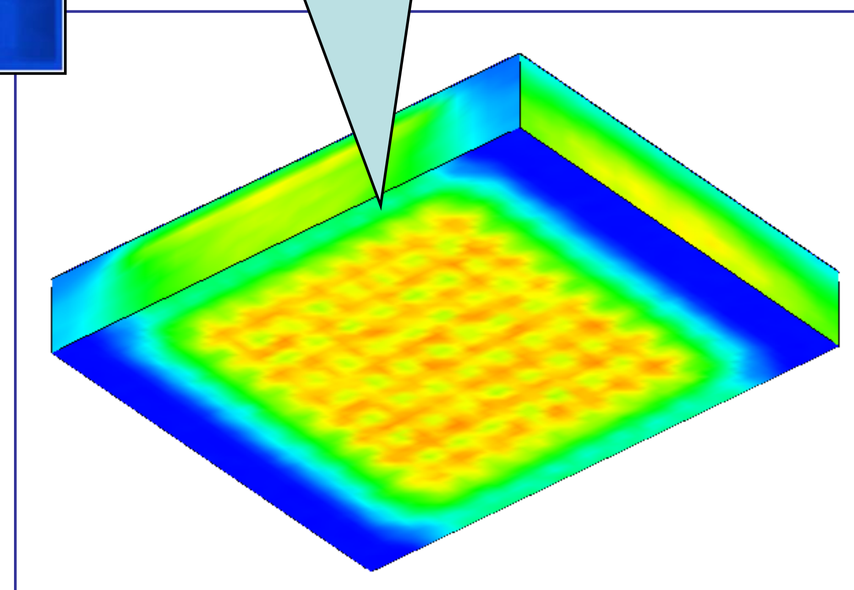
Very uniform distribution of the emission power among the pixels

