Confidential

Simulation of micro-LEDs by STR's software

(general scaling trends)

February 2017

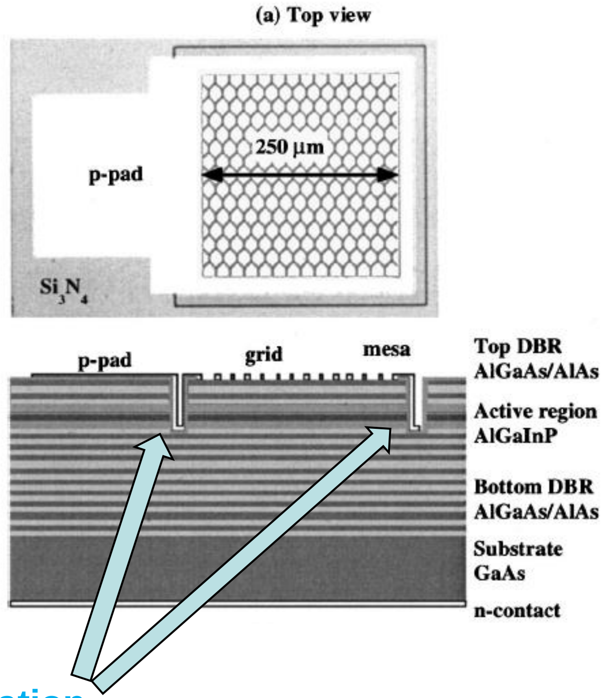
Outline

- Impact of surface recombination on the efficiency of large-size LEDs
- Scaling of LED dimensions towards μ-LEDs
  - external quantum efficiency (EQE) and shift of its maximum; (comparison) with experiment
  - current-voltage characteristics; comparison with experiment
  - size-dependent current crowding
  - LED self-heating
  - wall-plug efficiency (WPE): scaling with LED dimensions
  - electrical losses in the efficiency
- Comparison of scaling of InGaN-based (nitride) and AlInGaP-based (phosphide) LEDs

Surface recombination in large-size LEDs

Surface recombination effect on efficiency of red LEDs

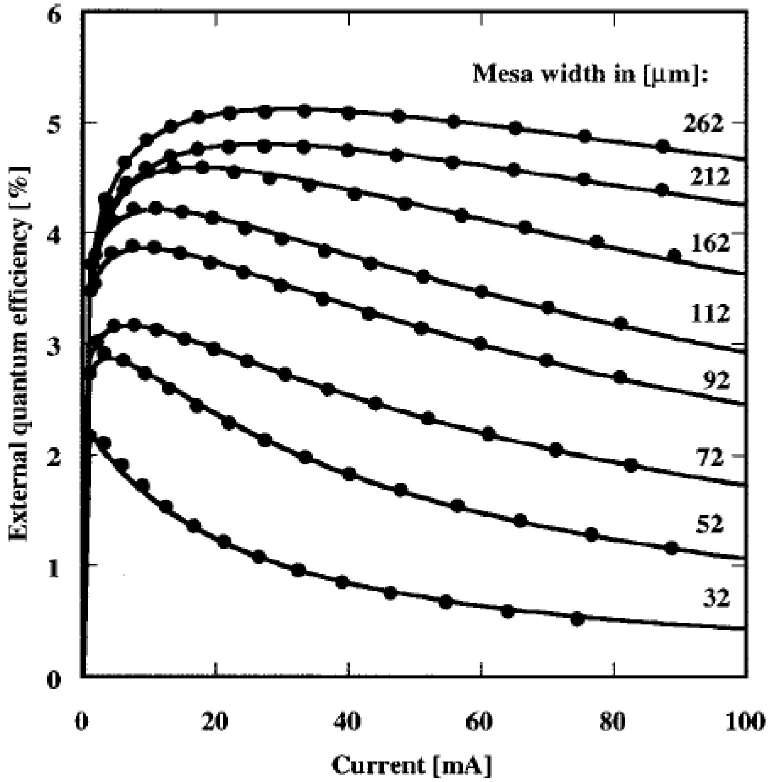
λ = 650 nm



recombination occurs at free surface of active region

surface recombination

surface recombination becomes a critical channel of the carrier losses at large active region perimeter (*P*) to area (*Σ*) ratio; it can be roughly characterized by equivalent non-radiative carrier lifetime $\tau_s \sim \Sigma/PS$ where *S* is the surface recombination velocity



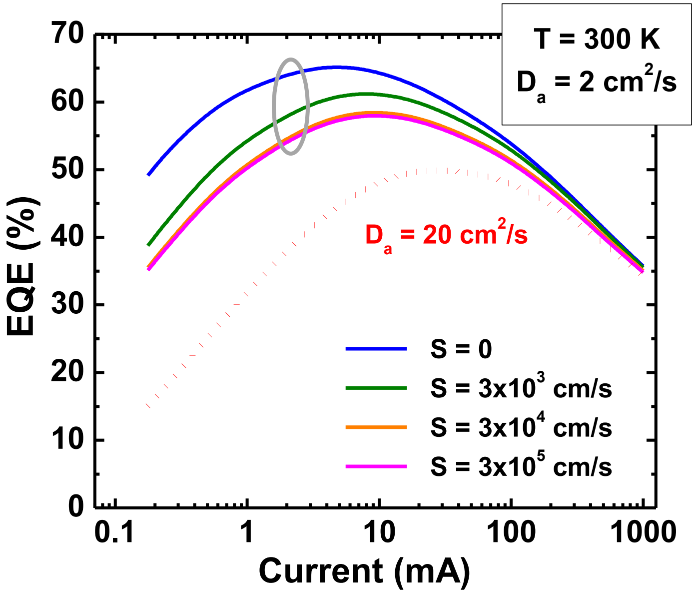
strong impact of surface recombination on LED efficiency and its decrease at high currents

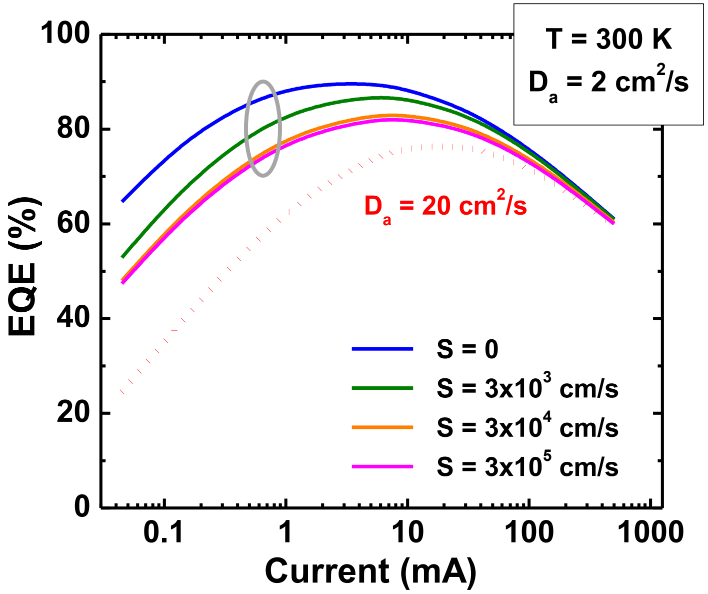
P. Royo et al., J. Appl. Phys. 91, 2563 (2002)

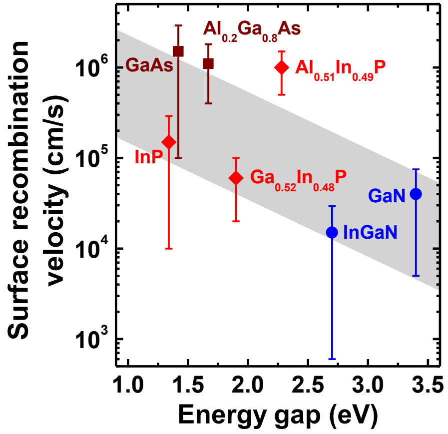
Surface recombination in nitride LEDs

factors affecting the rate of surface recombination:

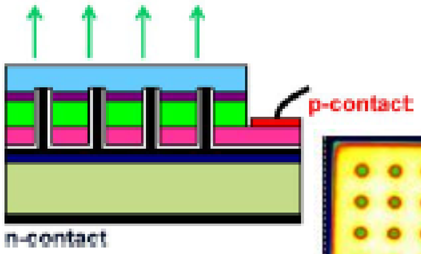
- ✓ recombination velocity
- ✓ P/Σ ratio
- ✓ diffusion length dependent on both ambipolar carrier diffusivity and their differential life time



