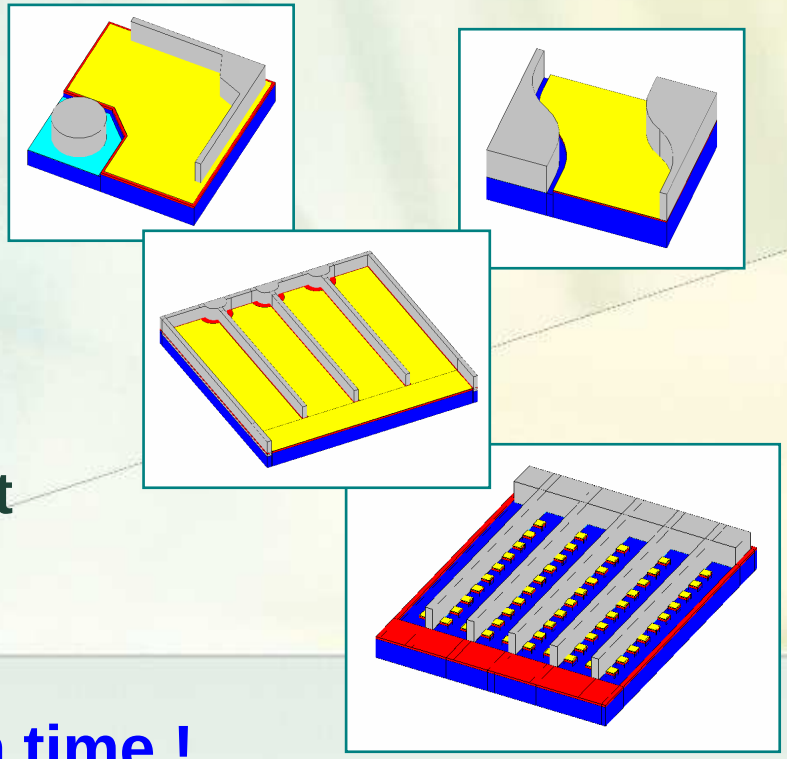
Coupled Modeling of Current Spreading, Thermal Effects, and Light Extraction in III-Nitride Light-Emitting Diodes

M. V. Bogdanov, K. A. Bulashevich, I. Yu. Evstratov, and S. Yu. Karpov

Semiconductor Technology Research, Inc.

Motivation

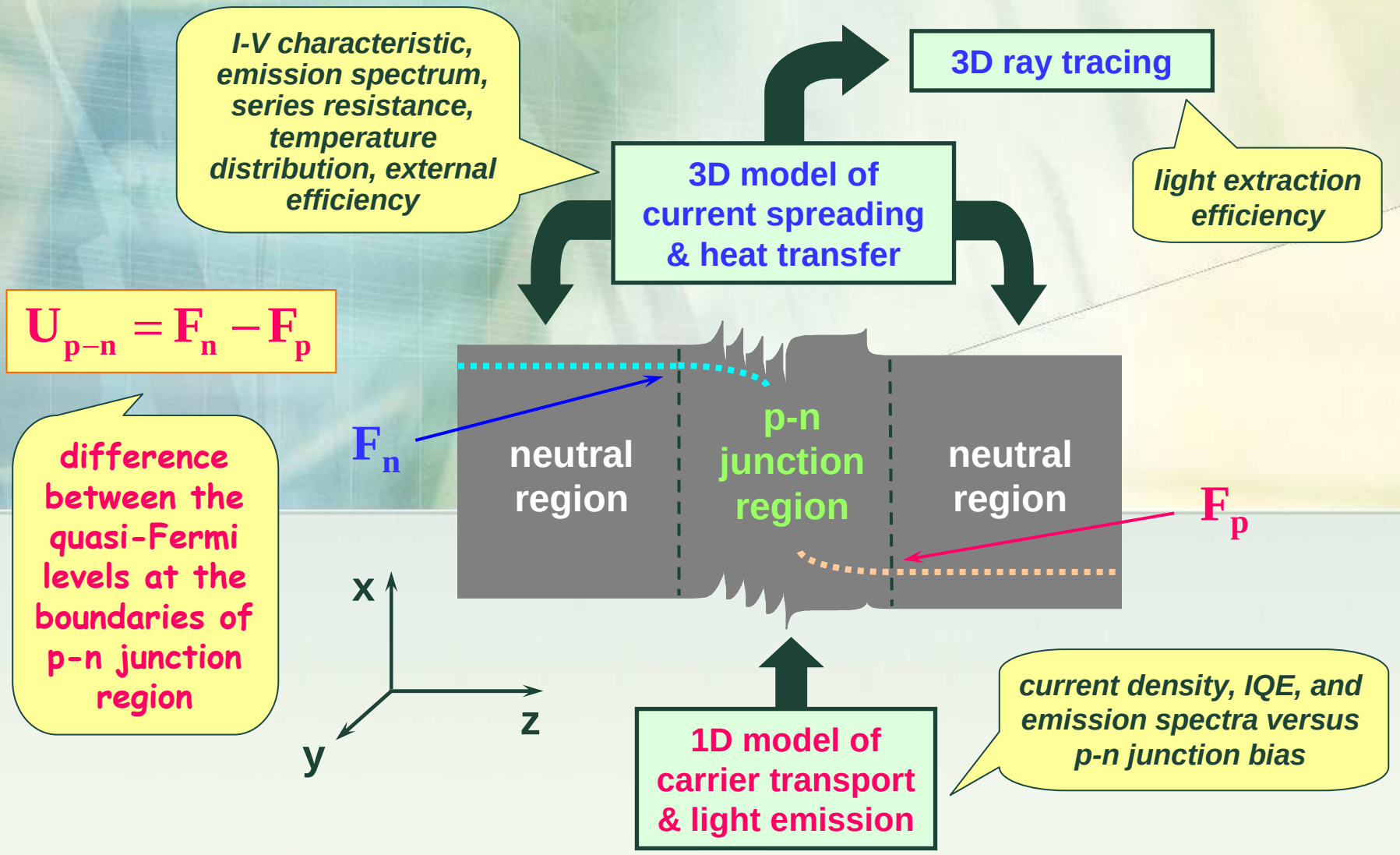
- Complex 3D geometry of advanced III-nitride LEDs
- Coupled non-linear transport equations for electrons and holes in the active region
- Interrelation between the current spreading and thermal effects



