APSYS Simulations of High-Brightness LEDs

Nathan Gardner and Christopher Kocot(+)

LumiLeds Lighting, San Jose, CA 95131, U.S.A.
(+)Agilent Technologies, San Jose, CA 95131, U.S.A.

The large polarization-induced dipoles at heterointerfaces in the AlInGaN/GaN material system can substantially affect the electrical and optical characteristics of high-brightness blue/cyan/green light-emitting diodes. The forward-biased voltage (V_f) drop, the rate of change of the peak emission wavelength with current, and the internal quantum efficiency at current densities above ~40 A/cm^2 are more accurately described when the effects of dipoles on the conduction and valence bands are considered.

In order to better understand the effects of the dipoles on device characteristics and to study techniques for mitigating these effects, we have performed 1-D numerical simulations of the LEDs using APSYS by Crosslight Software Inc. The device model solves the drift-diffusion equation and includes the ability to model the radiative recombination rate in quantum wells. The LEDs consist of a ~3.5 µm-thick *n*-GaN layer grown on a sapphire substrate, followed by an active region of three 25 Å InGaN quantum wells with 120 Å GaN barriers, followed by 300 Å of *p*-AlGaN and 800 Å of p-GaN. The difference in spontaneous polarization and the difference in strain between AlGaN and GaN results in fixed sheets of charge on both sides of the *p*-AlGaN layer, and the difference in strain between the InGaN quantum wells and the GaN barriers results in fixed sheets of charge on both sides of each quantum well. The magnitudes of the charges are calculated using Vegard's law and the parameters calculated by Bernardini et al [1].

We have observed large reductions in forward voltage of cyan and green LEDs after increasing the Si doping concentration in the quantum well barriers. Device simulations indicate that the forward voltage is sensitive to the magnitude of the dipoles at the well and barrier interfaces and to the dopant concentration in the barriers. We have observed, with different quantum well widths, changes in the shifts of peak emission wavelength with drive current that may be explained by the quantum-confined stark effect. Commercially available simulators of this effect are under development. Furthermore, we can explain the internal quantum efficiency vs. current density characteristics of InGaN LEDs in terms of the magnitude of the sheet charge density at the AlGaN/GaN heterointerfaces. At current densities exceeding ~40 A/cm^2, the AlGaN layer is not an effective potential energy barrier to electrons diffusing out of the active region. The barrier height is dramatically lowered by the presence of the sheet charges at the AlGaN/GaN heterointerfaces.

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[1] F. Bernardini, V. Fiorentini, D. Vanderbilt, Phys. Rev. B, vol. 56, pp. R10024-R10027, 1997.

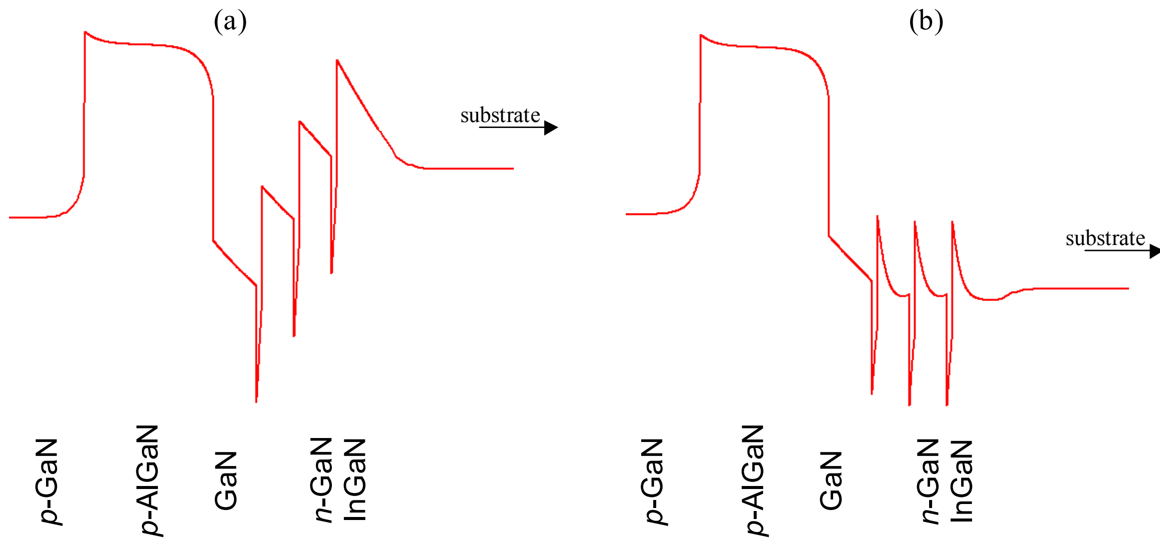

Figure 1. Conduction band diagram of the active region of an InGaN LED biased at 30 A/cm^2. Figure 1(a) represents a device with the quantum well barriers doped with [Si] ~ 5×10^{16} cm^{-3}. Figure 1(b) represents a device with quantum well barriers doped with [Si] ~ 5×10^{18} cm^{-3}.

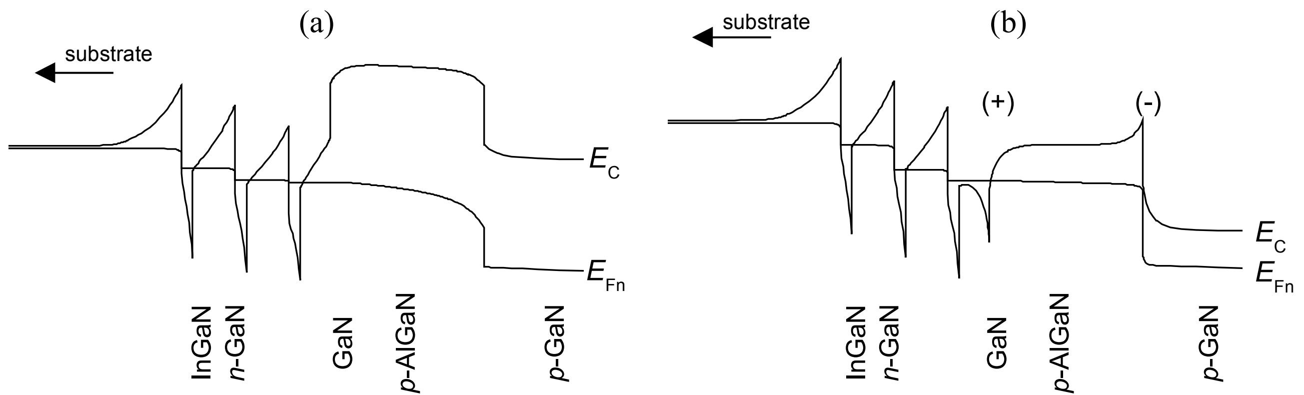

Figure 2. Conduction band diagram of the active region of an InGaN LED biased at 400 A/cm^2. Figure 2(a) represents a device without polarization-induced sheets of charge at the AlGaN/GaN heterointerfaces. Figure 2(b) includes the sheets of charge, illustrating the relatively small confining potential provided by the AlGaN layer.