experiment



Weak variation of emission intensity over the back sapphire substrate

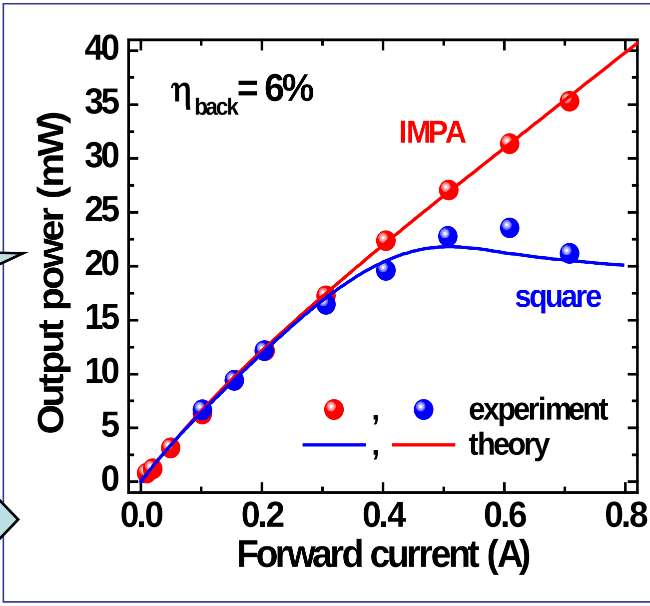


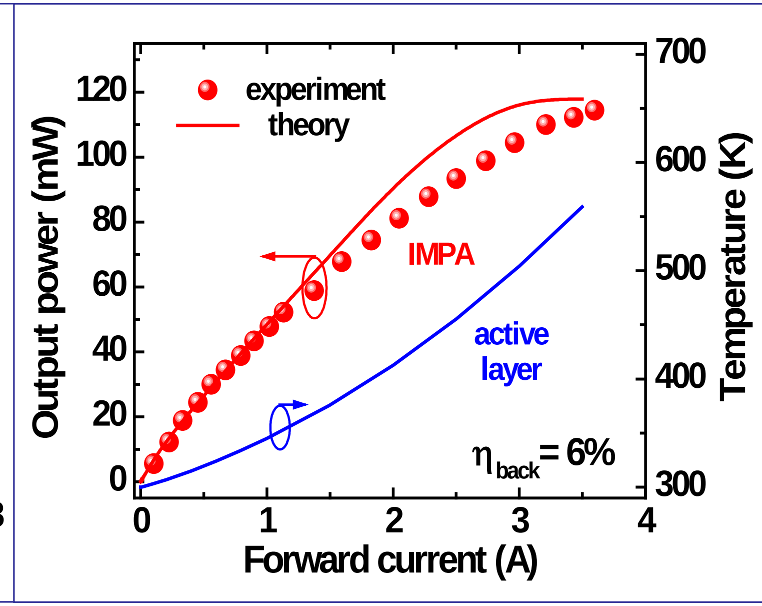


top view

bottom view

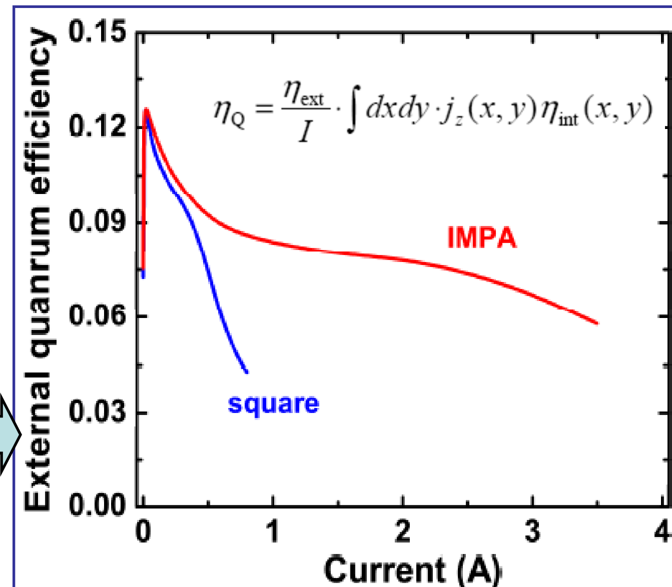
Competitive Advantage





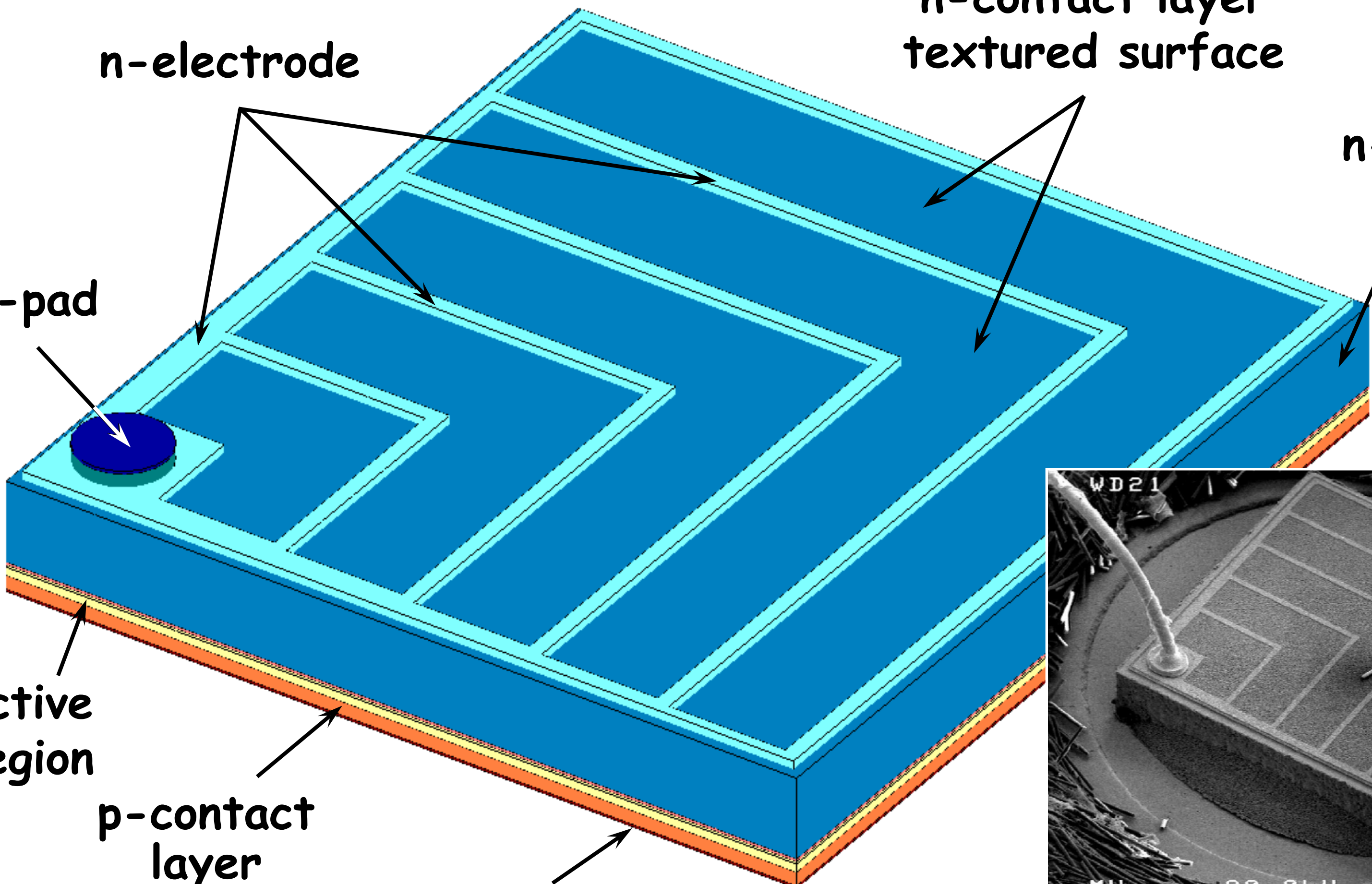
Overheating of square die does not allow power increase higher than 25 mW, whereas the dependence of power on current for IMPA die is close to linear up to current about 0.8 mA