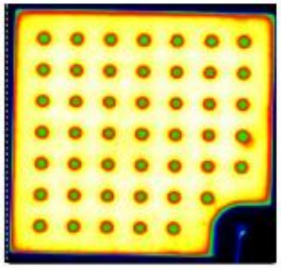




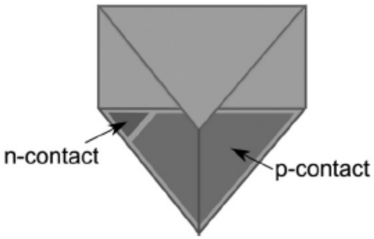
InGaN: S~10^2-10^6 cm/s



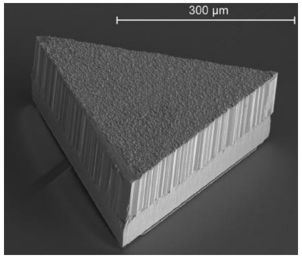
UX:3 chip



A. Laubsch et al., IEEE Trans. Electron. Dev. 57, 79 (2010)



triangular volumetric chip



C. A. Hurni et al., Appl. Phys. Lett. 106, 031101 (2015)

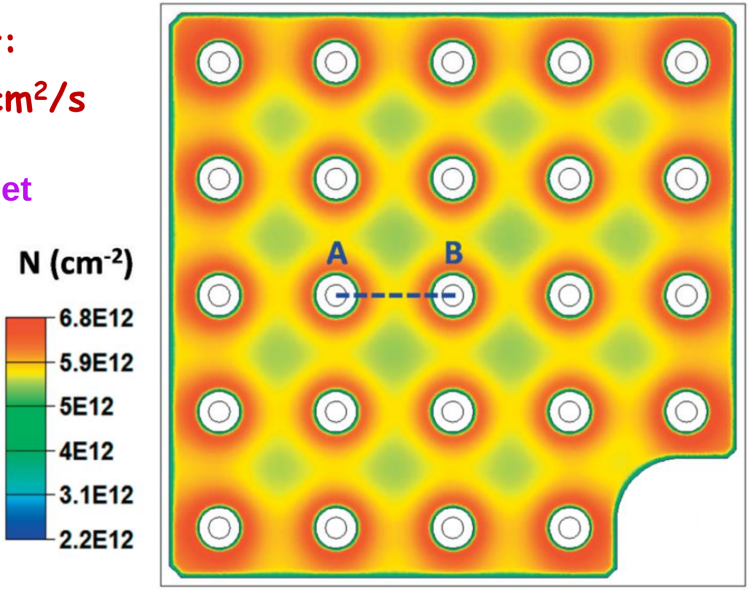
Impact of carrier diffusion length on surface recombination in nitride LEDs

Experiment:

$D_a = 0.5\text{-}2.5\ \mathrm{cm^2/s}$

green violet

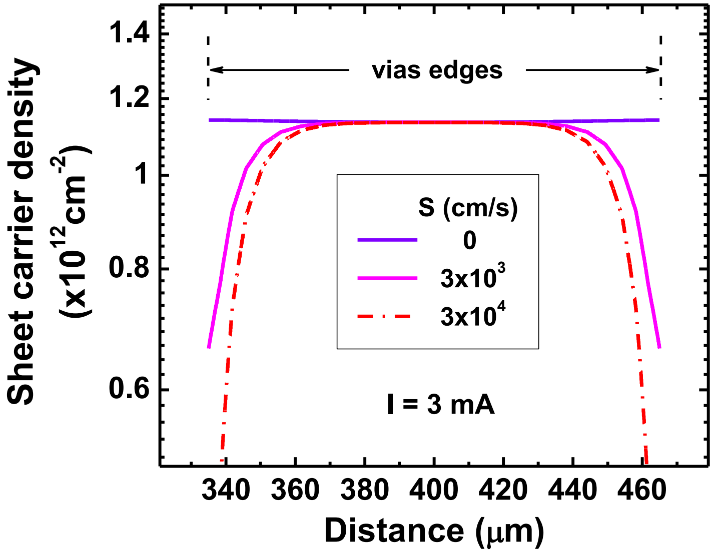
I = 100 mA

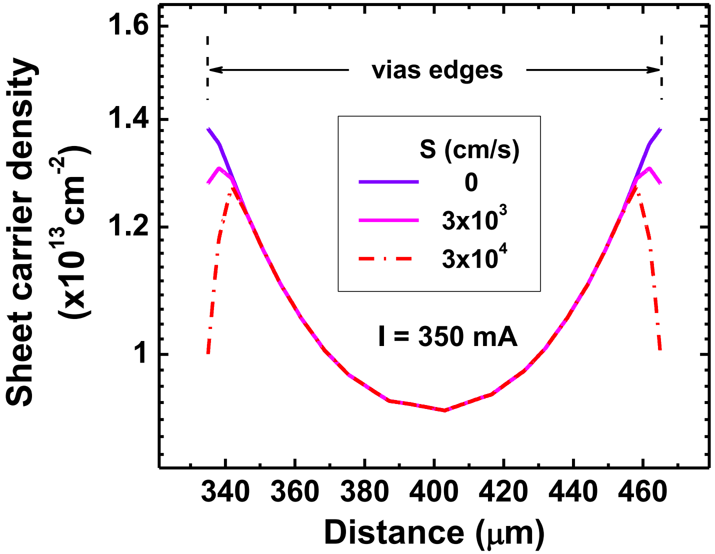


due to a high carrier concentration on the active region of nitride LEDs, the "dead" region adjacent to the free active region surface varies from ~ 20 μm at low currents to less than ~5-10 μm at high currents

μ-LEDs with lateral sizes < 10-20 μm are expected to suffer from the carrier losses caused by surface recombination

