Indirect Auger impact on nitride LED droop

Mike Cooke reports on the theory and experimental support from European research. Meanwhile, a US-Korean collaboration has made some observations on real-life internal quantum efficiency dependence on carrier density that does not fit the simple models generally used.

University of California Santa Barbara (UCSB) theorists say that they have cracked the nitride semiconductor light-emitting diode (LED) lighting performance problem commonly referred to as 'efficiency droop' [Emmanouil Kioupakis et al, Appl. Phys. Lett., vol98, p161107, 2011].

UCSB believes that this research "will help engineers develop a new generation of high-performance, energy-efficient lighting that could replace incandescent and fluorescent bulbs." LEDs have already begun to encroach on sectors of the lighting industry such as for traffic signals, where the benefits of high efficiency and long lifetimes are balanced against the somewhat higher initial costs. However, the efficiency droop problem needs to be overcome — reducing the number of LEDs in a unit and hence cost — for more general application.

Nitride semiconductor LEDs use layers of indium gallium nitride (InGaN) alloy of InN and GaN compounds to form wells in which electrons and holes recombine to create light. It has been found that such devices have an increasing efficiency up to a certain current. Unfortunately, at currents beyond this peak the efficiency drops, often dramatically.

There has been much debate on the mechanism for this unwanted efficiency droop. Although the droop behavior has been attributed by some to Auger recombination, others comment that the size of this effect should be small.

Auger recombination usually involves two carriers recombining and transferring their energy to a third carrier rather than producing light (Figure 1(c)). Since the process involves three carriers it requires a high carrier density and hence would tend to kick in at higher current densities. However, atom-level calculations of simple 'direct' Auger recombination have suggested that the effect should be small in nitride semiconductors.

The two other recombination mechanisms (and, at low current/carrier densities, the main, recombination mechanisms) are Shockley–Read–Hall (SRH) and light emission (Figures 1(a) and (b), respectively). In an ideal world, all the recombination would occur via light emission, at least for optoelectronic applications.

Phonon and alloy scattering

The theorists at UCSB have been working on indirect Auger processes for some time using varieties of density functional theory as an explanation for droop. In 2009, almost the same team proposed a resonant 'interband' Auger effect with an excited conduction band to account for the droop [Kris T. Delaney et al, Appl. Phys. Lett., vol94, p191109, 2009].

The new processes involve electron–phonon coupling, alloy scattering or Coulomb scattering by charged defects (Figure 1(d)). Phonons are the quantum description of lattice vibrations. The electron–phonon coupling is particularly strong in nitride semiconductors. Alloy scattering occurs because the crystal structure of InGaN is not uniform.

It is a particular problem with growth of high-indium-concentration InGaN that one finds regions of high and low content because of phase separation effects. In fact, the resulting localized states can even lead in some cases to higher-than-expected light emission.

According to UCSB, the effects from phonon coupling and alloy scattering are significant enough to account for the discrepancy between the observed degree of droop and that predicted by other theoretical studies, which only accounted for direct Auger processes (Figure 2).

The effect increases at smaller band gaps, explaining the 'green gap' difficulty in producing longer-wavelength nitride semiconductor LEDs. According to the UCSB team, the Coulomb scattering term "is not important in nitride devices."

In nitride LEDs, "these indirect processes form the dominant contribution to the Auger recombination rate," says Emmanouil Kioupakis, a postdoctoral researcher at UC Santa Barbara and lead author of the new UCSB paper. The paper comments: "The cumulative effect of these contributions to the Auger coefficient amounts to a sizeable value that agrees with experiment and can explain the efficiency droop in LEDs." ➤

It is hoped that, by understanding the causes of efficiency droop, techniques might be found to eliminate or ameliorate the effect. "Identifying the root cause of the problem is an indispensable first step toward devising solutions," comments professor Chris Van de Walle of the Materials Department at UCSB, who heads the research group that carried out the work. The paper concludes: "This knowledge is the first step to addressing the efficiency loss and the engineering of high-power and high-efficiency nitride light emitters."

Although the Auger effect is 'intrinsic', meaning LED droop cannot be eliminated entirely, the researchers believe it could be minimized by using thicker quantum wells in LEDs or by growing devices along non-polar or semi-polar growth directions in order to keep carrier densities low.

"With Auger recombination now established as the culprit, we can focus on creative approaches to suppress or circumvent this loss mechanism," Van de Walle adds.

The UCSB work was supported by the US Department of Energy funded Center for Energy Efficient Materials and by UCSB's Solid State Lighting and Energy Center.