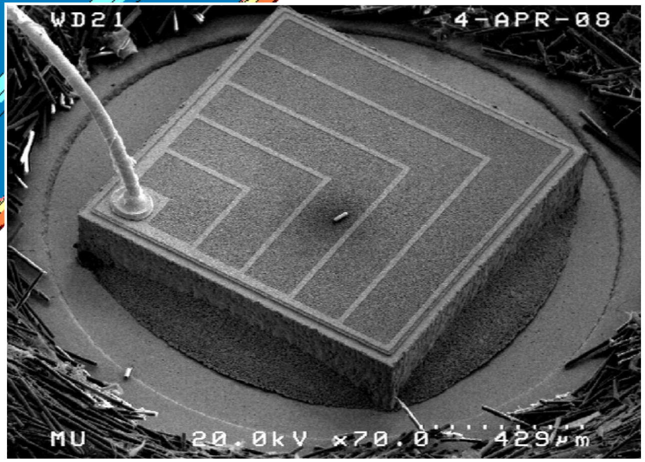
Due to suppressed current crowding and reduced overheating, the IMPA LED is capable of high current operation without significant droop of the EQE at the currents from 1 to 3 A



C. Analysis of Thin-Film LED operation

Basic design of 815×875 μm² blue LED die

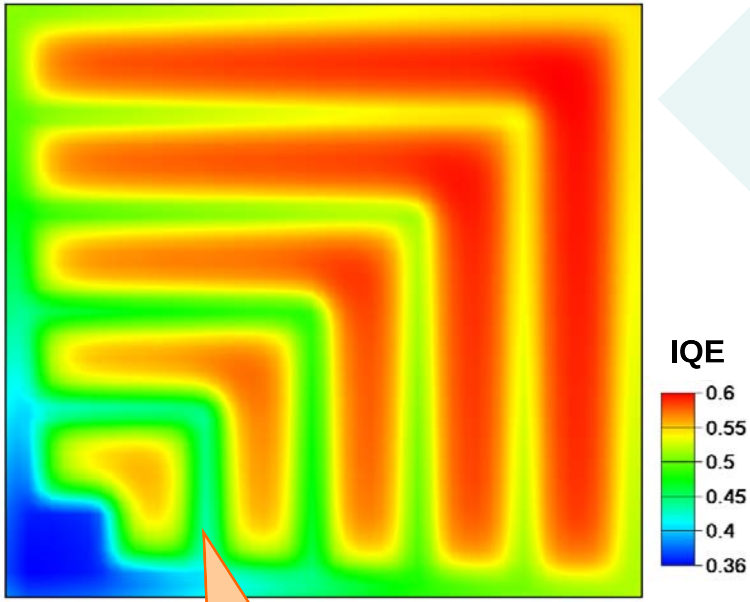




Micrograph of the die by MuAnalysis

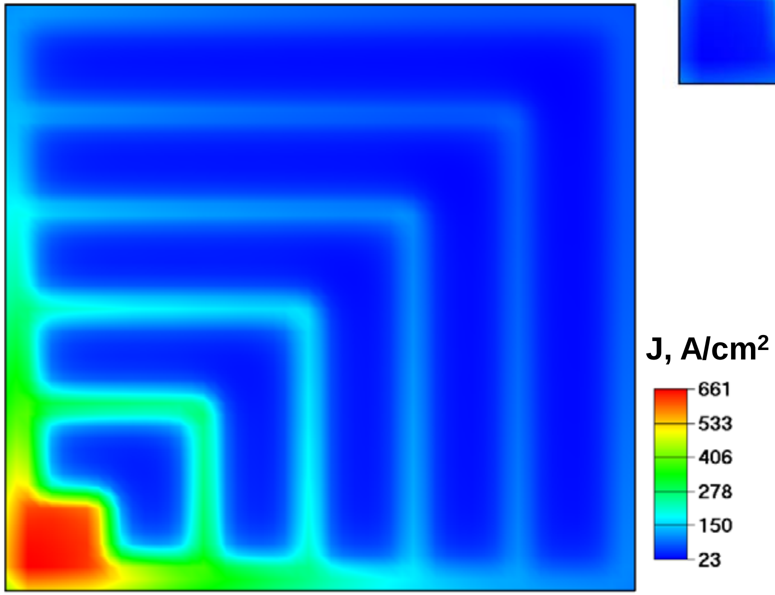
Current crowding near/under n-electrode at 700 mA

