Tracking down sources of efficiency droop

Researchers at UIUC have modified the ABC model to extract the impacts of Auger–Meitner recombination, charge polarization, and junction temperature.

University of Illinois Urbana-Champaign has modified the ABC model of light-emitting diodes (LEDs) to enable the extraction of internal quantum efficiencies (IQEs) and thus give an assessment of the various effects that reduce LED performance [P. Thirasuntrakul, Appl. Phys. Lett., v126, p211103, 2025].

The ABC model refers to a theoretical assumption that the rate of carrier recombination in the LED can be represented as a simple power series in the carrier concentration (n): $An+Bn^2+Cn^3$. The ABC coefficients are roughly associated, respectively, with

- Shockley–Read–Hall recombination,
- electron–hole recombination into photons producing the light we want from an LED, and
- Auger–Meitner recombination, where three carriers interact and the energy from two of them recombining is carried off by the third rather than a photon.

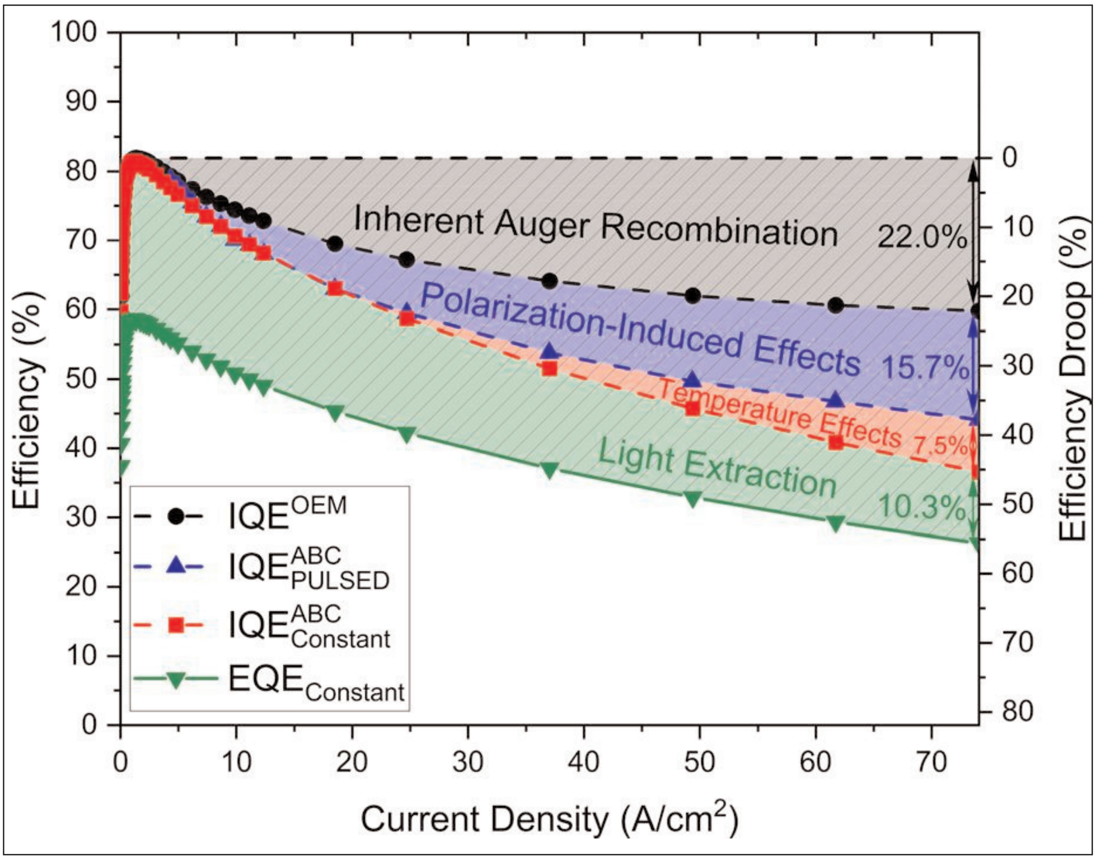

Figure 1. Green LED efficiencies as function of current density. Key: black circles, calculated internal quantum efficiency (IQE) using optical-electrical model (OEM); blue triangles, IQE under pulsed current; red squares, IQE under constant current; and, green inverted triangles; external quantum efficiency (EQE) under constant current; experimentally determined curves, solid; model derived curves, dashed.

The separation is not as clean as suggested. The indium gallium nitride (InGaN) system that is used to make blue and green LEDs has chemical bonds which are charge polarized, which introduces spontaneous and strain-dependent electric fields into multiple quantum well structures. These fields can adversely affect efficiency, complicating the analysis. The polarization effects become worse as the emission wavelength is lengthened by increasing the indium content.

The researchers report: "It is found that inherent Auger–Meitner recombination-induced droop is approximately 49% of the total efficiency droop in commercial green LEDs, while polarization-induced effects contribute about 35%, and thermal droop accounts for nearly 16%. These findings suggest, to quash the green gap, it is critical to search for materials and device designs with low inherent Auger–Meitner coefficients and polarization fields, respectively."

It is hoped to improve the efficiency of solid-state lighting by mixing red, green and blue (RGB) light from balanced LEDs, but the 'green gap' is a barrier to this. The team points out: "Current green LED wall-plug efficiency (WPE) is 19% at $100A/cm^2$. To meet the Department of Energy's (DOE) goal of reducing 196 million metric tons of carbon emissions by 2035, a WPE target of 55% has been set for green LEDs. Achieving this requires the efficiency droop contributors in InGaN green LEDs to be explored."