Experimental support

Following the UCSB work, Fraunhofer Institute for Applied Solid State Physics IAF and Ecole Polytechnique Fédérale de Lausanne claim to have measured a third-order charge carrier recombination coefficient for InGaN quantum wells in agreement with the theoretical predictions for phonon- and alloy-disorder-assisted Auger scattering [W. G. Scheibenzuber et al, J. Appl. Phys., vol109, p093106. 2011].

Relaxation oscillations and turn-on delay measurements were made on (Al,In)GaN laser diodes that emit ~415nm light (violet, photon energy ~3eV). These results were fitted to a rate-equation model with charge-density-dependent recombination rates with linear, quadratic and cubic terms (Table 1). These three terms are associated with SRH, spontaneous light emission and Auger recombination. This is often called the 'ABC model', since the recombination rate is represented as $An + Bn^2 + Cn^3$, where n represents the carrier density.

The Fraunhofer–Lausanne model also includes charge-carrier leakage as a separate term. The researchers used optical

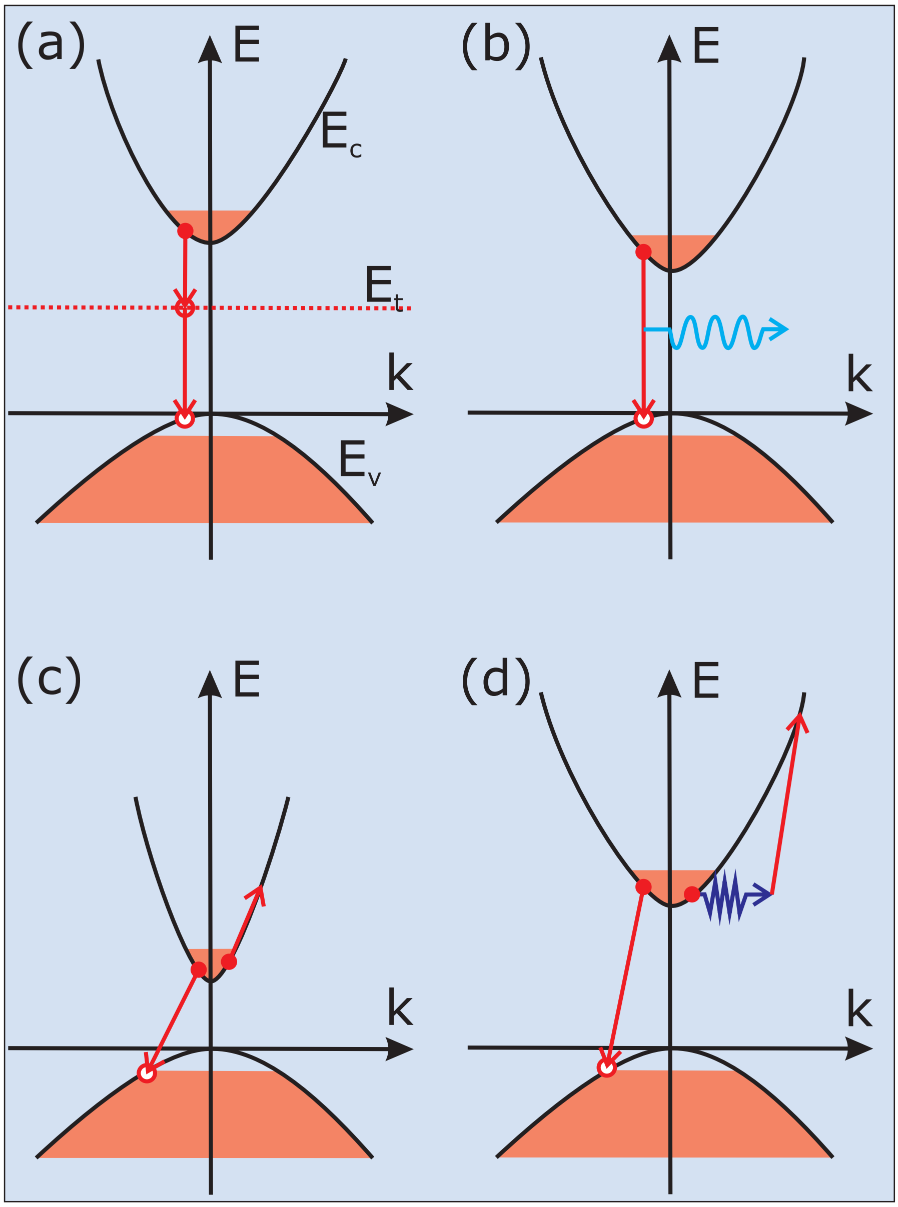

Figure 1. Schematic wavevector–energy (k–E) diagrams of the recombination mechanisms. (a) The Shockley–Read–Hall (SRH) indirect recombination mechanism occurs through transitions to and from localized energy states in the energy bandgap. (b) The direct recombination of electron and hole states results in the desired photon emission. (c) The direct Auger recombination process shown involves two electrons and a hole (eeh). One can also have processes with two holes and an electron (hhe). (d) Indirect Auger recombination, where the process is assisted by scattering mechanisms such as electron–phonon coupling, alloy disorder, or Coulomb scattering by charged defects.

Table 1. Coefficients measured by Fraunhofer–Lausanne researchers.

Symbol	Associated mechanism	Coefficient
A	Shockley–Read–Hall (SRH)	$(4.2\pm0.4)\times10^{7}$/s
B	Spontaneous emission	$(3\pm1)\times10^{-12}cm^3$/s
C	Auger	$(4.5\pm0.9)\times10^{-31}cm^6$/s