IQE distribution in the active region



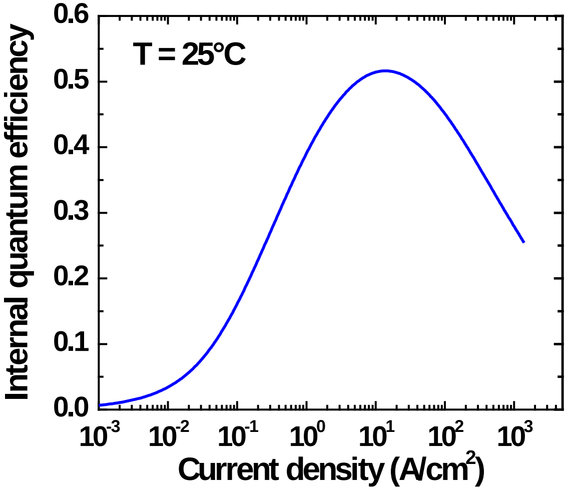
IQE distribution in the active region is essentially non-uniform

current density distribution in the active region



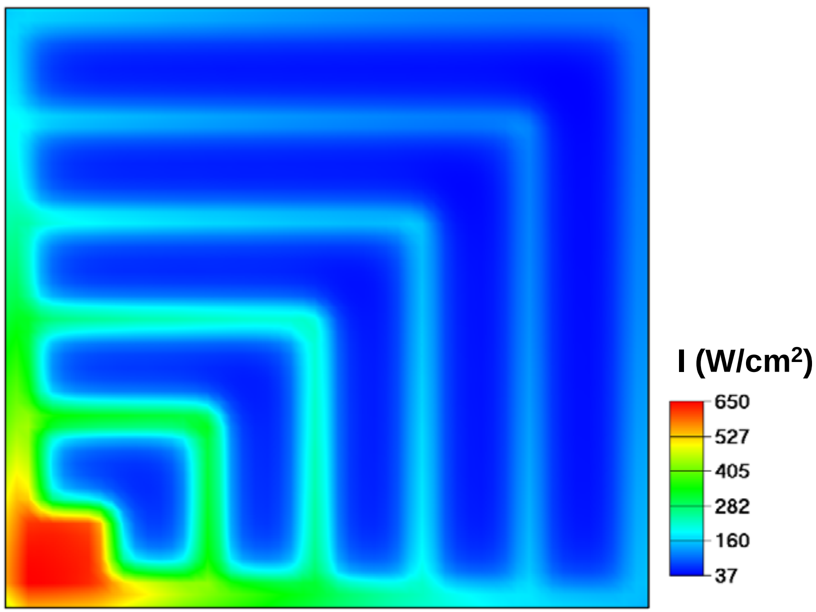
local IQE reduction in high-current density area

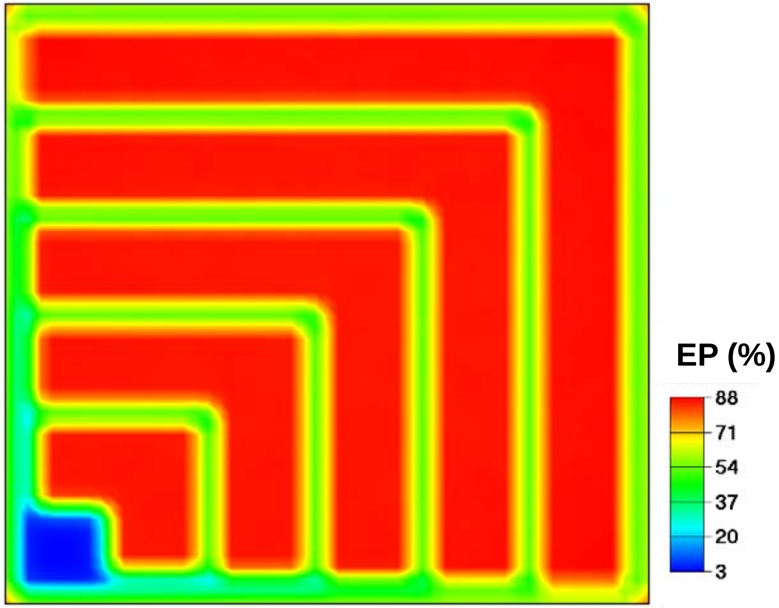
efficiency droop at high current density caused by Auger recombination



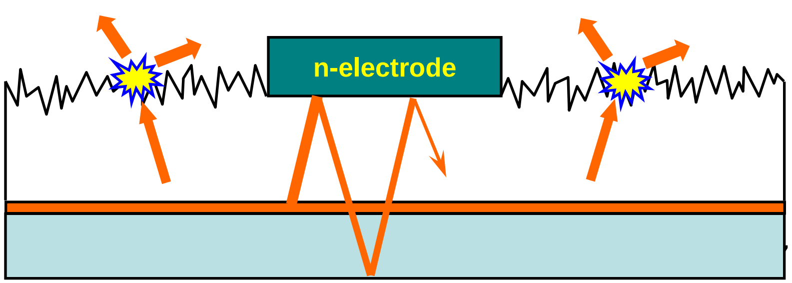
Emission intensity and probability of light extraction in the active region

Current I = 700 mA





probability of light extraction falls down under and next to n-electrode



maximum of emission intensity is located under/next to n-electrode, despite the IQE droop with current; light emission under the n-pad does not contribute at all to the extracted light !!

NB!