Using data from a Cree XLAMP XP-E2 InGaN green LED with the lens removed operated on a 25°C heating stage, the researchers estimated the contributions of various factors towards the droop effect from a modified 'ABC' model (Figure 1). At $75A/cm^2$ current density, the researchers estimate that inherent Auger–Meitner recombination accounted for a 22% drop, charge-polarization effects 15.7%, thermal effects 7.5%, and light-extraction 10.3%.

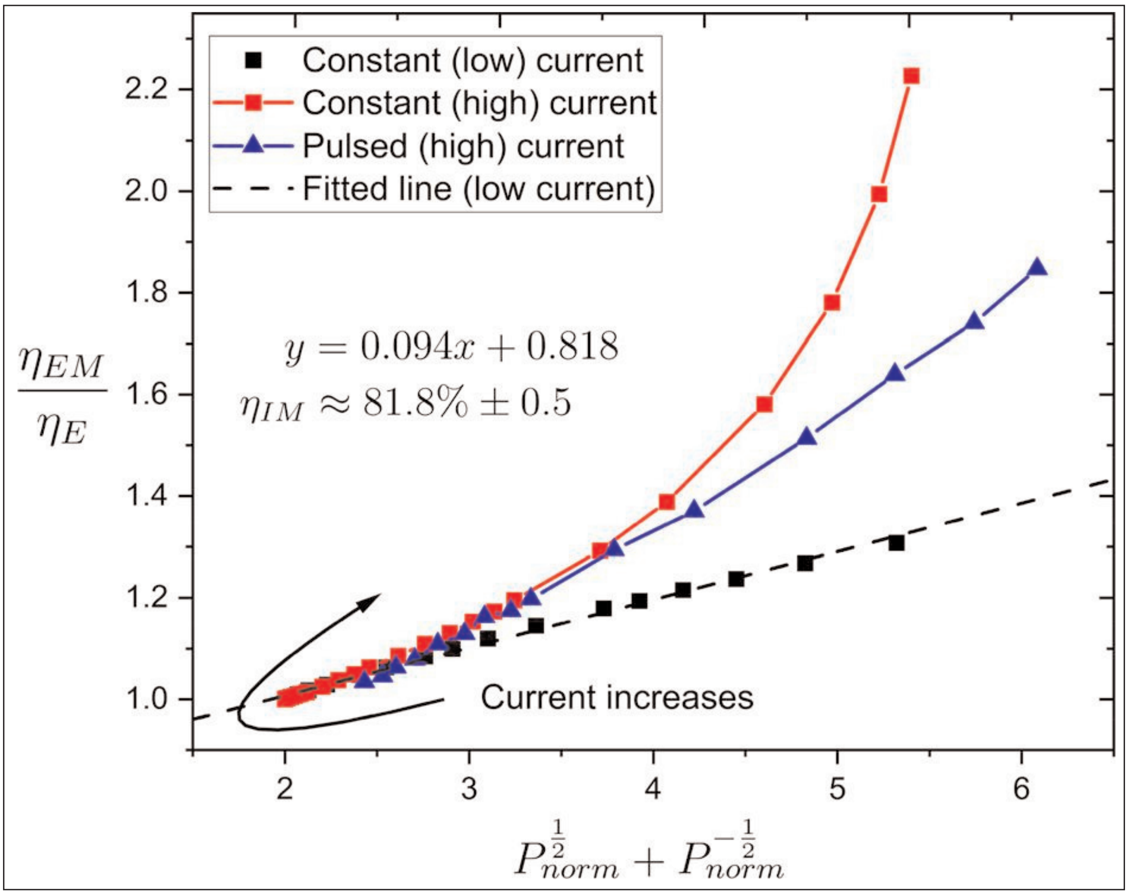

Figure 2. Inverse normalized EQE (η_{EM}/η_E) as a function of $P_{norm}^{1/2} + P_{norm}^{1/2}$.

The Auger-polarization-thermal effects constitute the 'efficiency droop', so these contributions to the droop are estimated at 48.7%, 34.7%, and 16.6% of the total, respectively.

The unmodified ABC model gives a linear relation between the inverse EQE ($1/\eta_E$) and a combination of square roots of the light output power measured in an integrating sphere (Figure 2), both normalized to their values at the maximum. The point (2,1) of the graph in Figure 2 represents the maximum of the EQE where $P_{norm} = 1$, and $\eta_E = \eta_{EM}$. The linear relation is seen to hold well for the low current side (i.e. before the maximum EQE is reached), but at high current (in the droop region) the curves become non-linear, more so when the injection is constant rather than pulsed. Pulsed measurements are typically used to reduce thermal effects on efficiency.

The linear equation in the variables $y = (\eta_{EM}/\eta_E)$ and $x = P_{norm}^{1/2} + P_{norm}^{1/2}$ is $y = \eta_{IM}(1 + x/Q)$ where η_{IM} is the internal quantum efficiency (IQE) and Q is a quality factor. The IQE can be extracted from the linear low current data as 81.8%.

The researchers used Raman spectroscopy to assess the variation of junction temperature with current injection. Assuming a typical exponential drop with temperature relative to optical power, the researchers extrapolate back to an output power without the thermal effect (P_{OEM}). The IQE_{OEM} on this optical–electrical–thermal model (OETM) can then be calculated using these power values as for the IQEs with constant and pulsed operation. ■

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Author: Mike Cooke