# RGB LED active region design and optimization with Genetic Evolution Algorithm

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*Abstract*— **Multi-quantum-well (MQW) LED is a complex distributed system with strong interaction between two opposite carrier flows, electrons and holes. For both types of carriers, the carrier injection into each QW depends on transport conditions across the whole active region (AR) and is affected by capture-recombination balance in all active QWs. Multi-color LEDs with different types of QWs are especially sensitive to the details of the active region's layout. In this work, we use genetic evolutionary analysis to design tri-color LED. We show that full RGB gamut coverage requires optimized compositional intermediate carrier blocking layers (ICBLs) separating the optically active QWs. We also show that compositional ICBLs cannot be replaced by optimized doping of quantum barriers (QBs) alone.**

***Keywords*— III-nitrides, light-emitting diodes, multi-color emission, full-color LED, intermediate carrier blocking layers**

## I. Introduction

Genetic evolutionary approach provides highly efficient algorithms for multi-parameter optimization and analysis of a variety of complex non-linear systems including optoelectronic devices [1]. This paper presents an example of four-parametric optimization of tri-color MQW LED covering the full CIE RGB gamut [2]. Two ICBLs separating correspondingly blue and green (B-G) and green and red (G-R) emitting QWs, are each optimized both in Aluminum composition and residual (donor minus acceptor) doping level; see Fig. 1. For RGB LED simulations we use COMSOL® -based software package developed at Ostendo Technologies Inc. [2] and tailored to adopt the genetic algorithm. CIE chromaticity diagram was chosen as RGB LED figure of merit; see Fig. 2. An objective function of inverse distances from standard CIE red, green, and blue color points to the LED gamut curve (evolution fitness) has been maximized in the course of genetic system evolution.

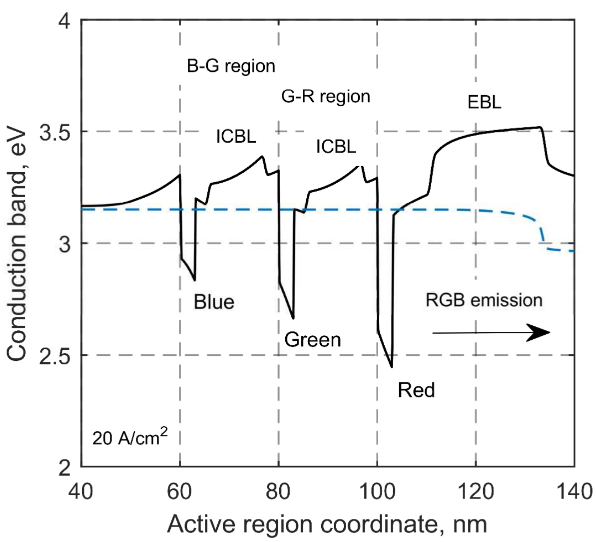


Fig.1. Conduction band diagram of tri-color RGB ICBL LED with Blue-Green-Red QW active region layout (counting from N-side of the diode) calculated at nominal injection of 20 A/cm$^2$. QW injection and RGB emission sequence from red to green to blue is controlled by doping and composition of blue-green (B-G) and green-red (G-R) ICBL regions.

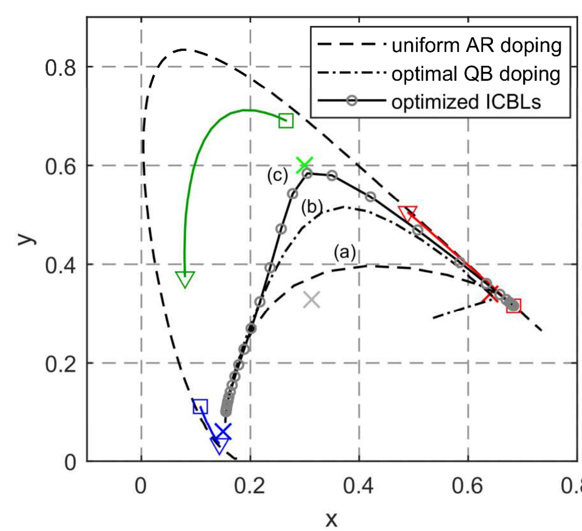


Fig. 2. CIE chromaticity diagram of tri-color RGB LED. Colored cross markers indicate standard CIE red, green, and blue color points. Black curves show LED color gamuts for different active region designs. Corresponding point-to-curve distances are minimized by layout optimization. Colored lines indicate QW emission blue shift with injection, from low(□) to high (Δ).