Characteristics of basic Thin-Film LED die

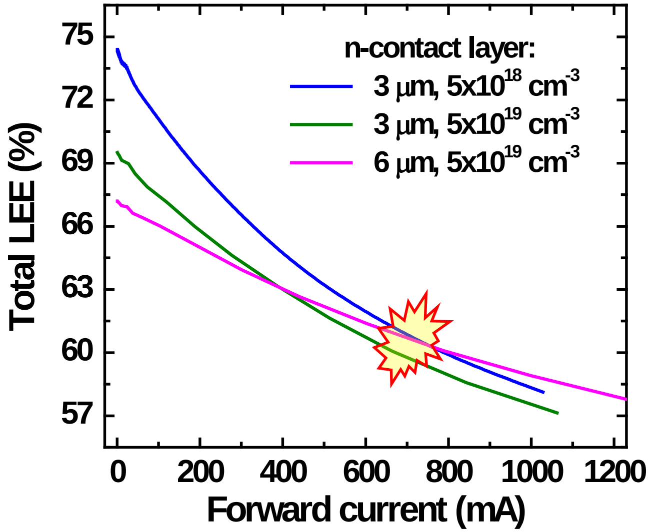
strong dependence of LEE on forward current

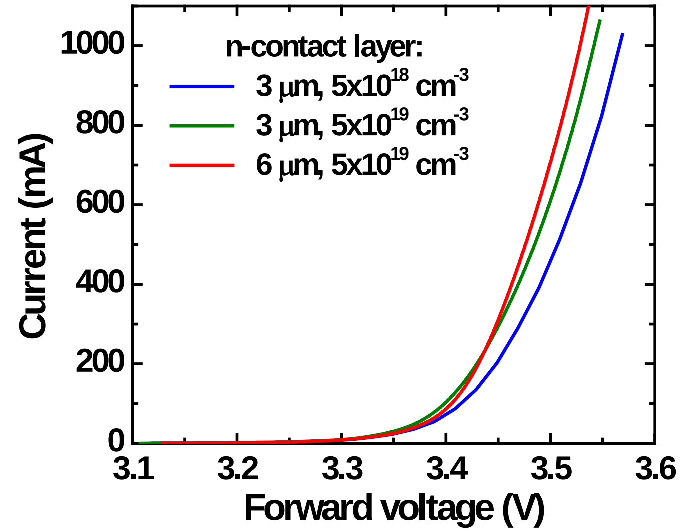
NB!

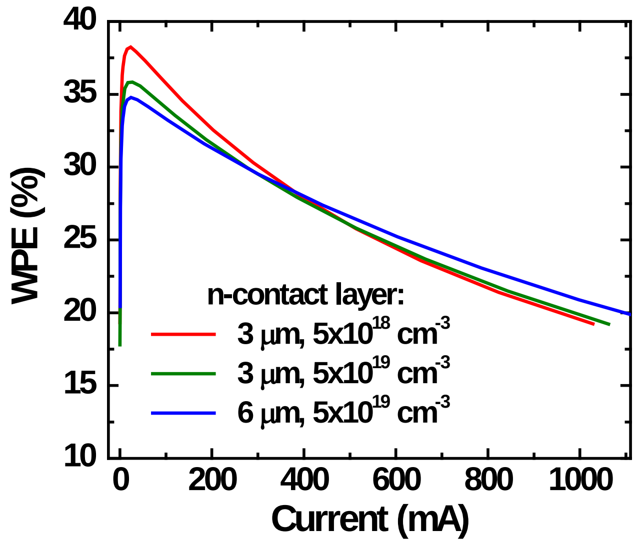
variation of n-contact layer parameters affects weakly the current crowding and, hence, the LEE at 700 mA