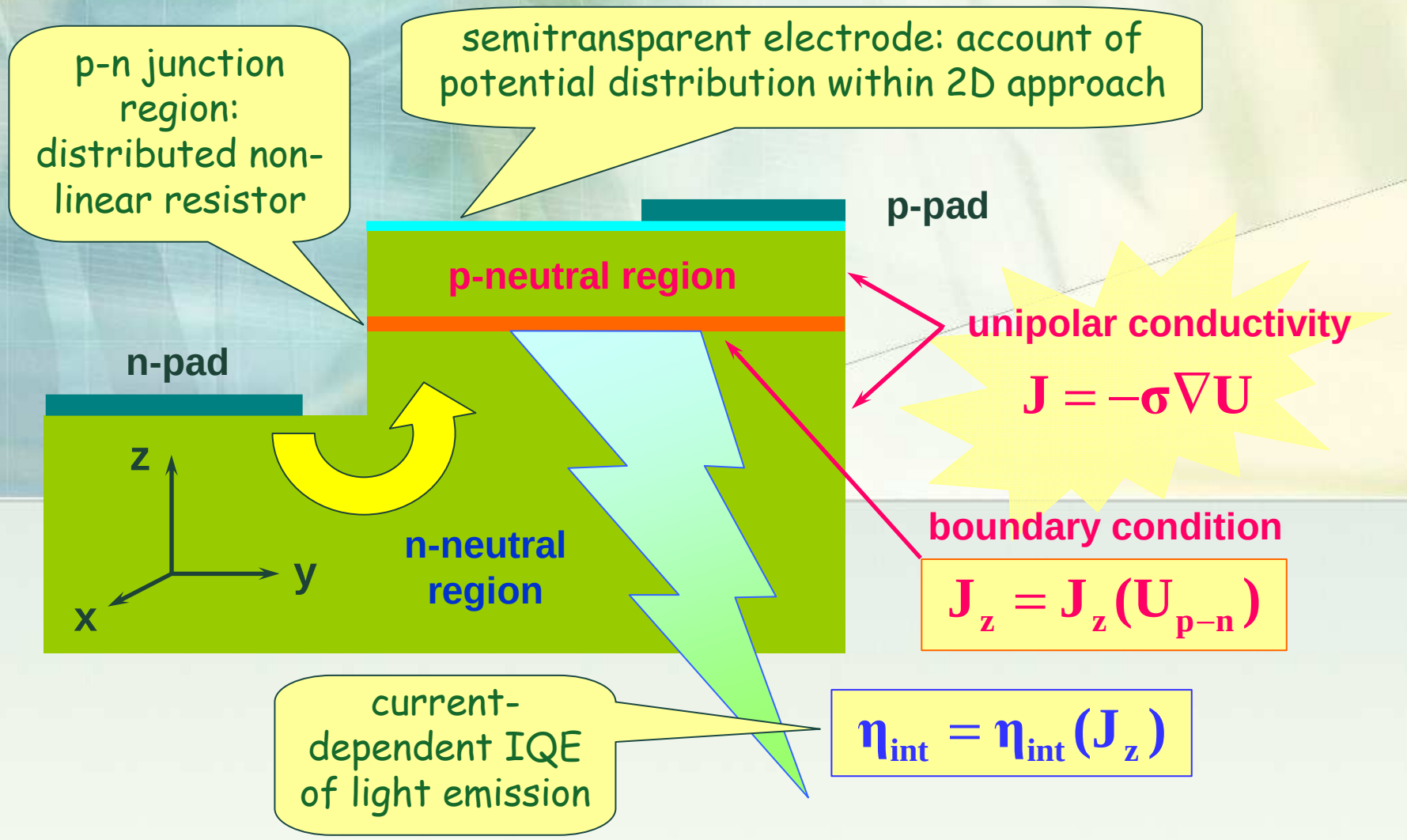
Huge increase of the computation time !

<u>Goal of the study:</u> testing and validation of approximate approach providing engineering optimization of III-nitride LEDs

Hybrid approach to modeling LED dice



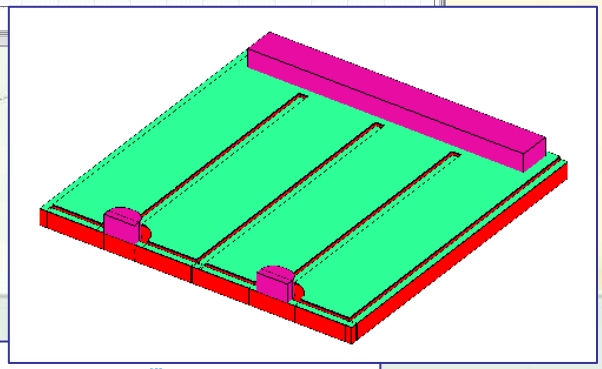
Hybrid approach to modeling LED dice



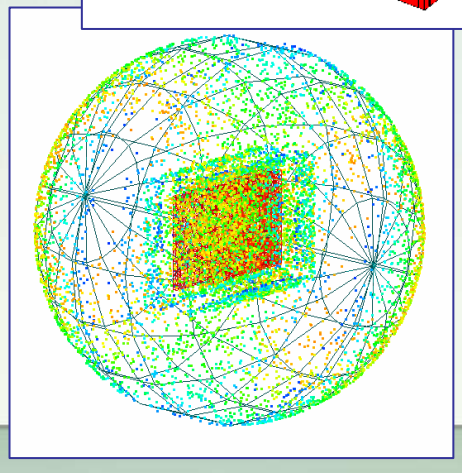
SimuLED package

SiLENSe™ – 1D simulator of carrier injection and light emission in III-N and II-O LED structures