http://www.str-soft.com/products/SimuLED/index.htm



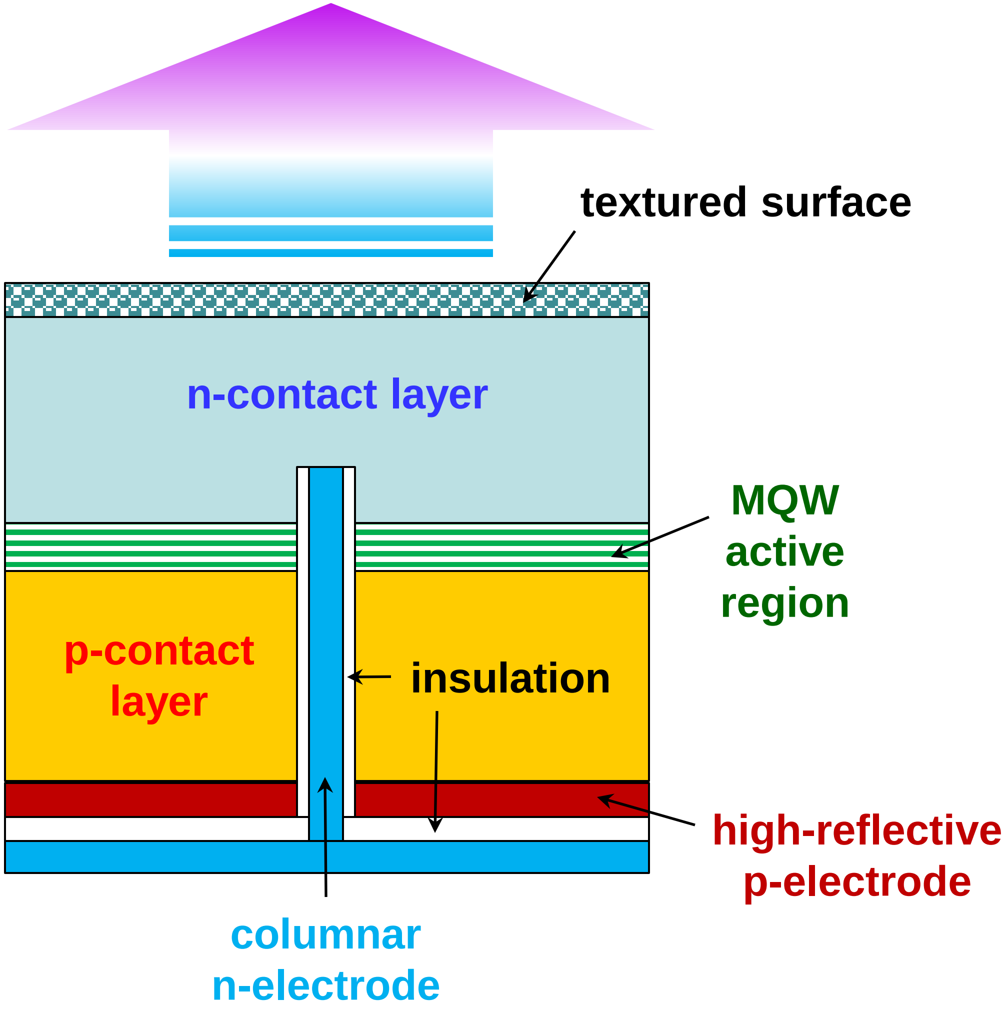


Critical factors for surface recombination impact on LED performance

- ✓ carrier life time in the active region is the primary factor determining the carrier diffusion length in the active region; ambipolar carrier diffusivity and surface recombination velocity affect much weakly the diffusion length
- ✓ the carrier life time becomes shorter with the carrier concentration; therefore, the relative contribution of surface recombination to the carrier losses becomes lower at high current densities
- ✓ optimization of the LED chip design should be aimed not only at improvement of light extraction efficiency but at suppression of surface recombination as well
- ✓ passivation of free active region surfaces is an important approach for diminishing the carrier losses caused by surface recombination

Scaling trends towards μ-LEDs

Schematic design of LED dice assumed in simulations



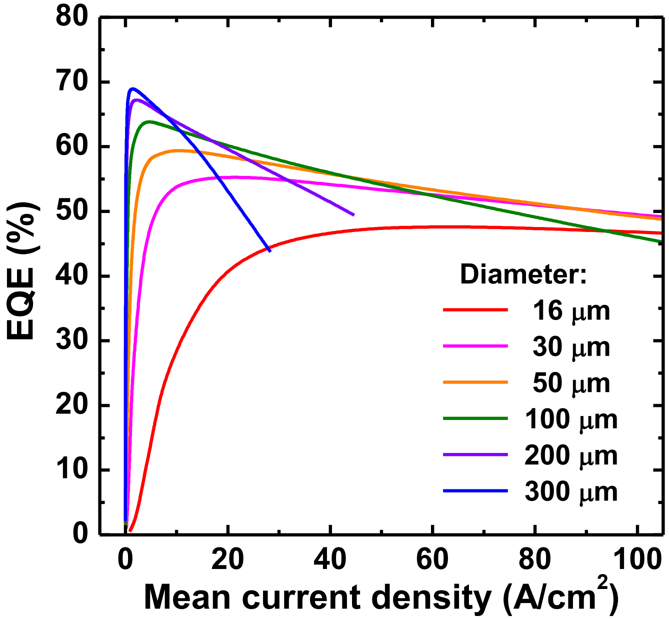
- ✓ MQW blue (440 nm) LED structure
- ✓ circularly-shaped LED dice
- ✓ outer diameter of etched aperture – 10 μm
- ✓ outer diameter of the LED die: varied from 16 μm to 300 μm
- ✓ both n- and p-contact resistances of 3×10^{-4} Ω·cm^2
- ✓ light extraction to an immersion medium with the refractive index of 1.5

self-consistent electrical / thermal / optical simulations

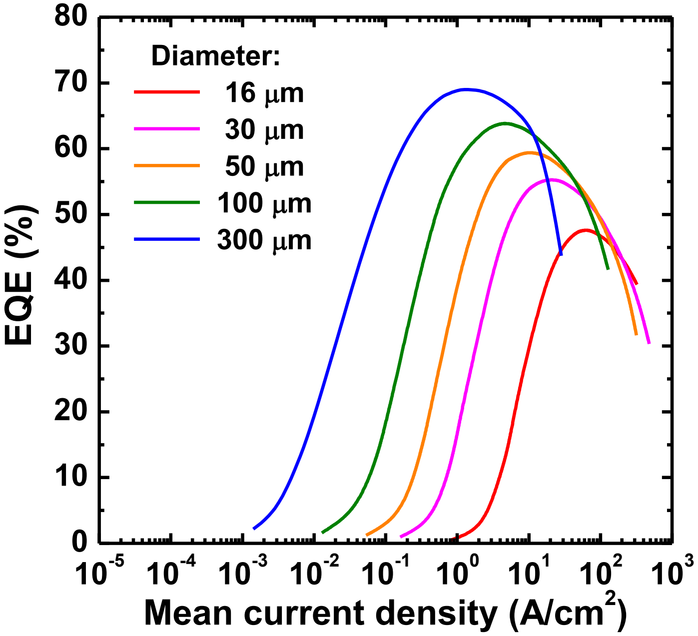
External quantum efficiency (EQE) of the LEDs

to compare LEDs of different dimensions, their efficiencies are plotted versus mean current density

linear scale

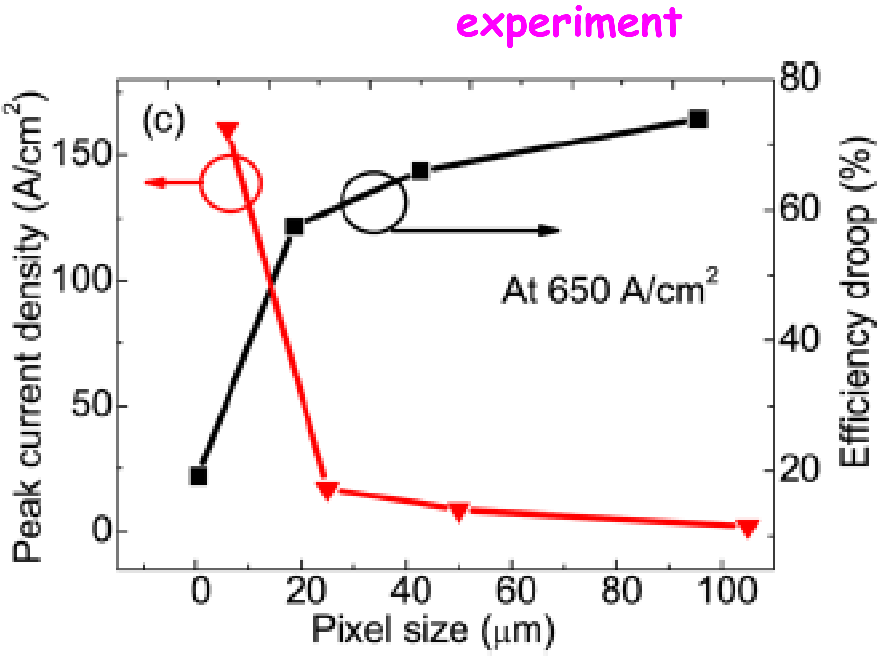


logarithmic scale

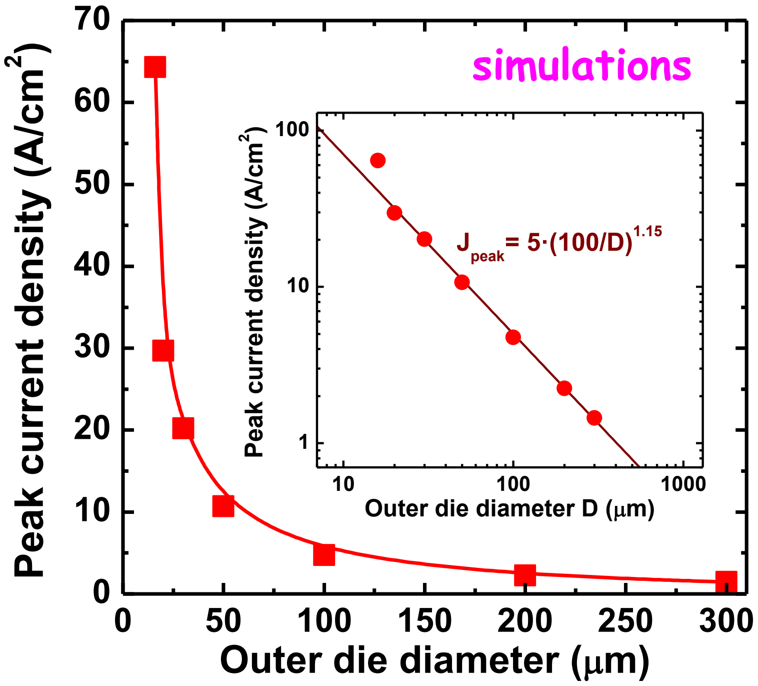


- ✓ strong shift of the EQE maximum towards higher current densities with decreasing LED size and decreasing of the efficiency droop
- ✓ at the current densities j < 10 A/cm^2, large-size LEDs are found to be most efficient
- ✓ at 10 A/cm^2 < j < 100 A/cm^2, there is a non-monotonous dependence of EQE on the LED die dimension (!)
- ✓ at j > 100 A/cm^2, the smallest-size LEDs are predicted to be most efficient