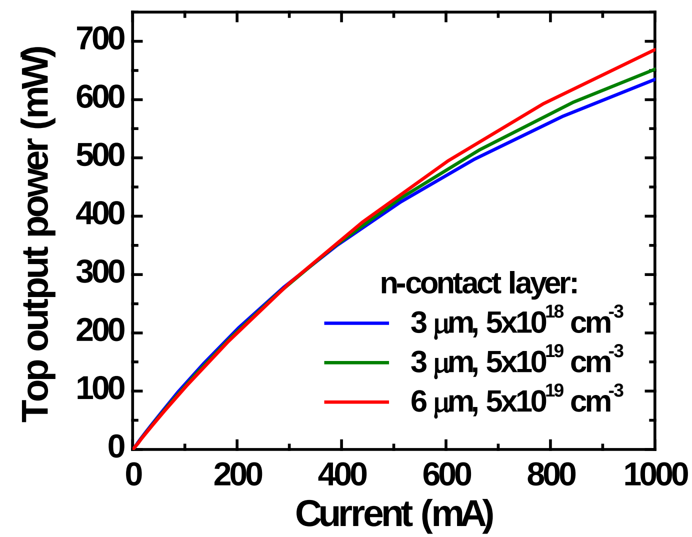
⇓

alternative approaches are required

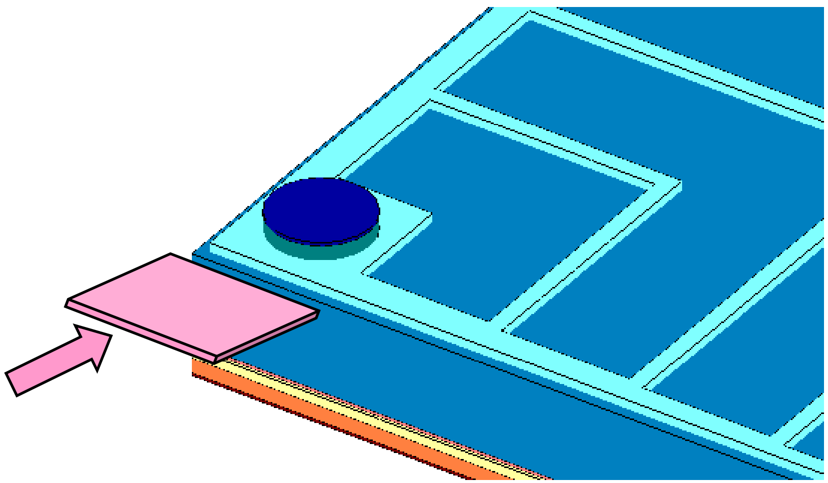


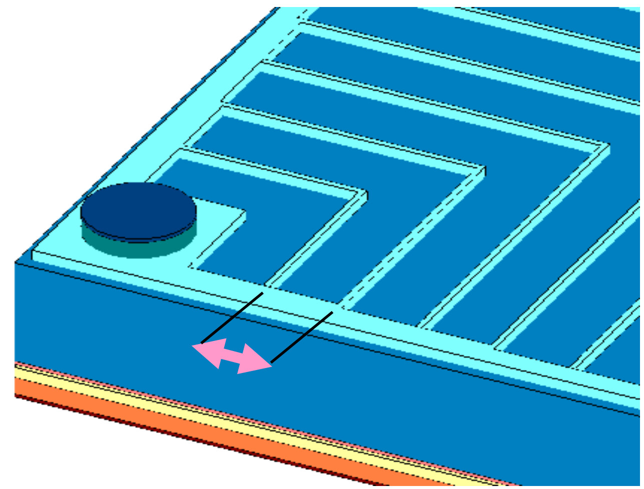






Two approaches for improvement of Thin-Film LED performance





Approach 1: insertion of a current blocking layer (thin insulating film) under the n-pad to avoid parasitic current flowing in this region

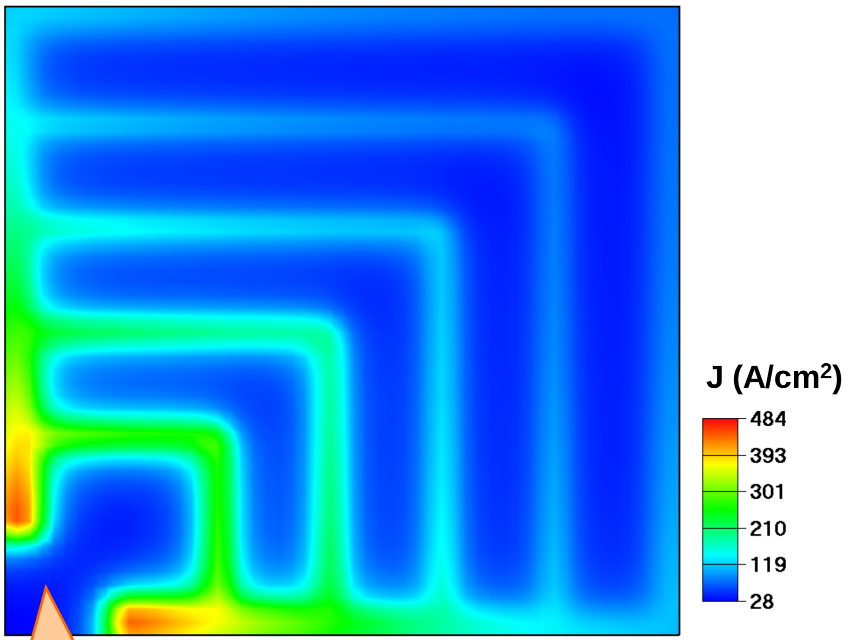
new

Approach 2: use of refined electrode structure with larger number of Γ-shaped electrode branches but with smaller width of each of them