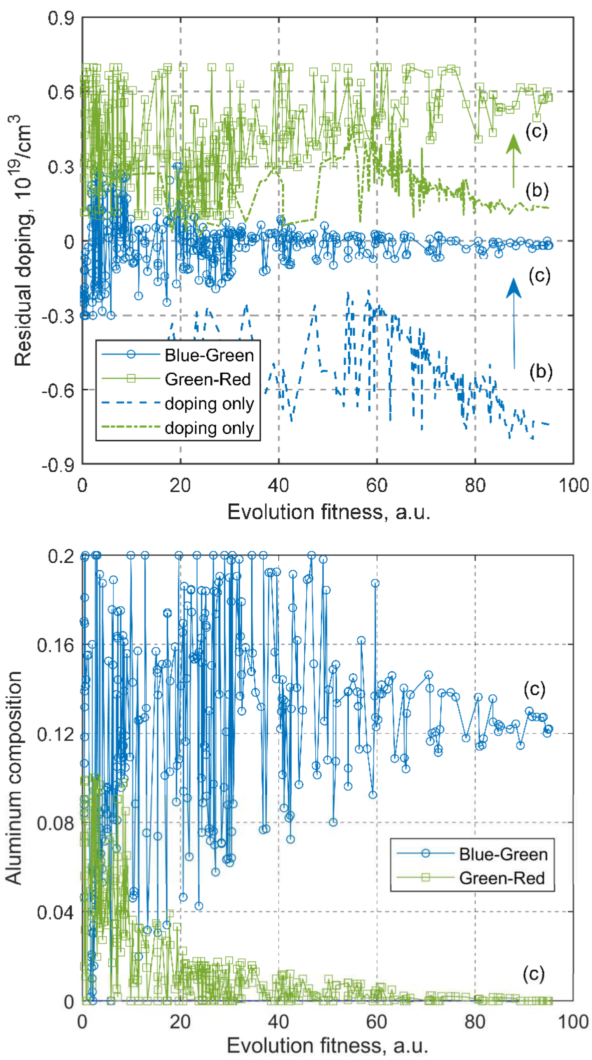


Fig. 3. Optimization diagrams for residual doping (upper part) and Aluminum compositions (lower part) of two ICBL regions separating correspondingly blue-green and green-red emitting QWs. In two-parameter (doping-only) optimization, genetic evolution process converges to active region layout with heavily P-doped blue-green QB and moderately N-doped green-red QB (lines *b* in upper panel). Four-parameter doping-composition optimization (lines *c*) replaces heavily P-doped blue-green QB with low-doped blue-green compositional ICBL. The whole optimization process takes about 10 evolutionary generations with populations of 50 'genes'each.

## II. Simulation Results

Figure 2 compares the RGB gamut coverage for three LED active region designs: (*a*) unoptimized active region with uniform unintentional donor doping at the level of $10^{18}$/cm$^3$, (*b*) two-parameter optimization of QB doping levels only, and (*c*) four-parameter ICBL optimization including both residual doping level and Aluminum compositions.

In uniformly doped active region the redistribution of LED emission spectra with injection is controlled by MQW depths and locations [4]. Emission starts from the deepest P-side red QW and moves to the N-side blue QW as hole injection progresses across the active region, however the coverage of the green portion of the CIE color gamut remains poor; see Fig. 2, line (*a*). Hole injection can be affected by P-doping of QB layers separating the active QWs, so as a first step we attempt to cover the full gamut by optimizing only the doping levels of blue-green and green-red QBs. QW injection control in this case comes from the space charge electrostatic Coulomb barriers in B-G and G-R regions. Line (b) in Fig. 2 shows that space charge induced injection redistribution is also insufficient for full RGB gamut coverage. In fact, excessive P-doping of blue-green QB can produce an undesirable blue shift of LED emission due to the excessive hole supply of blue QW from the adjacent P-doped QB. This trend can finally block the red and green emission altogether. Line (c) in Fig. 2 demonstrates full RGB gamut coverage by ICBL LED design.

Figure 3 illustrates the genetic evolution process involved in optimization. Each point represents a single mutated 'gene' i.e. a specific active region layout. The upper diagram compares the results of two-parametric (doping-only) QB optimization (lines *b*) with full four-parametric ICBL optimization (lines *c*) that also includes Al compositions. It is readily seen that as soon as the Aluminum composition is included into genetic phenotype, the optimal layout changes and highly P-doped blue-green QB is replaced by much lower doped compositional ICBL with Al contents ~12%.

Even with ICBL composition included into genetic phenotype, the optimal green-red ICBL region still remains of doped-only type with no Aluminum contents, though now it requires much higher intentional donor doping to sustain the electron supply to the red QW at low LED injection. It is interesting to monitor how the genetic evolution process forces the system to replace the Aluminum composition of green-red region with extra donor doping; compare the evolution of green lines (*c*) with square markers on upper and lower panels in Fig. 3. Since the residual charge of ionized donors is positive, this indicates that only the hole barrier is needed in green-red region for optimal injection carrier redistribution while the conduction band barrier is undesirable and is eliminated in course of genetic evolution by replacing Aluminum with a higher ICBL donor doping.

## References

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