Current density corresponding to the EQE peak: comparison with experiment



P. Tian et al., Appl. Phys. Lett. 101, 231110 (2012)

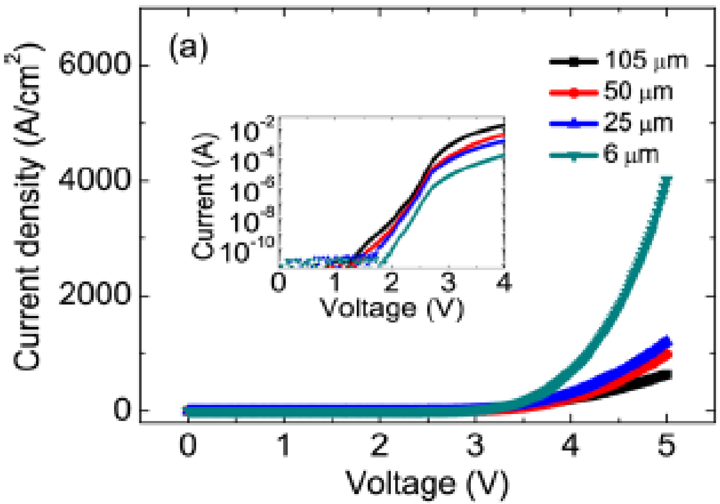


simulations reproduce also the experimental trend of increase in current density corresponding to the EQE peak with decreasing dimensions of the LED dice

the simulated dependence of the peak current density on the outer LED die diameter can be well approximated by an inverse power-like function, except for extremely small sizes

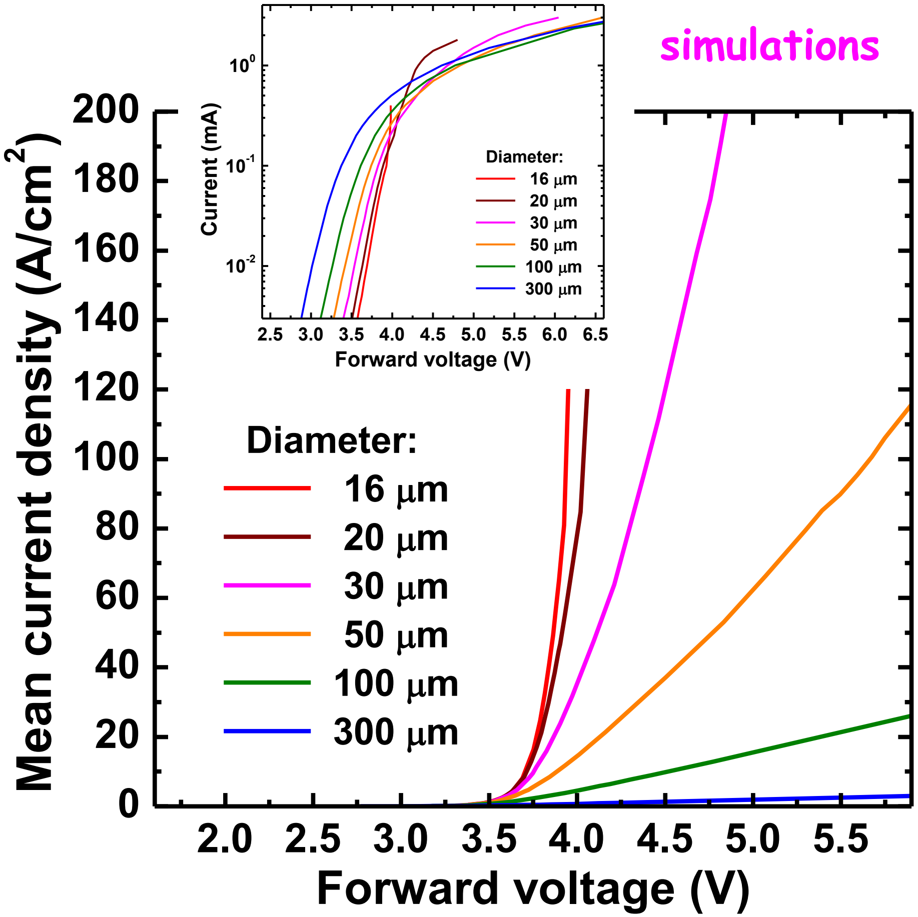
Scaling effect on current-voltage characteristics

experiment



P. Tian et al., Appl. Phys. Lett. 101, 231110 (2012)

simulations



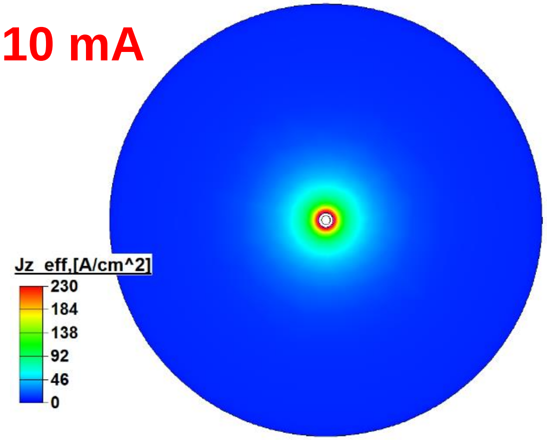
general scaling trends in current-voltage and current density-voltage characteristics predicted by simulations agree well with available observations

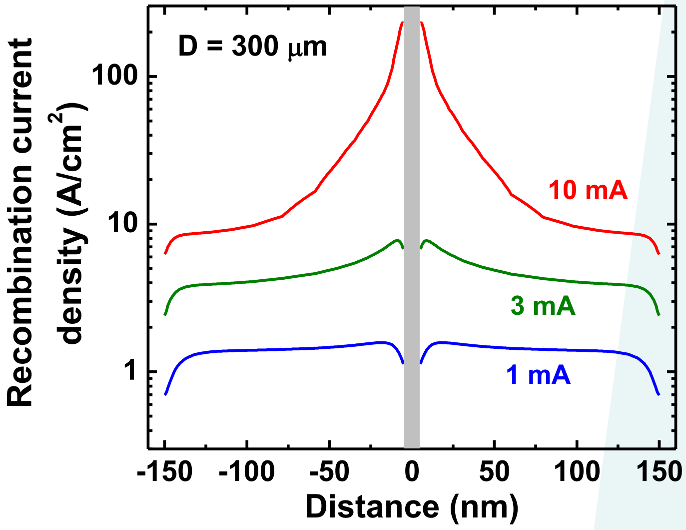
size-dependent current crowding is one of the most important factors that control the current/current density-voltage characteristics of μ-LEDs

