SURFACE RECOMBINATION IMPACT ON PERFORMANCE OF HIGH-POWER LIGHT-EMITTING DIODES

Kirill A. Bulashevich and Sergey Yu. Karpov
STR Group – Soft-Impact, Ltd. St.Petersburg, Russia

The paper considers surface recombination at the edge of the active region as the mechanism of carrier losses which has not yet been discussed with regard to III-nitride LEDs despite of its evident importance for AlGaInP-based light emitters. Neglecting surface recombination is, in part, due to the fact that nitride materials possess minimal surface recombination velocity among all III-V compounds. On the other hand, most of III-nitride LEDs have a one-side contact geometry with a mesa etched through the active region of the LED structure. Because of the current crowding occurring just next to the mesa edge, the impact of surface recombination may become important for nitride LEDs too. In the absence of experimental information on the role of surface recombination, we have carried out simulation study of its impact on performance of high-power LEDs.

The advanced 1×1 mm^2 thin-film chip design similar to that of the UX:3$^{\mathrm{TM}}$ fabricated by Osram OS [1] is chosen as a representative case. In this chip, silver-based electrodes were formed to the p-contact layer of the LED structure, after removing the sapphire substrate the back surface of the n-contact layer was textured to increase the efficiency of light extraction from the LED, and the current access to the n-contact layer was provided by metallic column electrodes passing through blind vias etched through the structure up to the n-contact layer (see [1] for more details of the chip design). Here, we consider a blue LED emitting at 450 nm and providing the efficiency of light extraction of 82% to an epoxy encapsulant [2]. Modelling of the LED operation has been carried out with commercial SimuLED package [3], modified in such a way, as to account for the ambipolar carrier transport in the LED active region and surface recombination at its perimeter.

3D simulations have been carried out for room temperature and realistic carrier diffusivity in the InGaN active region $D = 2$ cm^2/s. Because of experimental uncertainty in the surface recombination velocity S , its value was varied between 0 and 3×10^5 cm/s. The simulations predict the maximum wall-plug efficiency (maximum external quantum efficiency) to decrease by ~12% (10%) because of surface recombination even at a rather low $S = 3\times10^3$ cm/s. Higher values of S decrease these maxima further, although the difference between the results obtained at $S = 3\times10^4$ and 3×10^5 cm/s becomes negligible. At high operating currents, the surface recombination produces relatively lower efficiency losses: ~2-6% at 350 mA and ~1-5% at 700 mA, depending on the value of surface recombination velocity assumed. Such losses are, nevertheless, important in view of the battle for every additional percent of the emission efficiency in state-of-the-art LEDs.

Except for the recombination velocity, one more critical parameter controlling the losses induced by surface recombination is the carrier diffusivity in the active region. Due to a low carrier mobility in InGaN alloys and a relatively short recombination time, decreasing with operating current, the diffusion length of carriers is of a few microns, which is much smaller than specific size of the chip design (here, that is a distance between the vias of ~130 μm). The small diffusion length reduces the losses related to surface recombination. Simulations made with hypothetical diffusivity of 20 cm^2/s typical for conventional III-V compounds predict considerable decrease in the LED emission efficiency attributed to increasing carrier diffusion length. Accounting for this result, we conclude that surface recombination should be especially pronounced in multi-pixel LEDs with small specific size, near-UV LEDs with undoped GaN active region exhibiting high carrier diffusivity, and deep-UV LEDs where high surface recombination velocity is expected because of the presence of aluminum in the active region of the devices.

REFERENCES:

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[2] S. Yu. Karpov et al., Phys. Status Solidi RRL **9**, 312–316 (2015)
[3] http://www.str-soft.com/products/SimuLED/index.htm

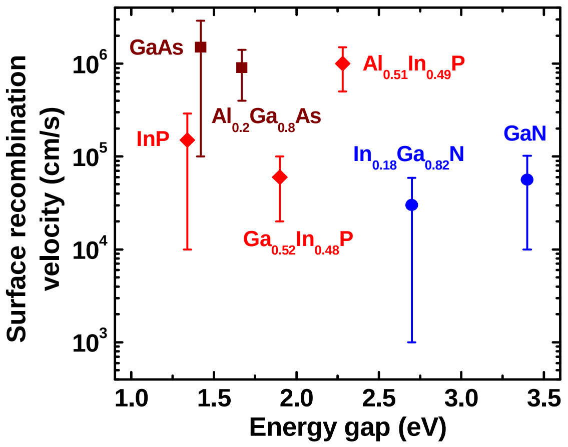

Figure 1 Experimental surface recombination velocities of III-V compounds used as active regions (GaAs, GaInP, and InGaN) and barriers (AlGaAs, AlInP, and GaN) in LED structures. Bars indicate the ranges of the recombination velocity variations reported in literature.