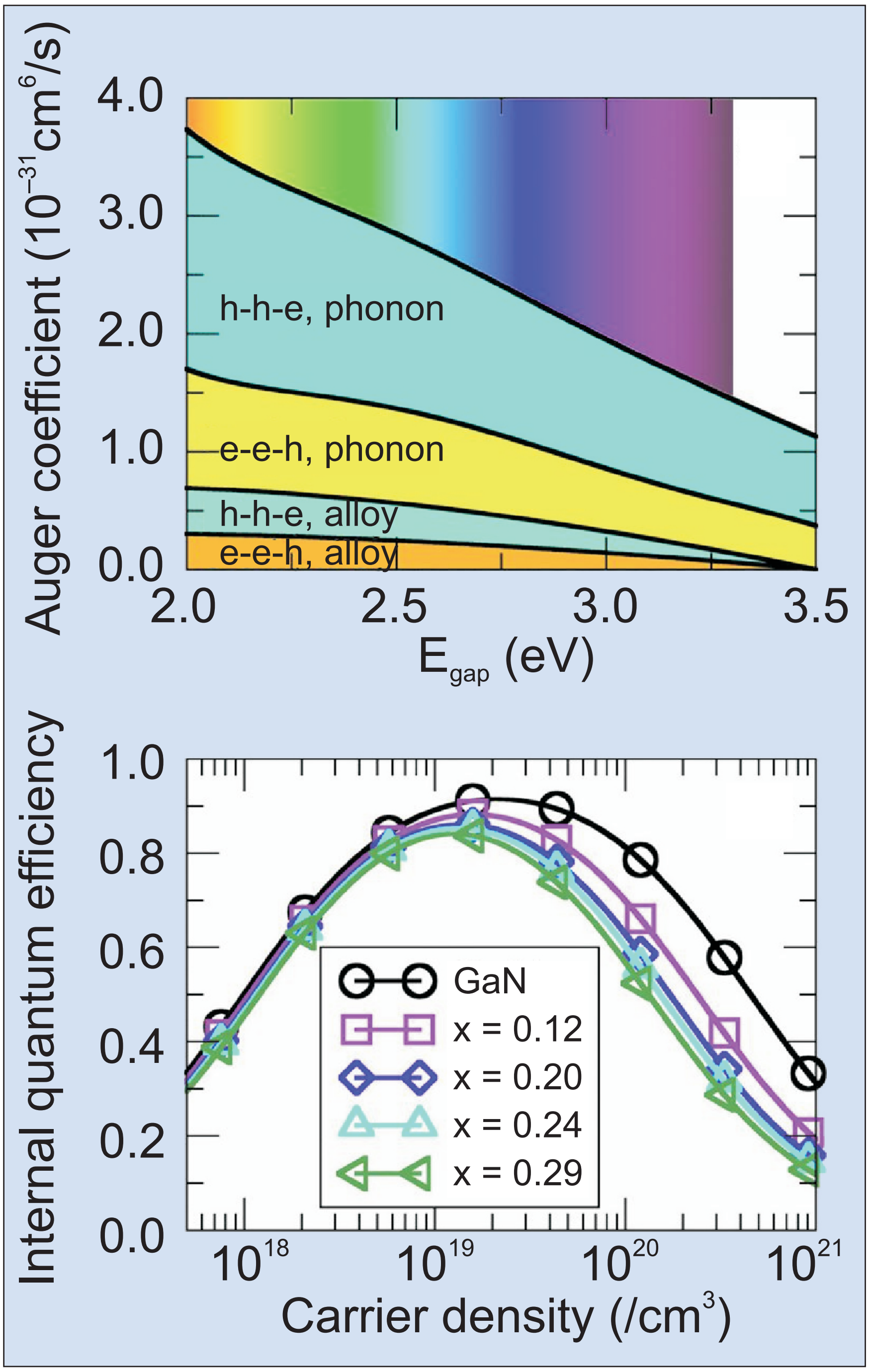

Figure 2. (a) UCSB predicted contributions of phonon- and alloy-assisted electron-electron-hole (e–e–h) and hole-hole-electron (h–h–e) processes to Auger coefficient of InGaN as a function of bandgap of active layer material. (b) LED internal quantum efficiency as function of carrier density for varying InGaN alloy composition.

gain spectroscopy to find the injection efficiency and thus to separate charge-carrier leakage from carrier recombination contributions. The spectra were found using the Hakki–Paoli method of electrically driving the laser diodes below threshold and measuring the gain. The researchers found a relatively low injection efficiency of ~68%, blamed on a deficient electron–blocking layer leading to significant electron overshoot into the p-type layers. Other groups have managed to create laser diodes with injection efficiencies close to 100%.

The research team comments on the relation of their results to the UCSB theoretical work: "The numerical value of the C-coefficient determined in this work agrees within a factor of two with a recent theoretical study of alloy-disorder- and phonon-assisted Auger scattering by Kioupakis et al, who found a value of about $2x10^{-31}cm^6/s$ for bulk InGaN with a bandgap of 3eV."

The team admits that they do not have 'direct evidence', but they do say that this agreement with the UCSB theory "indicates that the mechanism we observe is in fact related to the indirect Auger effect."

"The advantage of our method is the clear differentiation between injection and recombination, and it is clearly shown that there is a considerable nonradiative recombination term that goes (at least) with n^3 and is not related to charge-carrier leakage," they conclude.

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Symmetry of ABC model

Researchers based in the USA and Korea have recently pointed out that the simple ABC model is inadequate to describe the behavior of most LEDs [Qi Dai et al, Appl. Phys. Lett., vol98, p033506, 2011]. In particular, if the ABC model is correct, then the internal quantum efficiency (IQE) plotted against carrier concentration with a logarithmic scale should present symmetric curves about the peak.