Size-dependent current crowding

LED with D = 300 µm

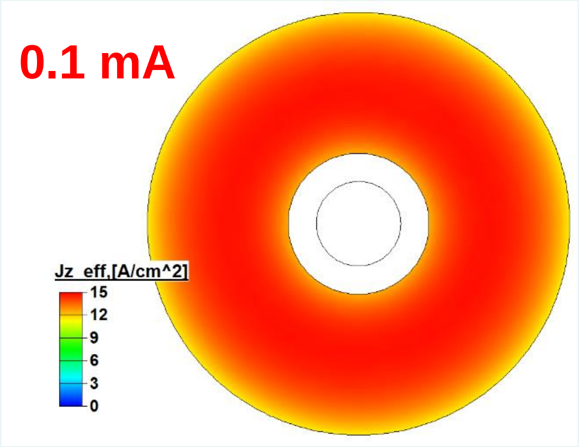
10 mA



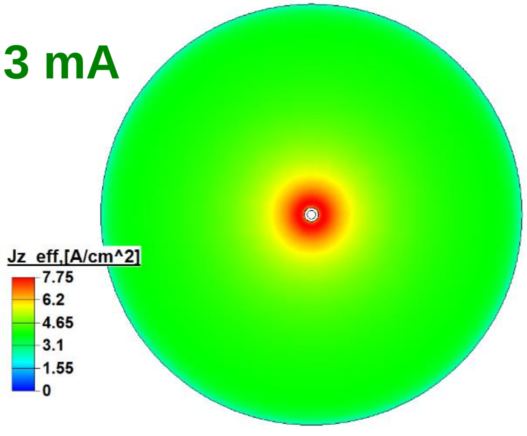


LED with D = 30 µm

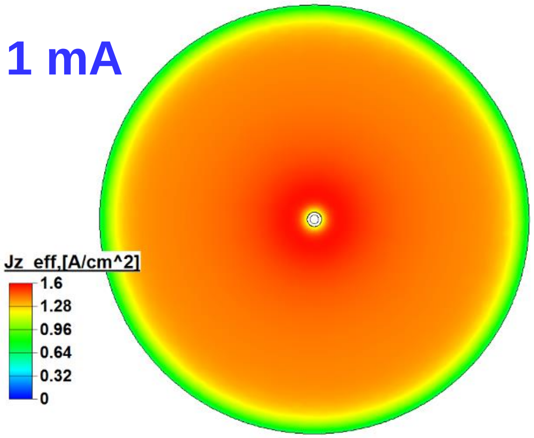
0.1 mA

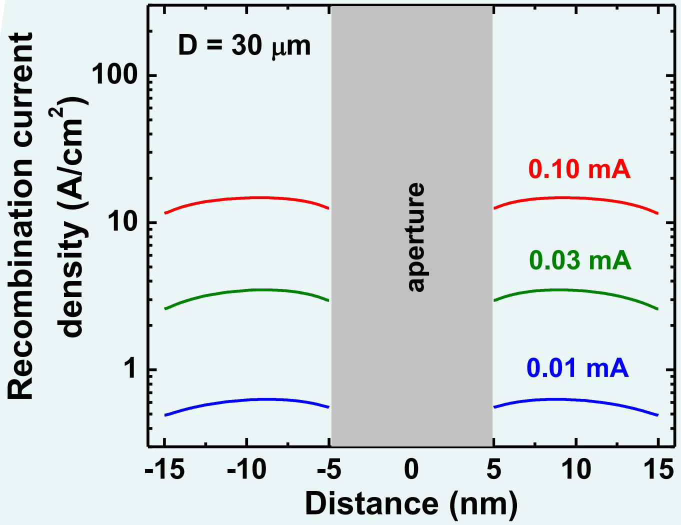


3 mA



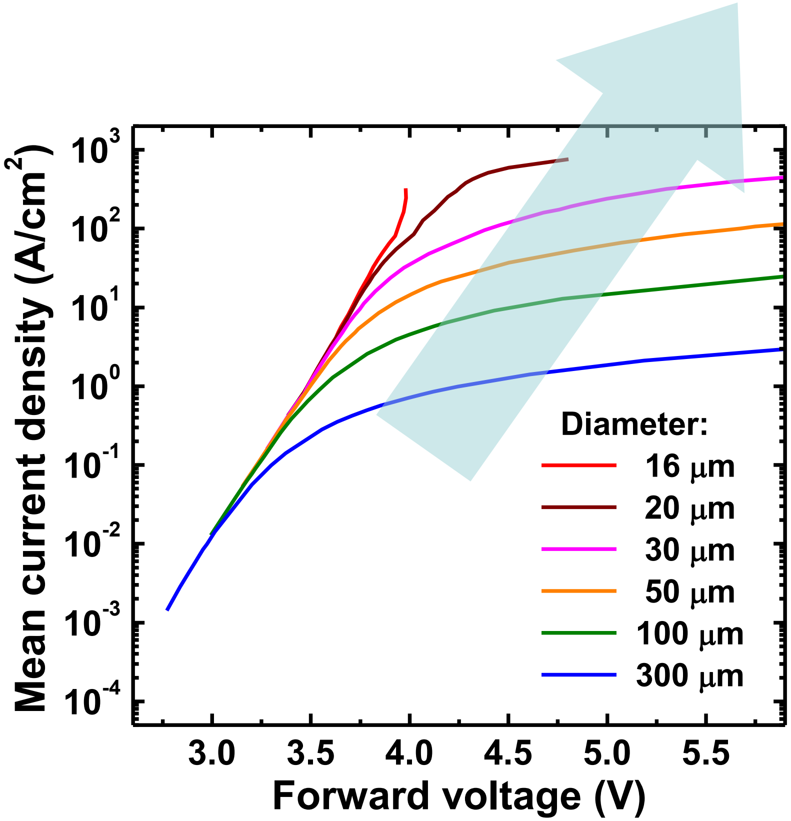
1 mA

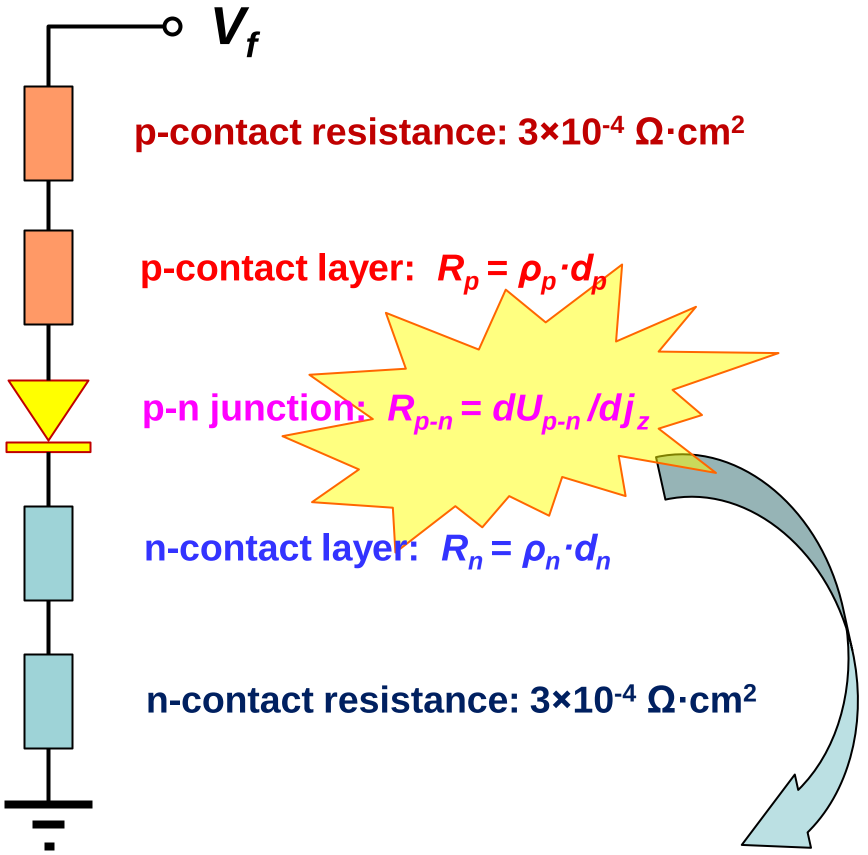




Decrease of μ-LED series resistance due to current crowding suppression

decrease of specific series resistance at smaller LED size





p-contact resistance: 3×10^{-4} Ω·cm^2

p-contact layer: $R_p = \rho_p \cdot d_p$

p-n junction: $R_{p\text{-}n} = dU_{p\text{-}n} / dj_z$

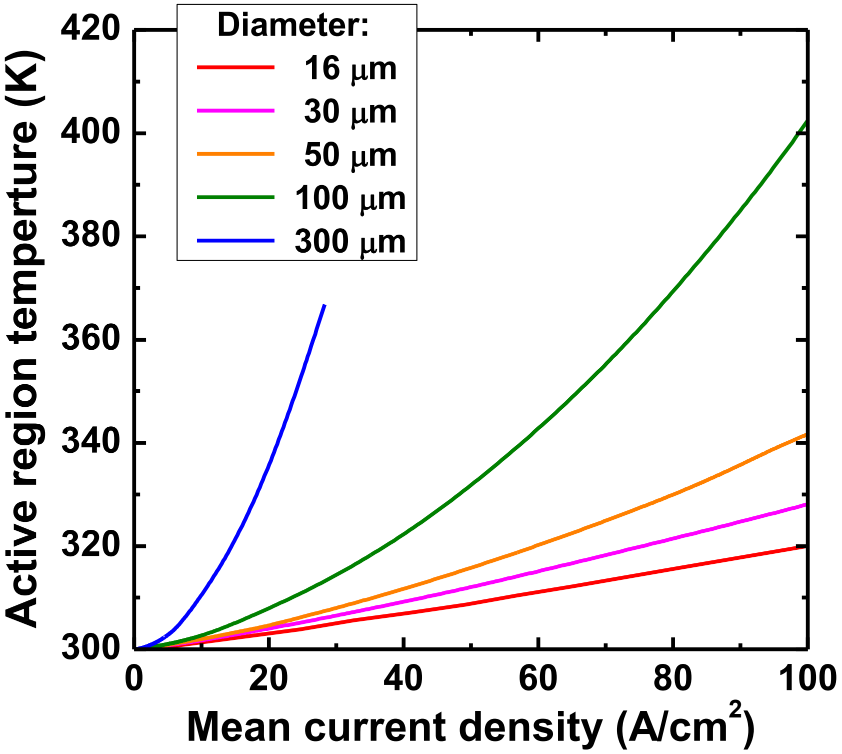
n-contact layer: $R_n = \rho_n \cdot d_n$