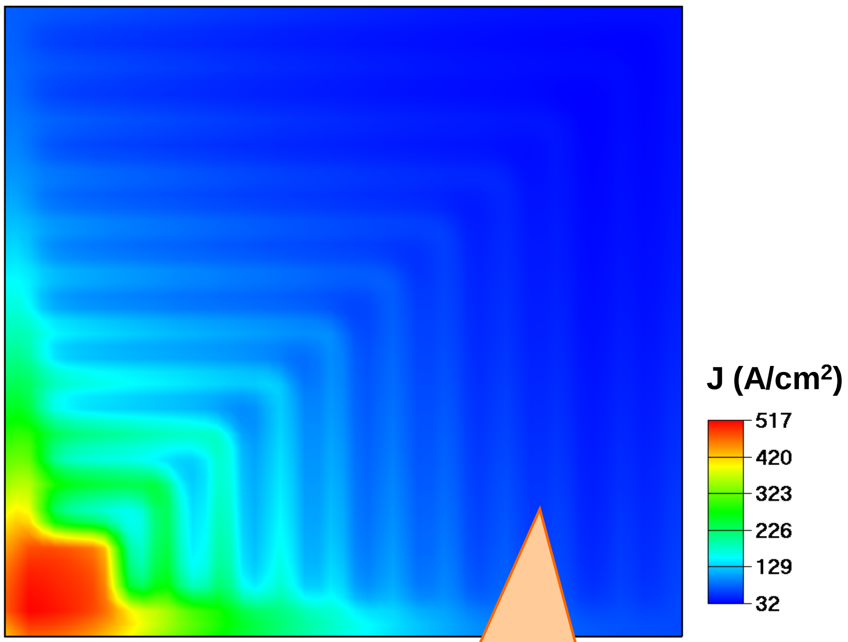
new

Current spreading in LED dice of improved design

Approach 1



Approach 2



parasitic current flow under the n-pad is partly suppressed

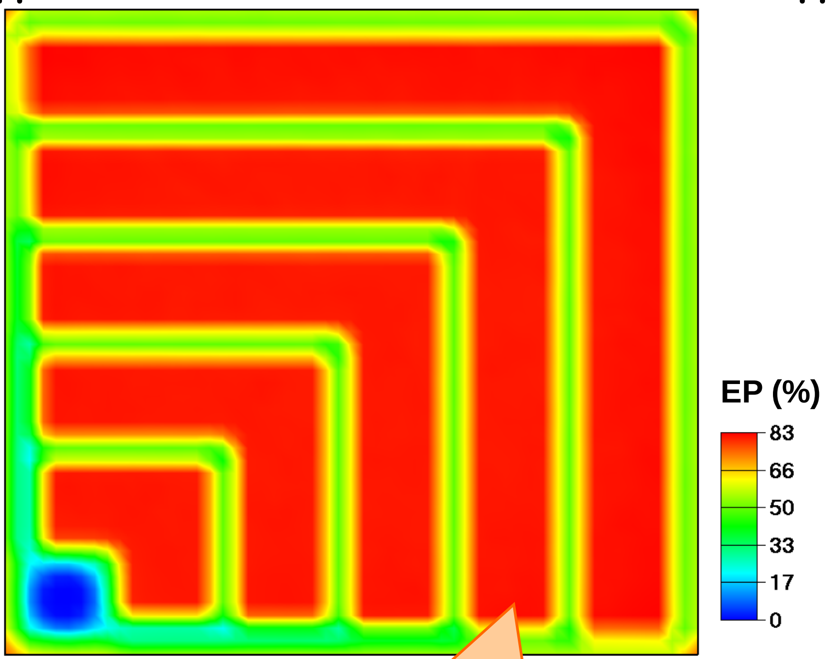
both approaches are found to work well

reduction of the current density contrast on the die periphery

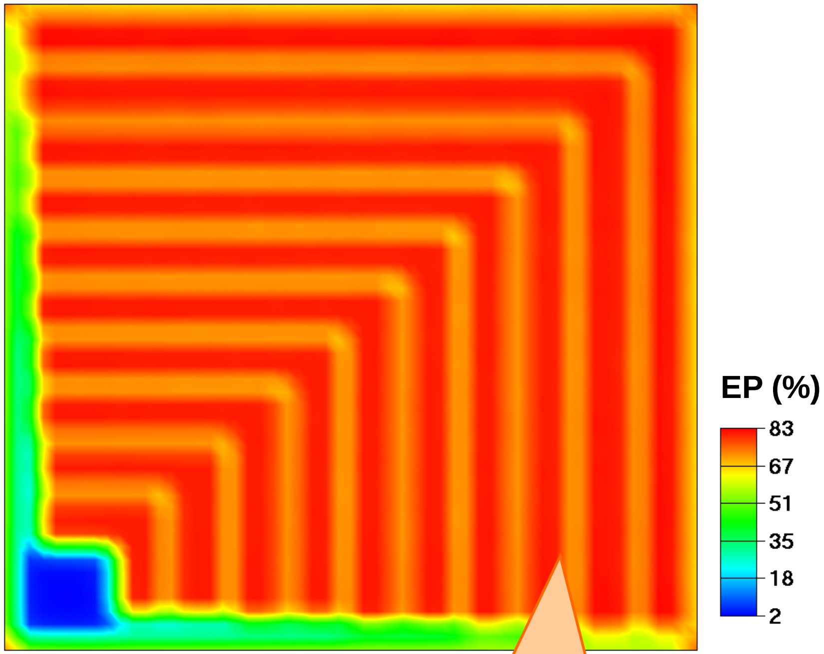
Total current through the diode I = 700 mA