SpeCLED™ – 3D simulator of current spreading and heat transfer in LED dice

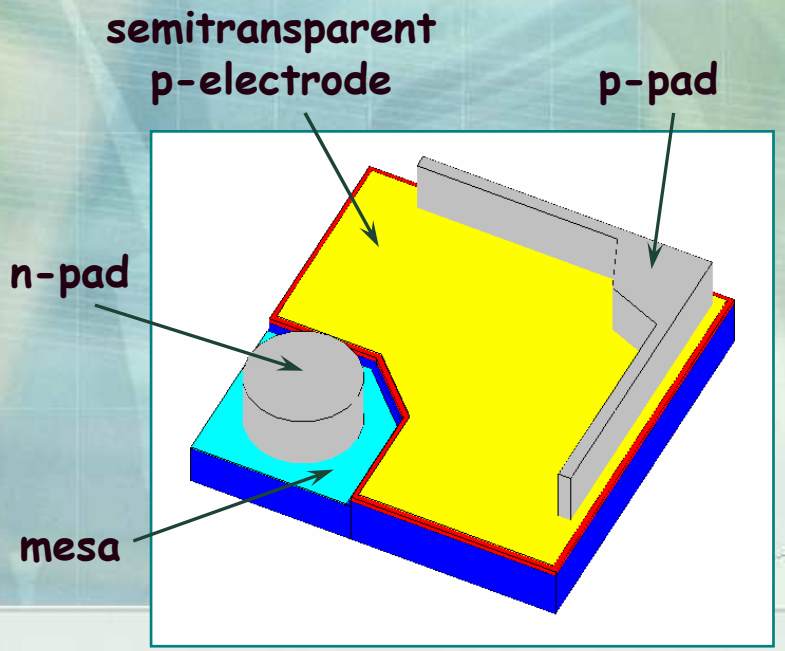


RATRO™ – 3D ray-tracing analyzer of light propagation and extraction in LED dice



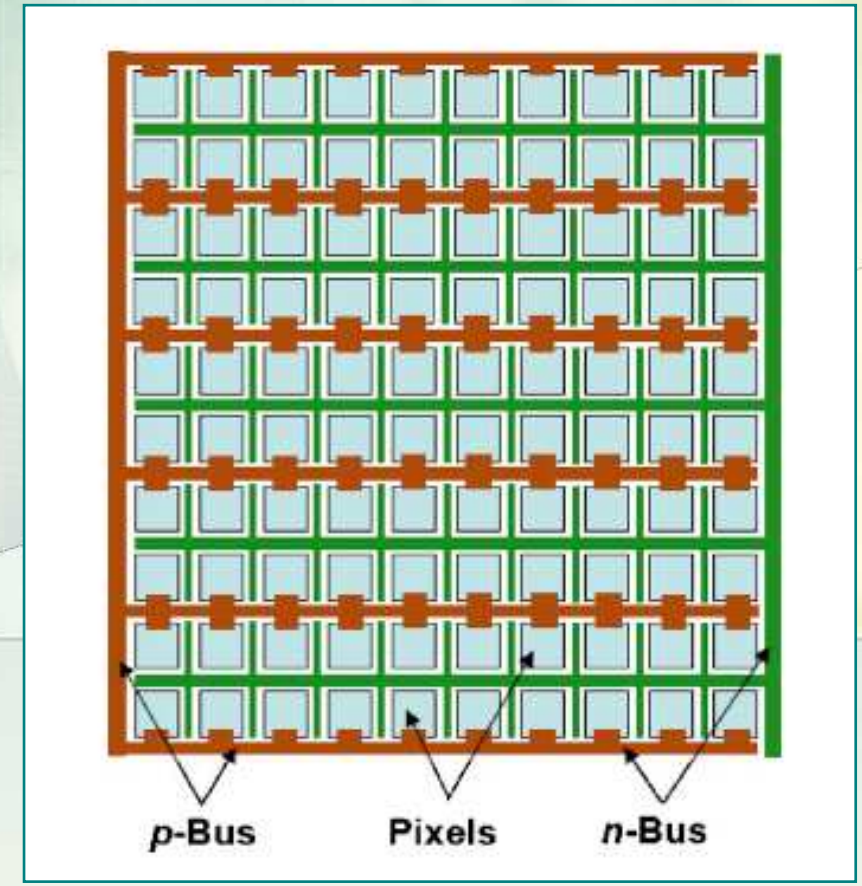
http://www.semitech.us/products/

Application to IMPA and conventional violet LED dice



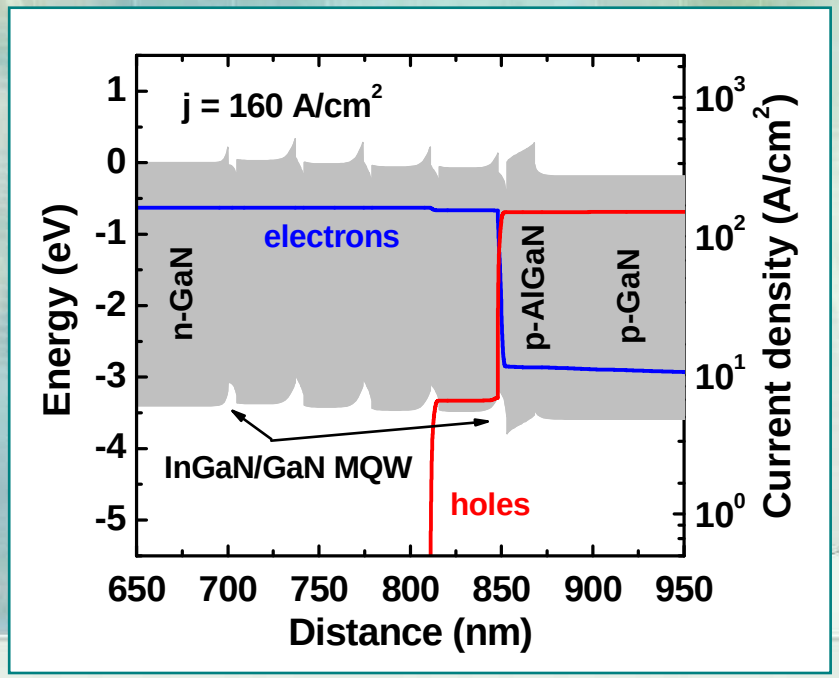
300×300 μm² square LED

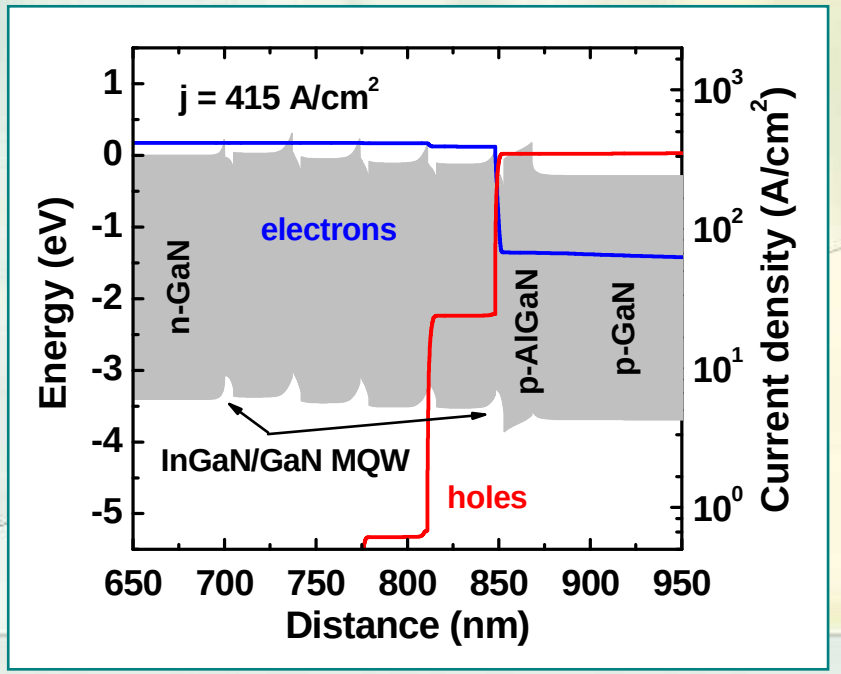
A. Chakraborty et al. (UCSB), Appl.Phys.Lett 88 (2006) 181120