n-contact resistance: 3×10^{-4} Ω·cm^2

decrease of specific series resistance is caused by a more uniform current spreading inside the LED die, resulting in lowering the p-n junction non-linear resistance

LED self-heating: effect of current crowding

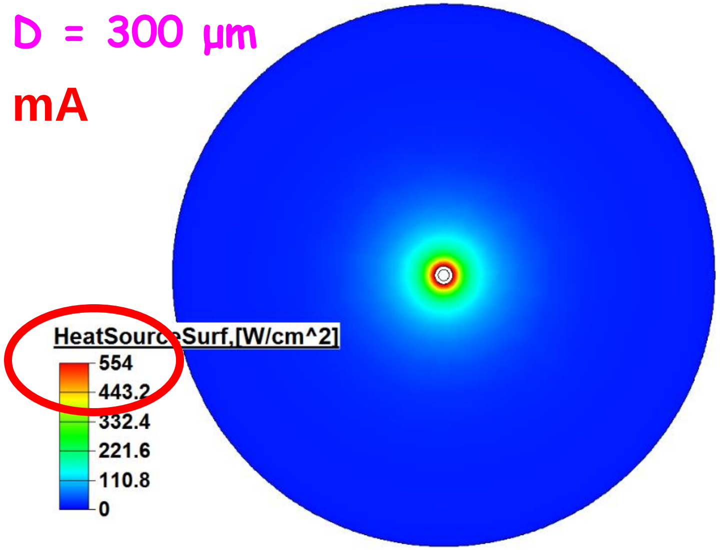
more uniform current spreading due to suppressed current crowding results in lower device self-heating, which is an advantage of µ-LEDs



LED with D = 300 µm

10 mA

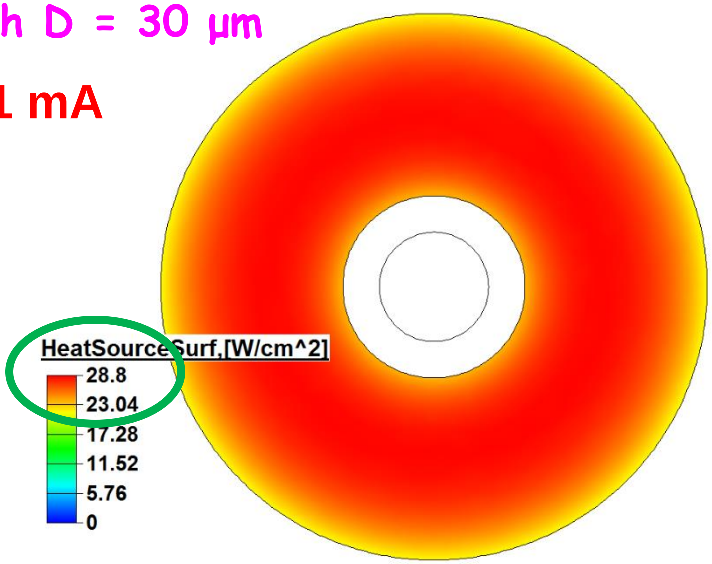
!



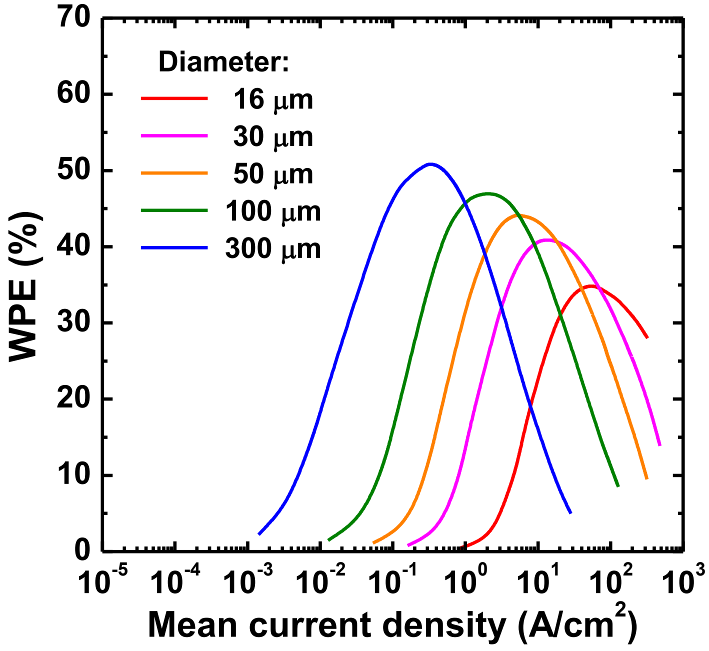
LED with D = 30 µm

0.1 mA

!!

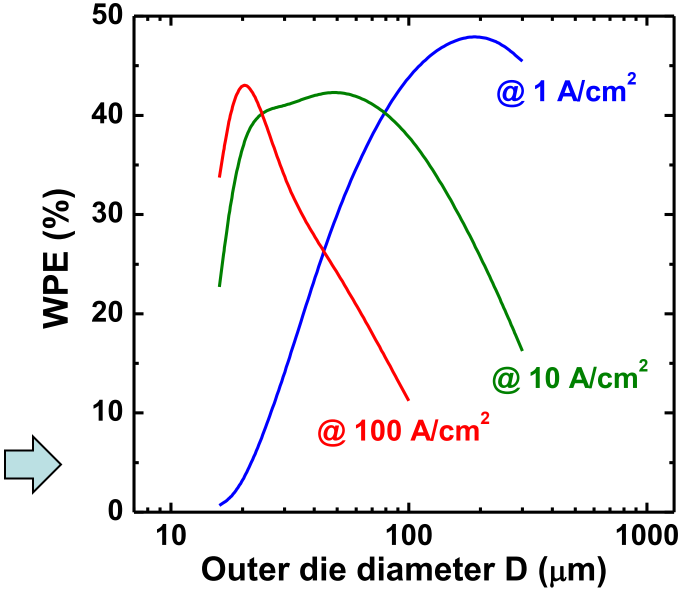


Wall-plug efficiency (WPE) of the LEDs



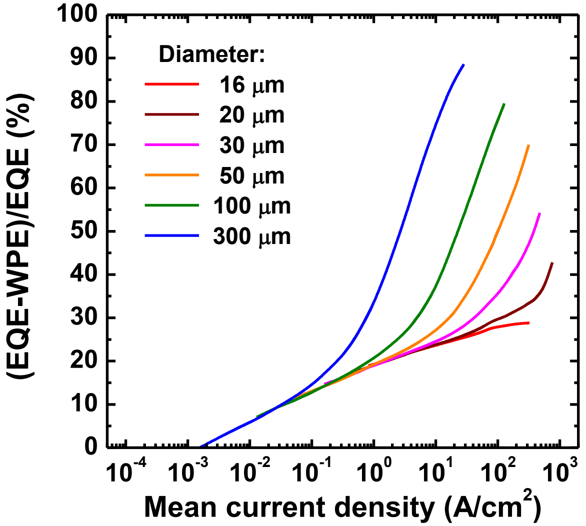
non-monotonous WPE dependence on the LED die dimension

optimal LED size and operating current density are interrelated with each other !



