Using the genetic algorithm to design GaInN/GaN light-emitting diodes with reduced efficiency droop and reduced spectral instability with respect to injection current

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ABSTRACT

Today we are witnessing a fast growing trend that is redefining the concept of lighting. Numerous governments from all over the world have passed legislation to phase out incandescent light bulbs, with the objective of encouraging energy-efficient lighting. Until recently, the only alternative to conventional incandescent lamps was the fluorescent lamp. But light-emitting diodes (LEDs) are now able to replace incandescent and fluorescent lamps in many commercial settings. They have evolved from an object of curiosity to a product with annual sales of several billion dollars. LEDs are energy-saving, environmentally friendly, and have long lifetimes. However, today's LEDs have not yet reached their potential, and as a result, adoption by consumers and industry is gradual. Several obstacles must be overcome to advance the state-of-the-art in LEDs.

One challenge investigated by researchers is the reduction in the luminous efficacy of radiation (LER) of a white light source as the color rendering index (CRI) of a light source is maximized. The CRI is a metric used to measure the color rendering ability of a light source. Another metric, used to measure the luminous flux produced by an LED per unit optical power, is the luminous efficacy of radiation (LER). The trade-off relationship that exists between these two metrics has raised interest in this area of research.

CRI and LER are used to characterize white light sources. The most common type of white LED is created from the combination of a blue LED and a wavelength down-converting phosphor. In this dissertation, a novel approach – referred to as the dual-blue approach – is introduced to enhance both, CRI and LER in white light sources. A dual-blue LED is one in which the emission spectrum contains two distinct peaks in the blue spectral region. It is shown that the use of a dual-blue emitting active region LED, instead of a single-blue emitting active region LED, with the combination of yellow phosphor, improves both color rendition and luminous efficacy of radiation. Despite the trade-off relationship between CRI and LER, simultaneous enhancements are achieved, 15% and 6%, respectively. The dual-blue approach is a novel method that has not been previously reported in the technical literature.

Additional challenges to be addressed in this dissertation are (i) spectral instability in dual-color LEDs and (ii) the "efficiency droop". First, the spectral instability occurs when, with increasing injection current, one of the LED's two emission peaks becomes

increasingly dominant. This can cause a substantial change in the color perceived by the human eye. Second, efficiency droop refers to the gradual decrease in efficiency of a GaInN LED with increasing injection current. Designing LEDs to reduce these deleterious effects has proven to be difficult. In this dissertation, a shift in the way in which LEDs are designed is introduced.

The conventional process of designing an LED to match the requirements of a particular application typically starts with a standard LED, which is then modified according to the knowledge and experience of a designer. Unfortunately, when the application and its requirements are new – as is the case for ultra-high efficiency LEDs, or LEDs that render colors in a particularly pleasing way – this knowledge and experience may not be sufficient.

The genetic algorithm (GA) is a fundamentally different way to design LEDs. A GA is a sophisticated, non-heuristic, probabilistic approach that examines the design space in order to locate design candidates which approach the global maximum of performance (rather than a local maximum of performance) as defined by a variety of figures of merit. As the name suggests, the GA applies principles of evolutionary biology to identify the "fittest" among the members of a population, and does not depend upon the educated guess of a designer. When applied to LEDs, the GA can lead to LEDs that are more efficient and have a more pleasing color.

In this dissertation, color stability is realized by granting the GA freedom to select some of the active region parameters, such as the number of layers, layer thickness, doping, and material composition. A dual-color LED, emitting at λ_1= 450 nm and λ_2= 490 nm, is optimized to have a stable ratio of its two emission peak intensities at an injection current density of 10, 35, and 70 A/cm^2. Even though the LED emission power increases with increasing current, the chromaticity itself remains unchanged to the human eye.

The GA is also used to study the effect of n-type doping in the quantum barriers and its impact on the efficiency droop. Four $Ga_{0.85}In_{0.15}N$/GaN LED structures are used, distinguishable only by their number of n-type doped quantum barriers, where either 1, 2, 3, or 4 of the quantum barriers are doped at $N_D \approx 3\times10^{18}$ cm^{-3}. Both simulation and experimental results confirm that GaInN/GaN multiple quantum well LEDs with a lower number of n-type doped barriers suffer less from the efficiency droop. This is due to a more uniform carrier distribution among the quantum wells.