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

Operation of LED heterostructure



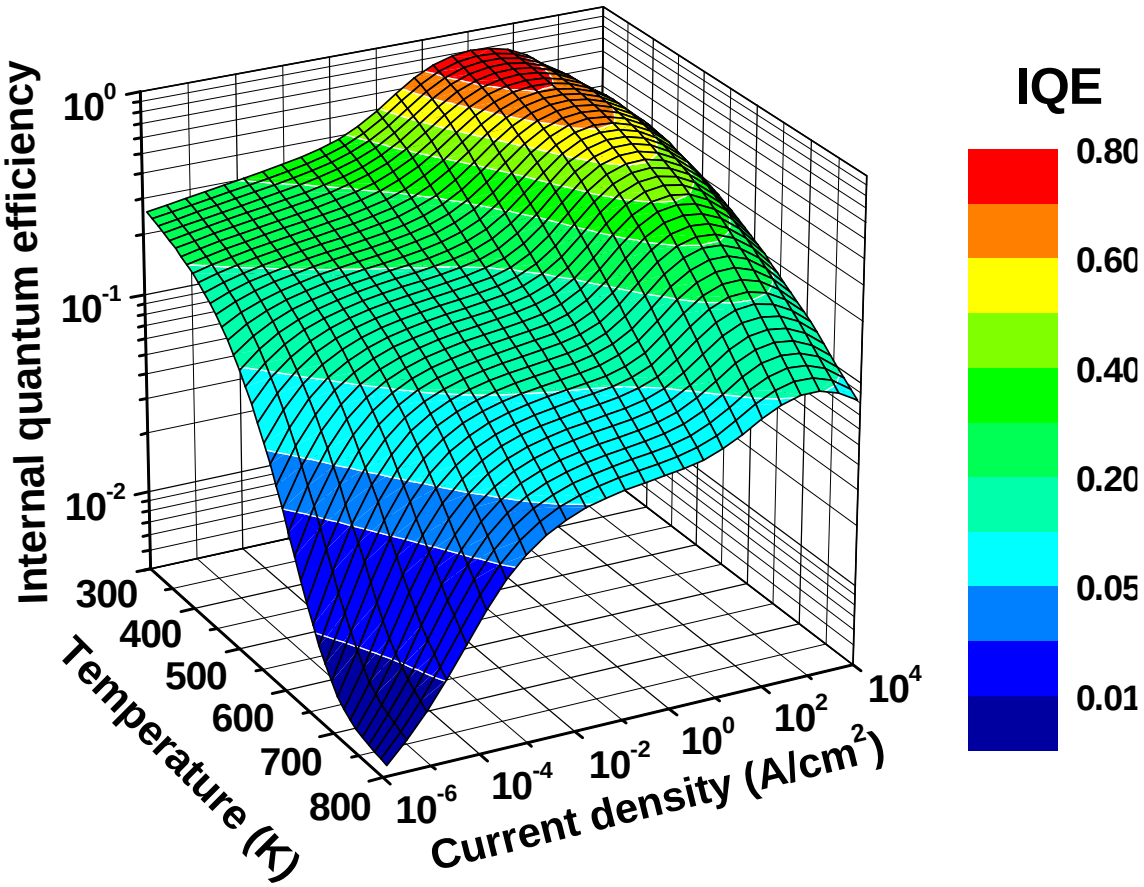


electron leakage ~7%

electron leakage ~16%

Holes are mainly injected in the quantum well adjacent to the p-AlGaN blocking layer. As a result, more than ~95% of all photons are emitted just from this well. The other wells operate under non-optimal conditions.

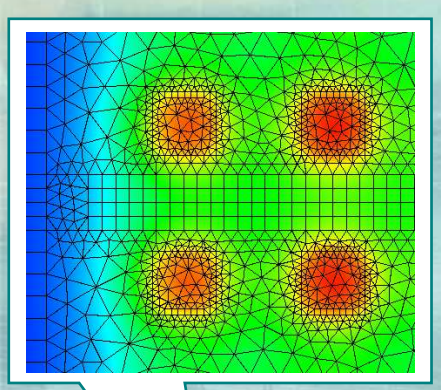
IQE as a function of current density and temperature



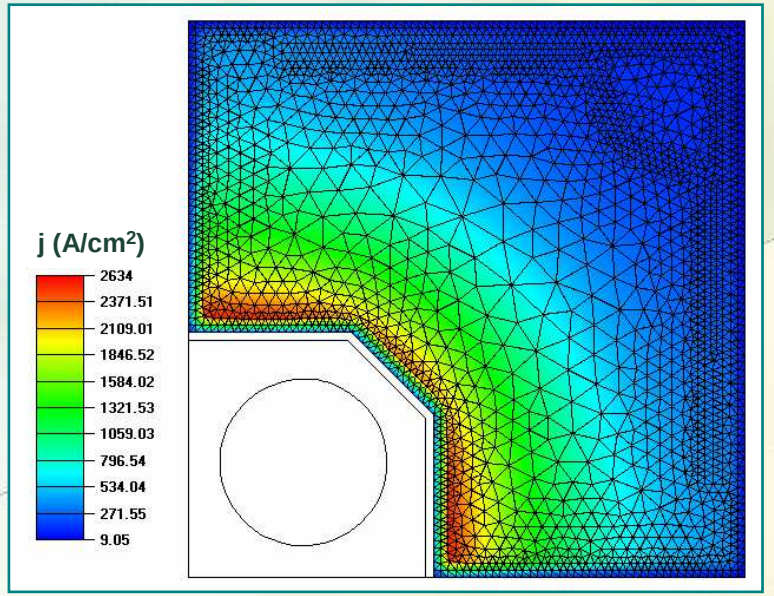
Auger recombination and electron leakage are the main factors controlling IQE at high current densities

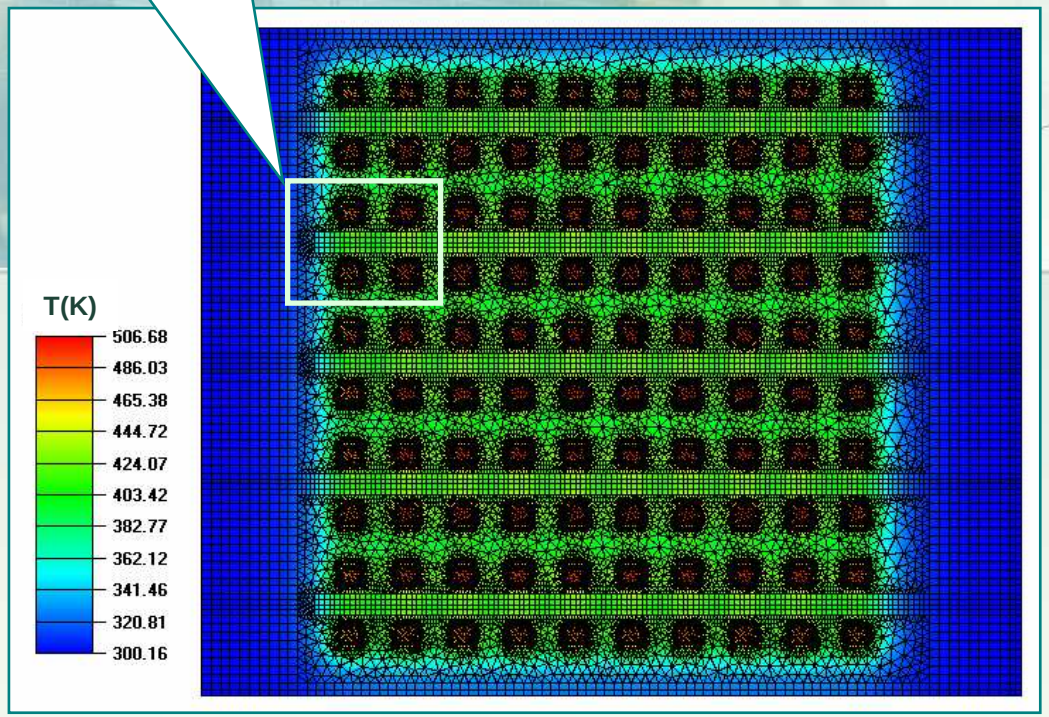
obtained by 1D modeling of LED structure

Simulation of current spreading and heat transfer



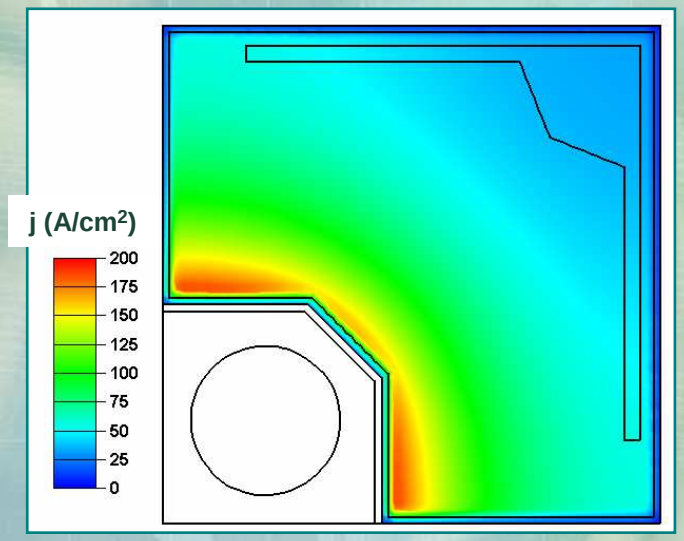
Square-LED: unstructured 3D grid with 85 000 cells





Multi-pixel LED: 3D grid with 1 100 000 cells combining structured and unstructured meshes