electrical losses in LED efficiency may be characterized by the parameter (EQE-WPE) / EQE ;

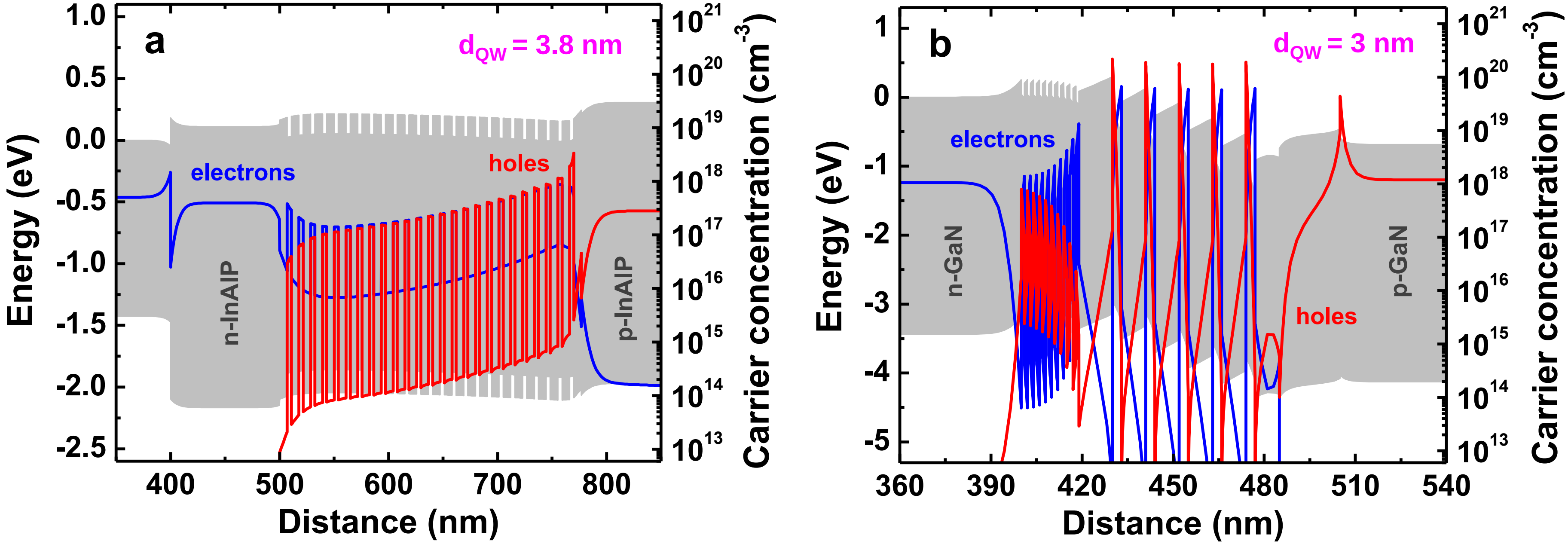
dramatic increase of the losses in large-size LEDs originates from the current crowding, which is considerably suppressed in μ-LEDs



Comparison of InGaN-based and AlInGaP-based LEDs

Carrier concentrations in nitride and phosphide LEDs

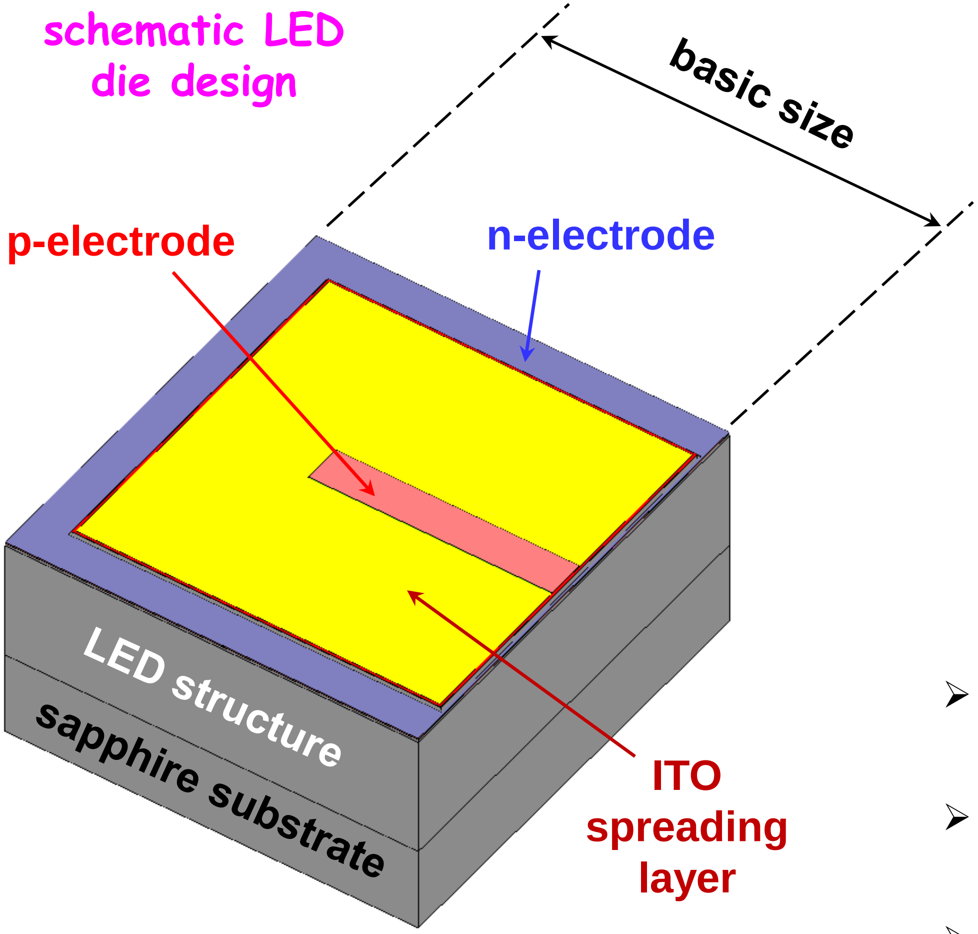
simulation of AlGaInP (a) and InGaN (b) LED structures operating at the current density of 40 A/cm^2



at the same current density, non-equilibrium carrier concentration in the active region of nitride LEDs is ~1-2 orders of magnitude higher than that in phosphide ones, which is caused by different materials properties: carrier mobilities, band offsets, recombination constants, etc.

this results in considerably longer carrier life time in phosphide LEDs

Comparison of nitride and phosphide LEDs



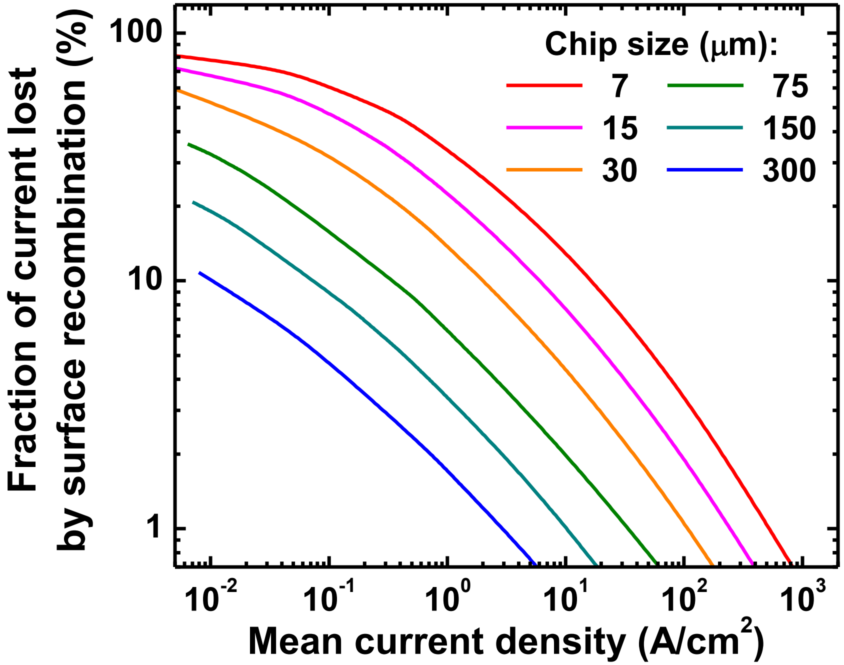
- ✓ MQW blue (450 nm) and red (620 nm) LED structures
- ✓ square-shaped LED dice with all scalable dimensions
- ✓ square side length: varied from 7 µm to 300 µm
- ✓ light extraction to air (no approaches to increase light extraction efficiency)