As one might expect, real life is more complicated, with LEDs showing both positive and negative asymmetry. The researchers from Rensselaer Polytechnic Institute (RPI), Sandia National Laboratories and Samsung LED comment that such asymmetry requires a fourth-power or higher-power contribution to the recombination rate.

The US–Korean team found a left-asymmetry in two LEDs that it grew and tested (Figure 3), suggesting a positive higher-order contribution. The researchers also note that some IQE vs carrier density plots seen in the literature are skewed to the right, indicating negative higher-order contributions. According to the US–Korean researchers, this could be due to either carrier leakage or polarization field effects (proposed by

RPI as an explanation for droop over a number of years).

Of course, simply adding extra parameters to improve a fit is not satisfactory — as the mathematician John Von Neumann apparently once commented: "With four parameters I can fit an elephant, and with five I can make him wiggle his trunk."

However, it seems clear that a simple association of the linear, quadratic and cubic terms with SRH, radiative and Auger recombination, respectively, is inadequate.

A further aspect to consider is that these simple associations give only the 'leading' behavior for these recombination mechanisms. For example, one of the devices grown and tested by the US–Korean group had a significant non-radiative quadratic contribution with only about 44.5% of the 'B' term contributing to radiation.

Professor E. Fred Schubert of RPI comments: "The efficiency droop is a unique phenomenon that is associated with GaN-based LEDs. It does not occur in other semiconductor materials. It has been our view that the origin of the efficiency droop lies in the unique properties of the III-V nitride material system. Two properties that are uniquely associated with the GaN material family are:

- the large polarization fields inherent to the III-V nitride family;
- the large asymmetry in transport characteristics between electrons and holes.

"It has been shown that these two unique properties can result in (i) electron leakage or (ii) insufficient injection of holes (both are the two sides of the same coin).