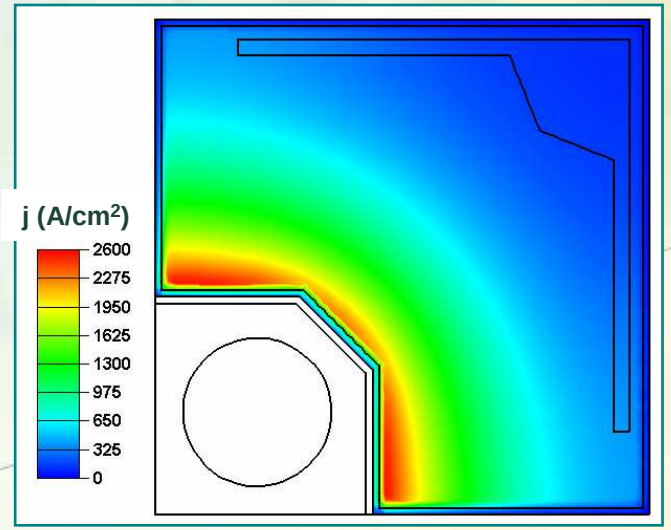
Current crowding in square LED die and active region overheating

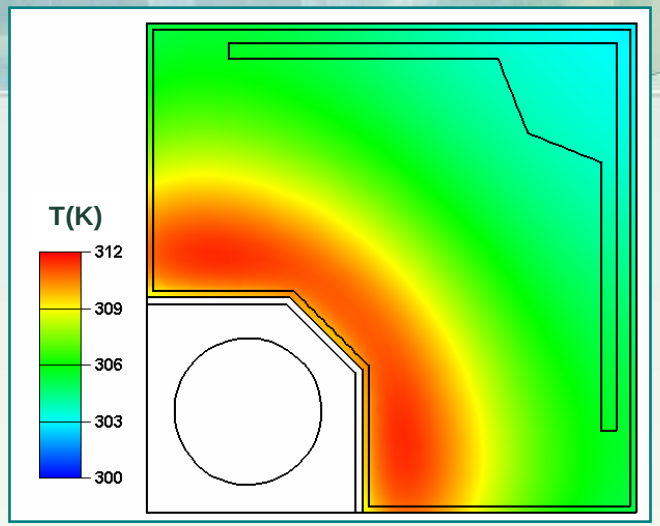


I = 50 mA

L_{sp}~ 80 μm

ΔT = 12 K

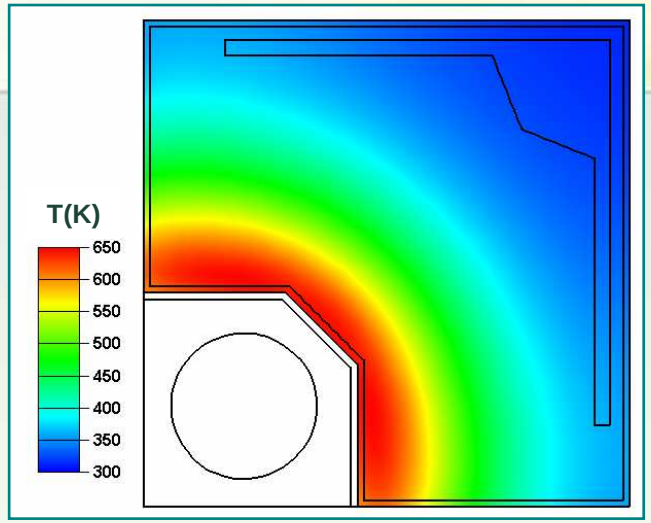




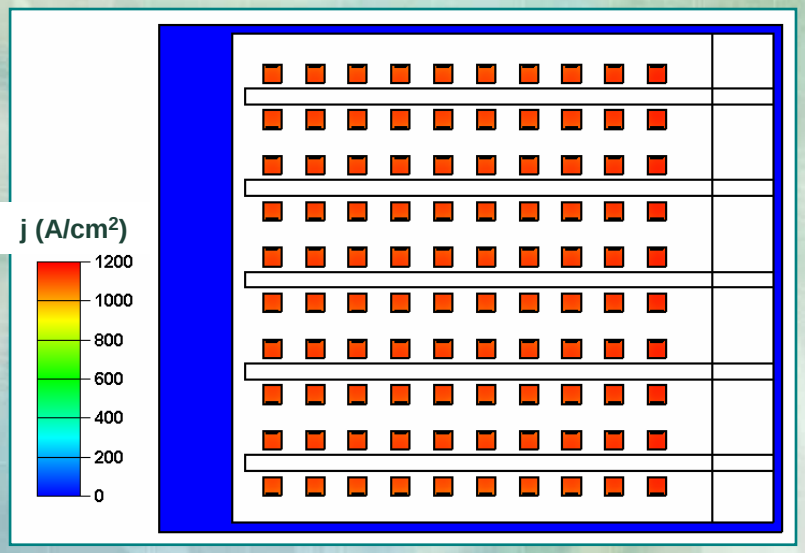
I = 500 mA

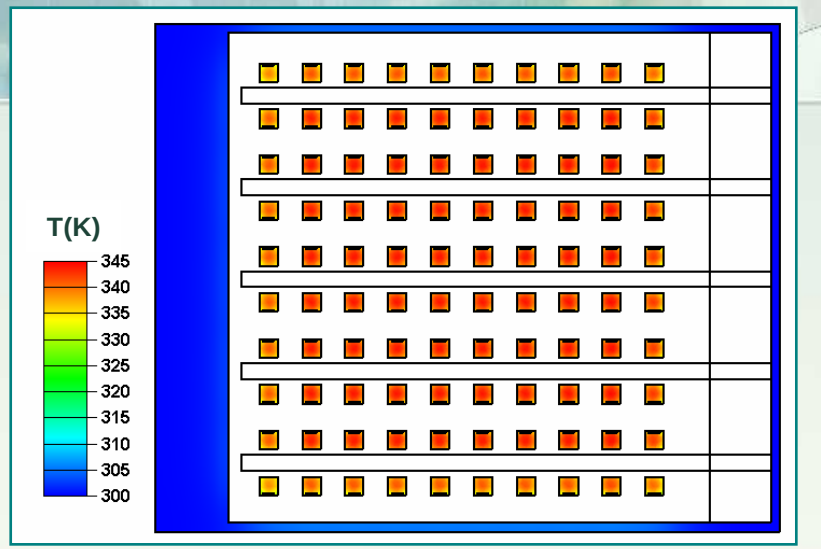
L_{sp}~ 70 μm

ΔT = 350 K



Current crowding in IMPA LED die and active region overheating





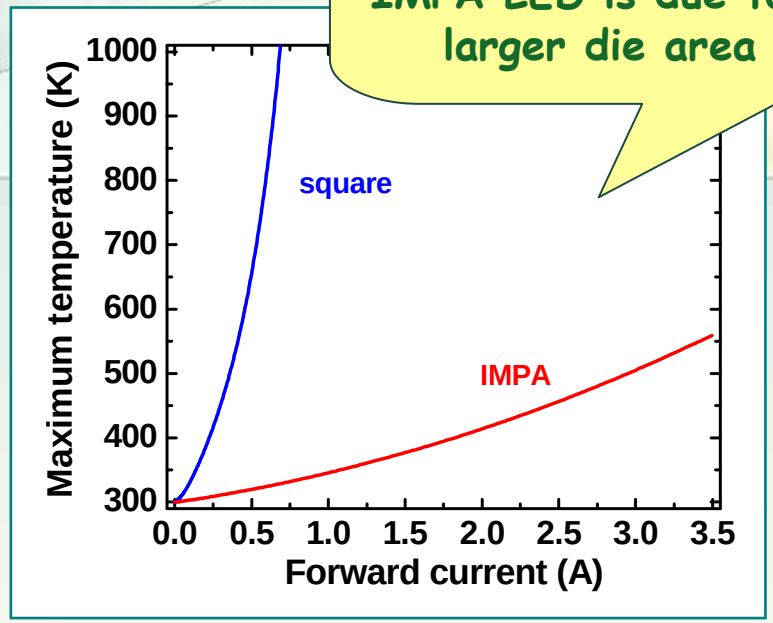
I = 1000 mA

L_{pix}= 30 μm

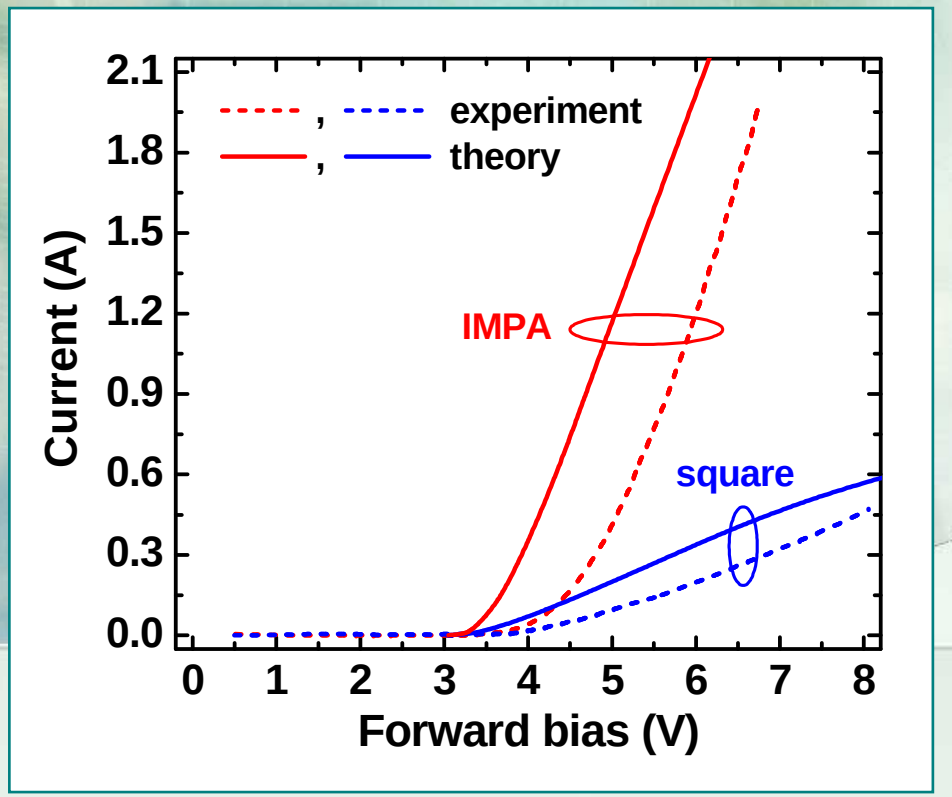
ΔT = 45 K

Extremely high current density (~1%) and temperature (~6%) uniformity is predicted