<u>Simulation approach:</u>

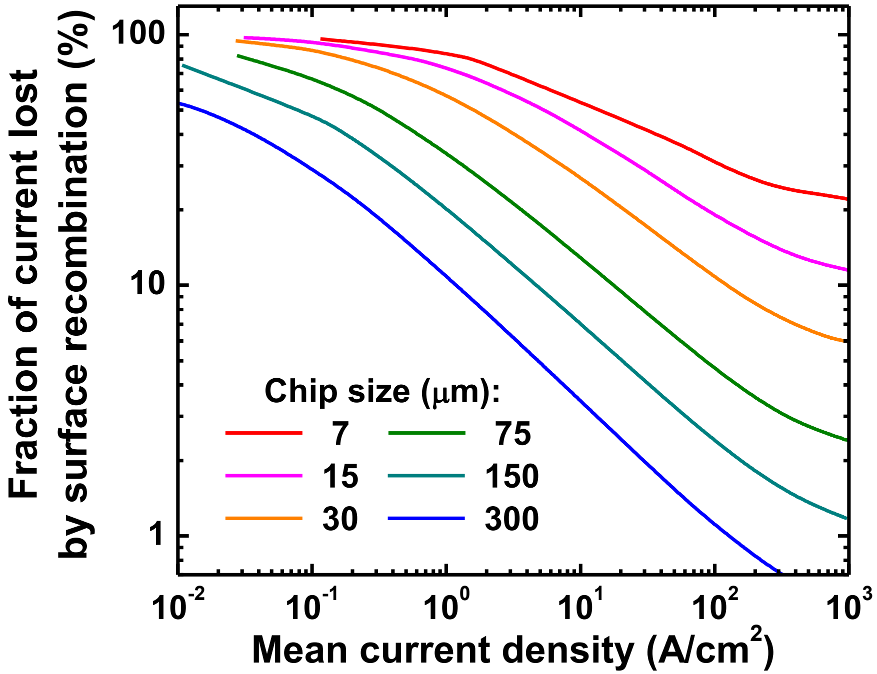
- ➢ **ambipolar diffusivity: 2 cm^2/s for blue and 20 cm^2/s for red LEDs**
- ➢ **surface recombination velocity: 10^3 cm/s for blue and 10^5 cm/s for red LEDs**
- ➢ **no heat transfer taken into account**

Carrier losses caused by surface recombination

nitride LED

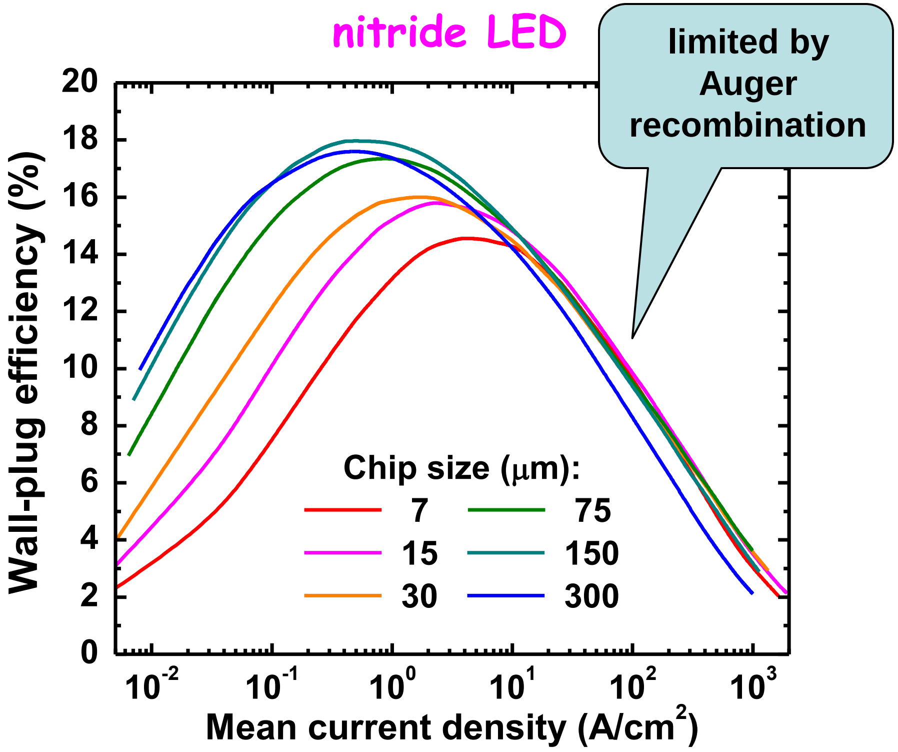


phosphide LED



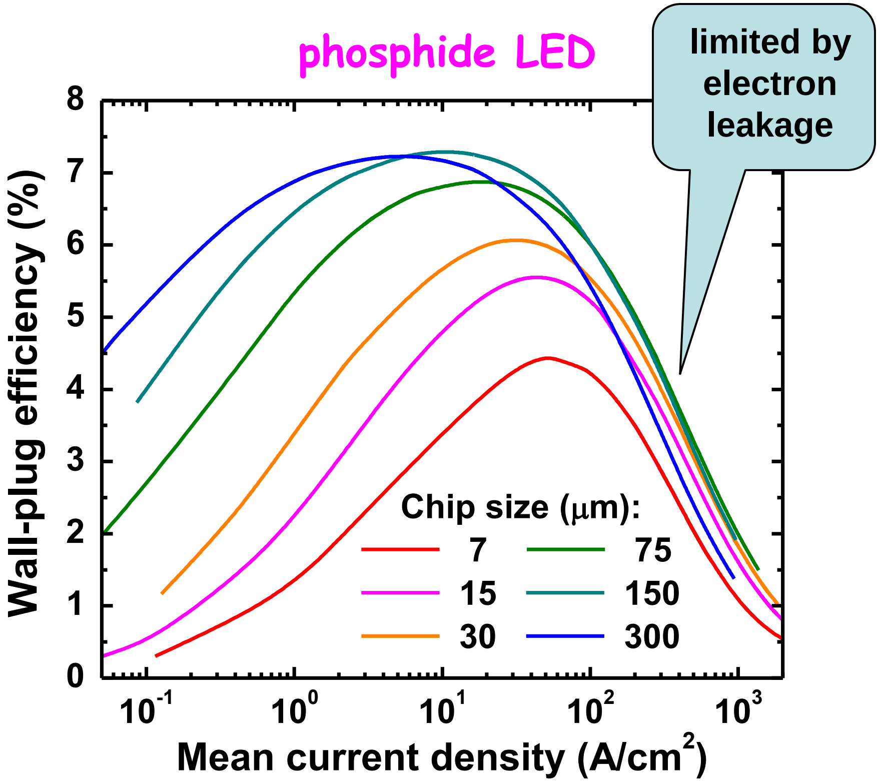
because of higher carrier diffusivity and surface recombination velocity and longer carrier life time the carrier losses originated from surface recombination are much higher in phosphide LEDs compared to nitride ones; the losses become generally reduced at high current densities due to life time shortening

The use of strain-compensated structures for green/yellow LEDs



nitride LED

limited by Auger recombination



phosphide LED

limited by electron leakage

stronger impact of surface recombination leads to remarkable reduction of the LED efficiency (both EQE and WPE) in small-size phosphide devices; this implies that more careful chip design is required for phosphide LEDs aimed at both surface recombination suppression and light extraction efficiency improvement

Conclusions

- ✓ Current crowding, surface recombination, device self-heating, and Auger recombination are principle important mechanisms limiting efficiency of μ-LEDs
- ✓ Interplay of the mechanisms determines specific features of μ-LED operation: shift of EQE and WPE peaks to higher current densities, current-voltage characteristics, non-monotonous efficiency dependence on the LED die dimensions, active region temperature, etc. In some aspects, μ-LEDs may become advantageous over large-size LEDs.
- ✓ Different impact of surface recombination on performance of InGaN-based and AlInGaP-based LEDs originates from different materials properties of the alloys
- ✓ Careful optimization of the μ-LED chip design is necessary aimed at both suppression of surface recombination and increase of light extraction efficiency