"Our experiments reported in the literature have demonstrated that the efficiency droop is fully consistent with carrier leakage out of the active region and insufficient hole injection. We showed that the simple ABC model is inadequate to comprehensively describe recombination in GaInN LEDs. An additional term, which we attributed to transport effects, is needed to adequately describe recombination in LEDs." ■

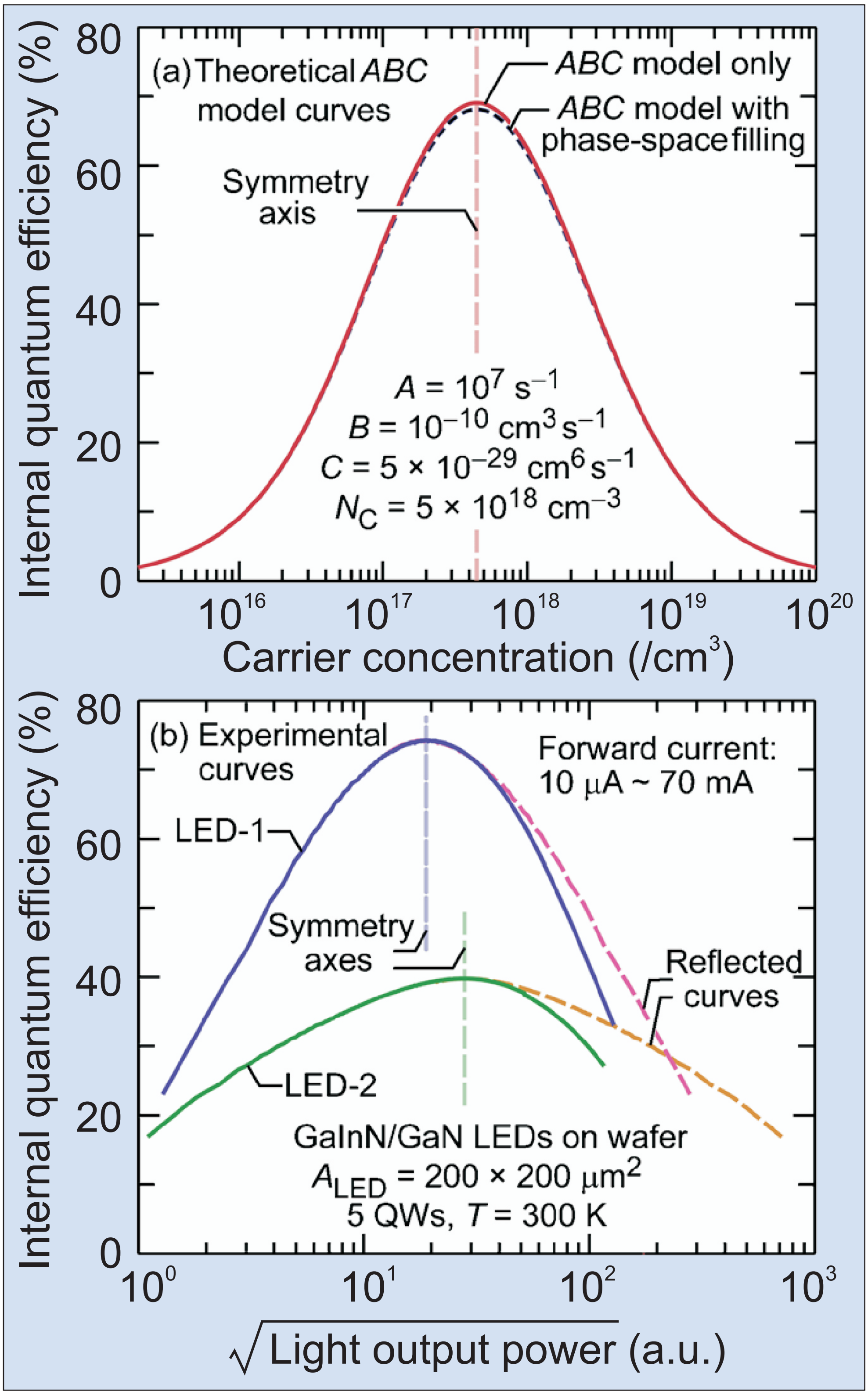

Figure 3. (a) Theoretical IQE-vs-n curves based on the ABC model (without and with phase-space filling) showing even symmetry. (b) Experimental IQE curve showing asymmetry, where carrier density is assumed to be proportional to the square root of light output power (since emission is due to 'B' quadratic term). Experimental curves are skewed to the left.

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