Much lower active region overheating of IMPA LED is due to a larger die area



Current-voltage characteristics



Series resistance (Ω)		
	Theory	Experiment
Square	7.2-9.5	8
IMPA	1.2	1

Excellent agreement between the predicted and measured series resistance

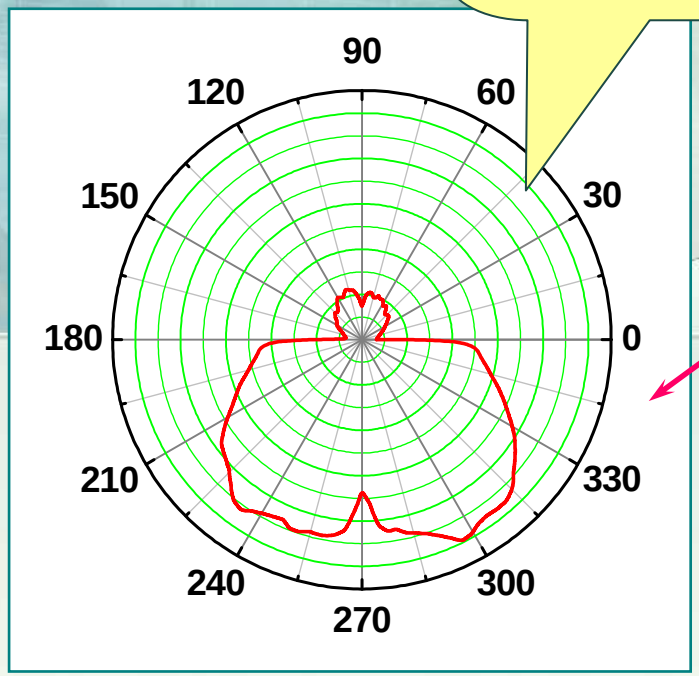
Discrepancy between the theoretical and measured turn-on voltage is attributed to non-ohmic behavior of p-contact.

$$R_{square} \approx (L_{sp}/\sigma d_c p)^{-1} = 7\,\Omega$$

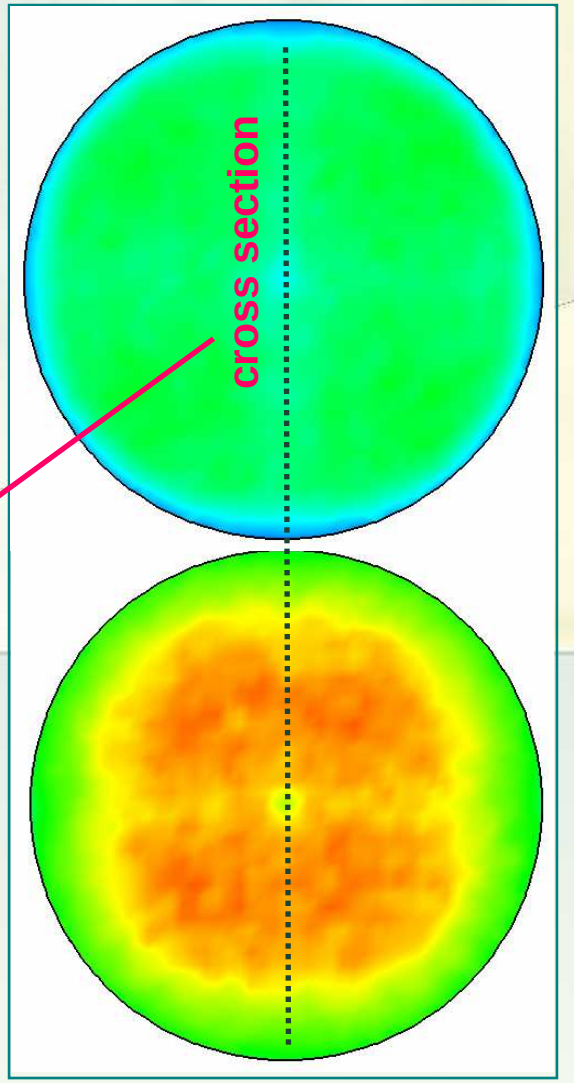
Ray-tracing simulation of light extraction from the dice