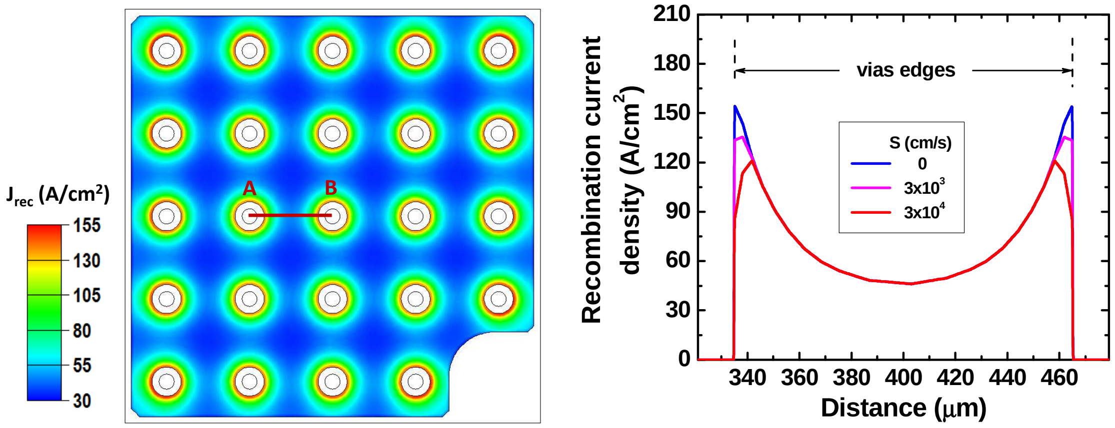

Figure 2 2D distribution of recombination current density in the active region corresponding to the surface recombination velocity $S = 3\times10^3$ cm/s and ambipolar diffusion coefficient $D = 2$ cm^2/s (left picture) and detailed distribution of the recombination current density in the cross-section AB calculated for various recombination velocities (right plot). The LED operating current is 500 mA.

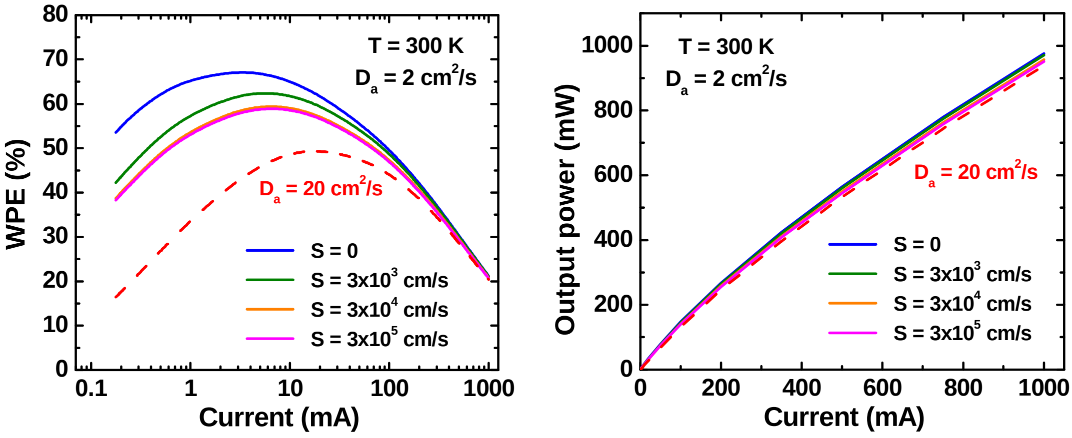

Figure 3 Wall-plug efficiencies (left) and light-current characteristics (right) of the blue LED computed for various surface recombination velocities (solid lines). Dashed line shows similar curves obtained with hypothetical diffusivity value of 20 cm^2/s and $S = 3\times10^4$ cm/s.