Local probability of light extraction from improved LED dice

Approach 1



Approach 2



probability of light extraction is comparable with that of the basic die design

considerable enlarging of the area with high probability of light extraction

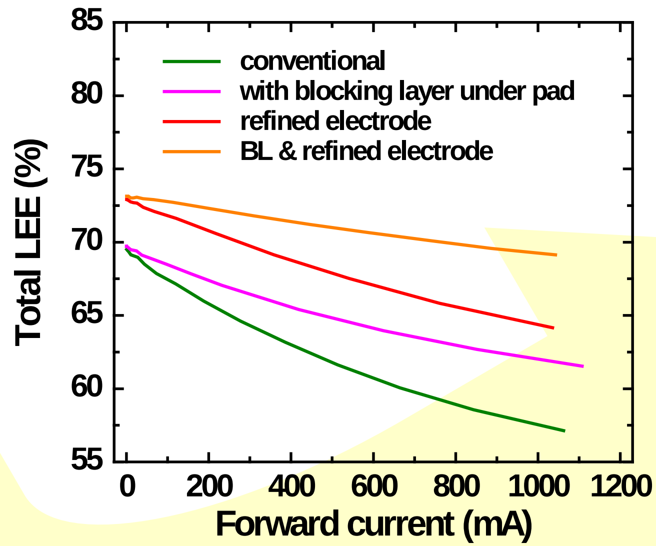
Total current through the diode I = 700 mA

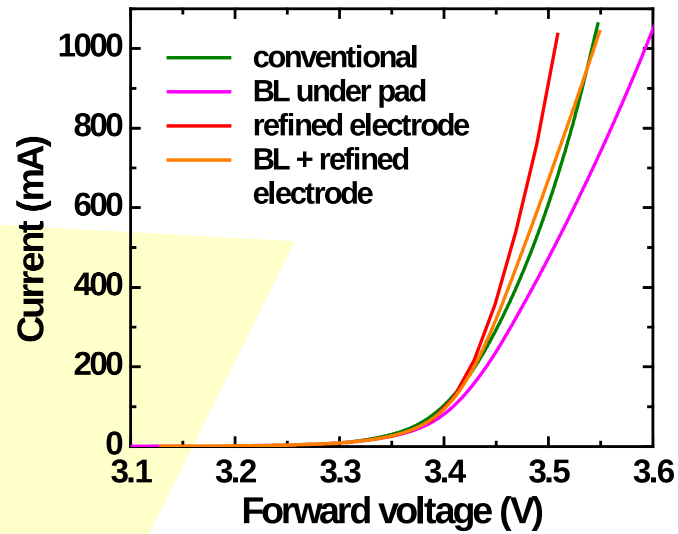
Assessment of performance improvement due to variation of LED die design

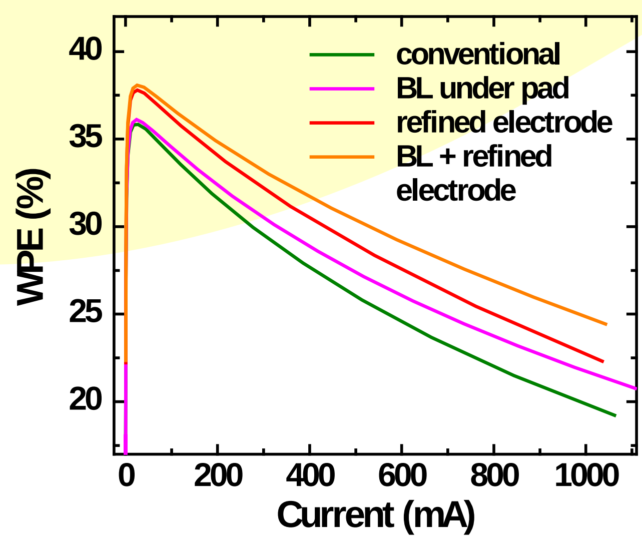
Performance improvements at the current of 700 mA:

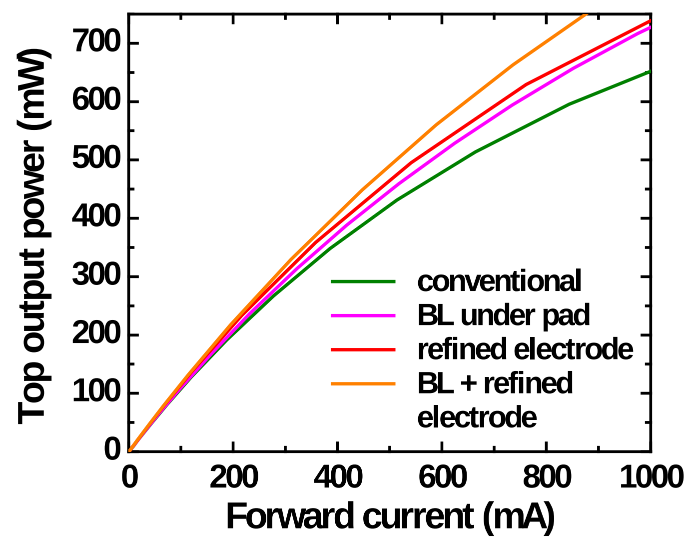
- LEE ⬆ from 60 to 70%
- V_f remains the same
- optical power ⬆ from 530 to 635 mW (by 20%)
- WPE ⬆ from 23 to 28%

Competitive Advantage









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