Top – 3%
Bottom – 6%
Side walls – 6%

20 million rays is used to generate a smooth far-field radiation pattern



far-field emission pattern

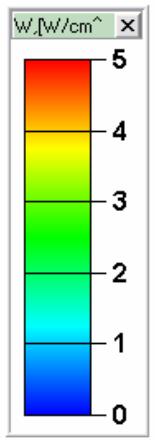


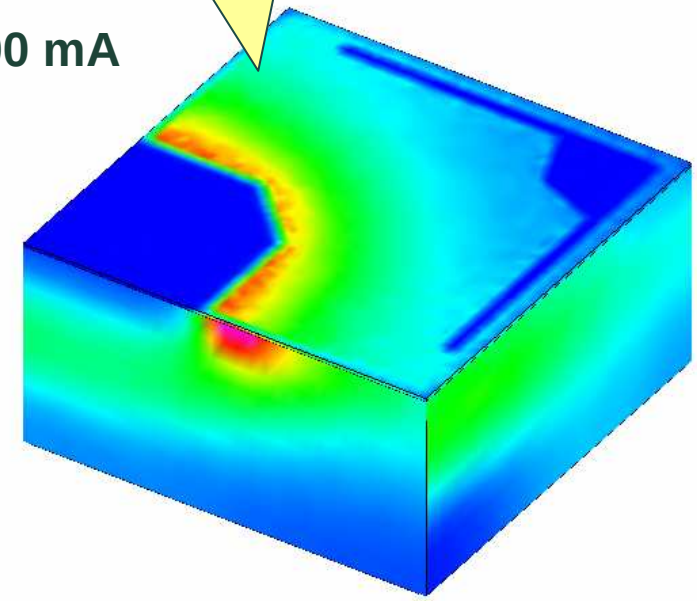
Light extraction from square LED die

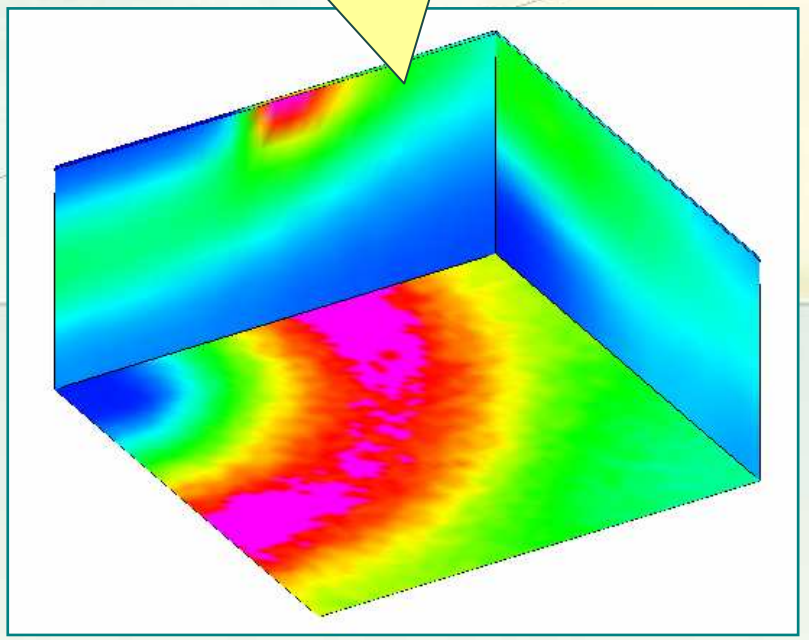
Non-uniform distribution of the optical power over the die surfaces

Wave-guiding resulted in strong light extraction through the side walls of sapphire substrate

I_F = 100 mA







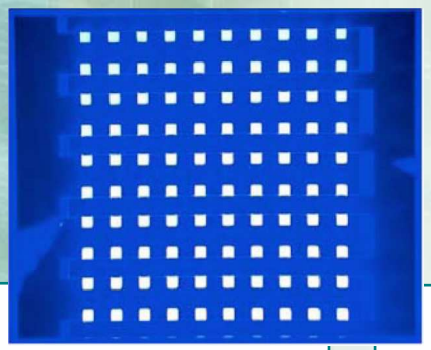
top view

bottom view

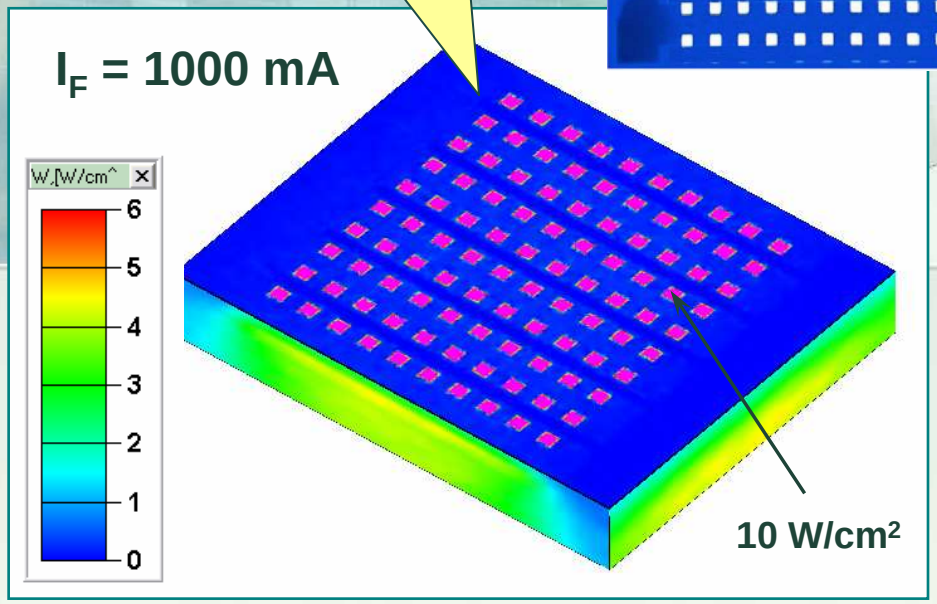
Light extraction from square LED die

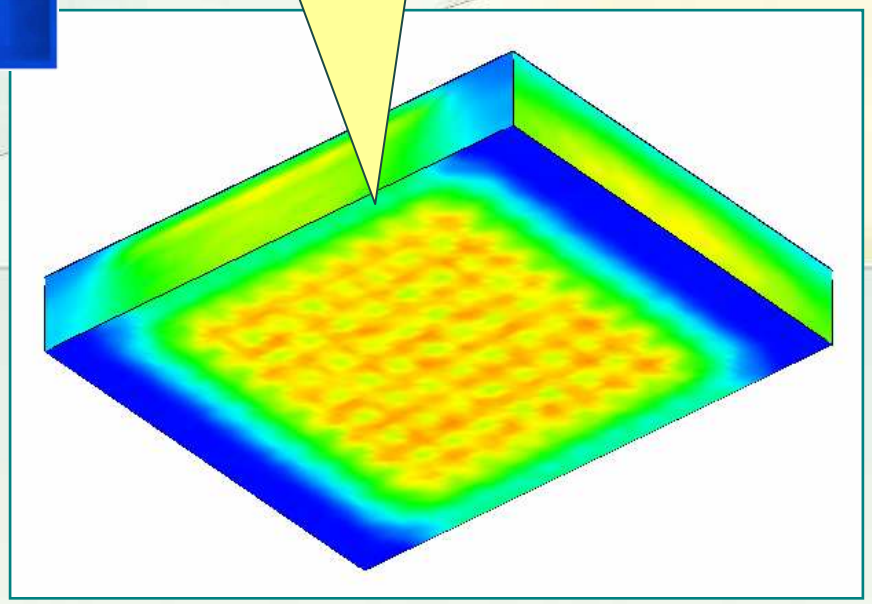
Very uniform distribution of the emission power among the pixels

experiment



Weak variation of emission intensity over the back sapphire substrate

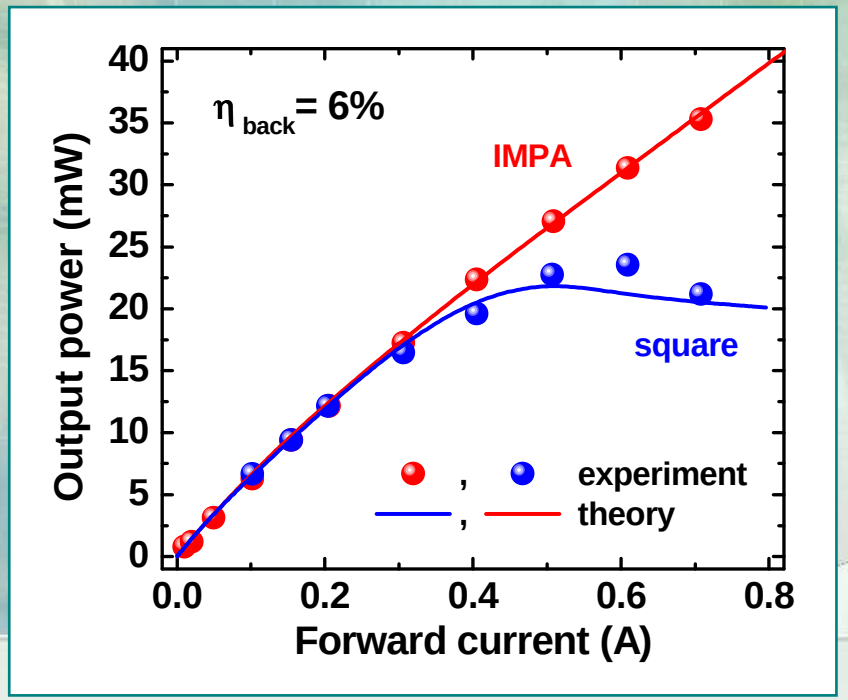


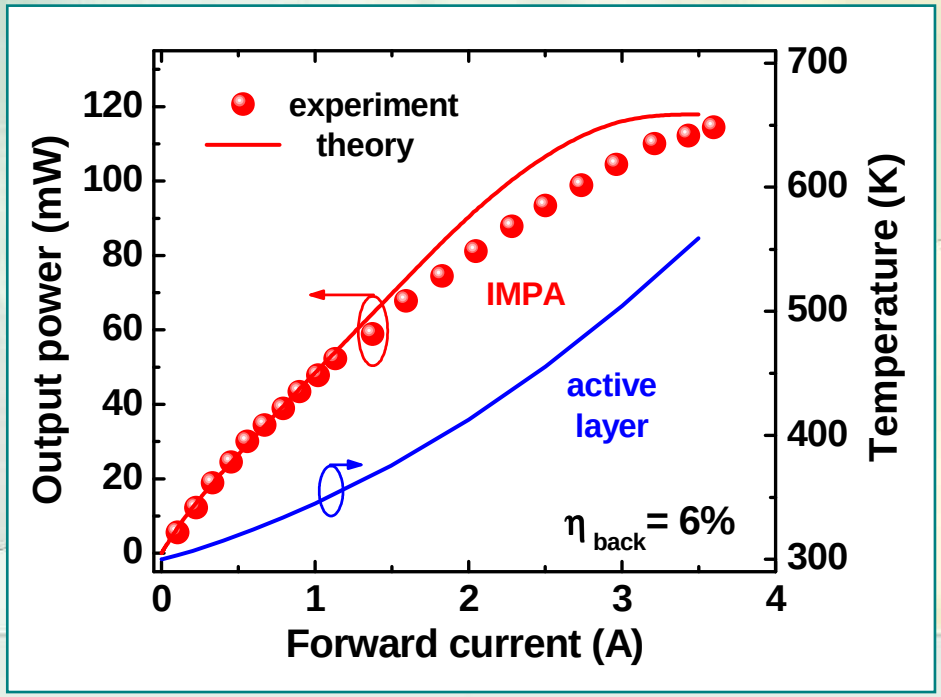


top view

bottom view

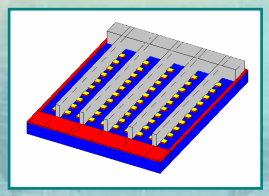
Output optical power as a function of current





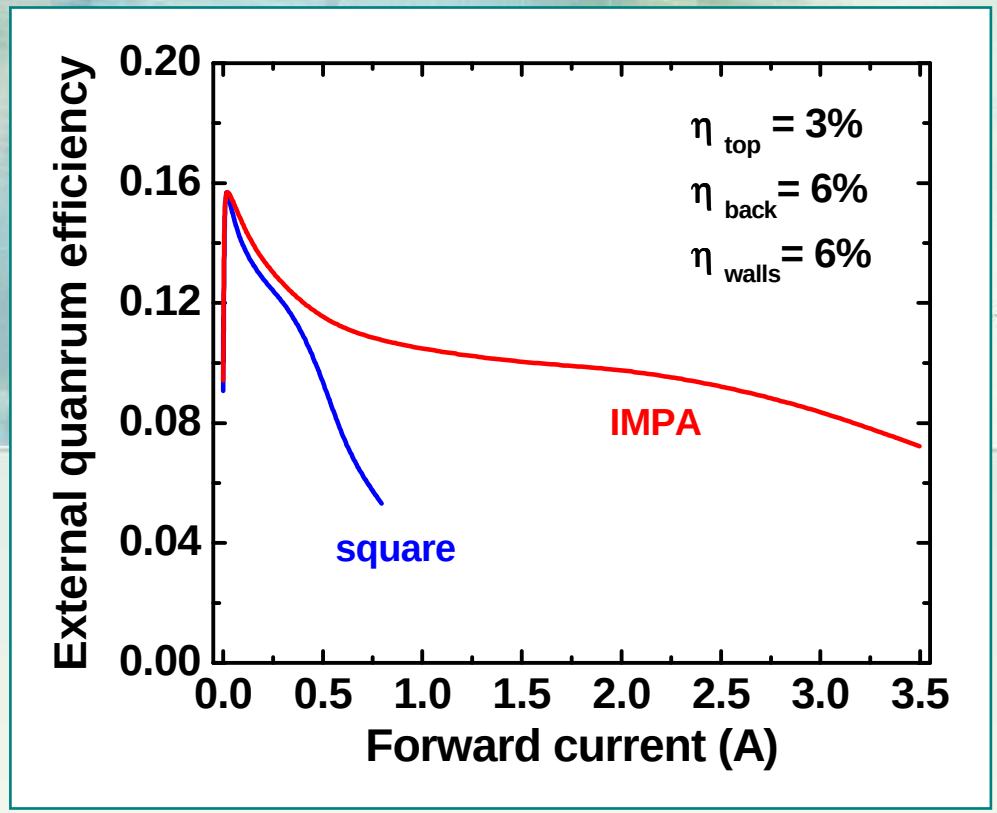
Deviation of the theoretical curve from experimental points may be caused by insufficiently accurate approximation of temperature-dependent materials parameters.

IMPA LED as a high-power light emitter



Advantages of using the IMPA die design:

- low series resistance
- suppression of current crowding
- a lower active region overheating due to a larger die area



IMPA LED is promising for high-power operation

Conclusions

- Coupled modeling of current spreading and heat transfer in III-nitride LED dice is critical for quantitative prediction of device characteristics
- Hybrid approach forms a good basis for every-day device engineering based on simulations
- IMPA die design allows considerable suppression of current crowding and reduction of LED series resistance
- IMPA die design provides good device performance for high-power operation conditions