Solutions don't solve droop controversy

Indium gallium nitride light emitting diodes suffer a nasty fall-off in efficiency as the current through the device increases. Although some companies say they have solved the problem, debate about the cause continues. Dr Mike Cooke reports on some recent developments.

The world has been promised general lighting based on nitride semiconductor light emitting diodes (LEDs) for some time. The aim is to produce illumination with high efficiency compared with tungsten and even compact fluorescent light bulbs. Nitride semiconductors produce light at the higher-energy end of the visible spectrum from green through to ultraviolet. Combined with suitable phosphors, packaged devices can produce white light. But one barrier to this is finding suitable semiconductor structures that can efficiently support high-power light emission.

Semiconductor light-emitting devices depend for their operation on the ability of electrons and holes to recombine, with the resulting energy reduction of the system being compensated by photon emission (Figure 1). There are also a number of competing processes where, instead of producing light, the semiconductor system itself absorbs the energy released and (eventually) heats up. One route, the Shockley–Read–Hall (SRH) mechanism, is through intermediate levels (recombination centers) in the energy band gap. Such levels result from impurities and defects in the semiconductor crystal structure. Surface and interface states are other routes to non-radiative recombination.

Traditional nitride-based LEDs have a single active layer where the holes and electrons recombine to emit photons (Figure 2). One approach to increasing the light output is to make the active layer thicker. Unfortunately, such thicker-layer double heterostructure devices are difficult to produce with suitable properties and sufficient quality for efficient photon emission.

An added complication in producing InGaN LEDs is that magnesium is the material used to create the p-type material that is the source of the holes injected into the active region. Where Mg is present, electron–hole recombination tends to be non-radiative. Active layers are usually undoped. Many devices use an extra barrier layer to block electrons from reaching the luminance-killing Mg in the p-GaN region or even the top contact.

Rather than having one thick layer of doubtful quality, devices have been produced based on multi-quantum wells (MQWs) with a number of thin high-quality active layers (Figure 3). However, the problem with MQW InGaN LEDs is that, above a certain current density (typically 10A/cm^2, or about 50mA current for typical sized devices), the light output external quantum efficiency falls off or 'droops' (Figure 4).

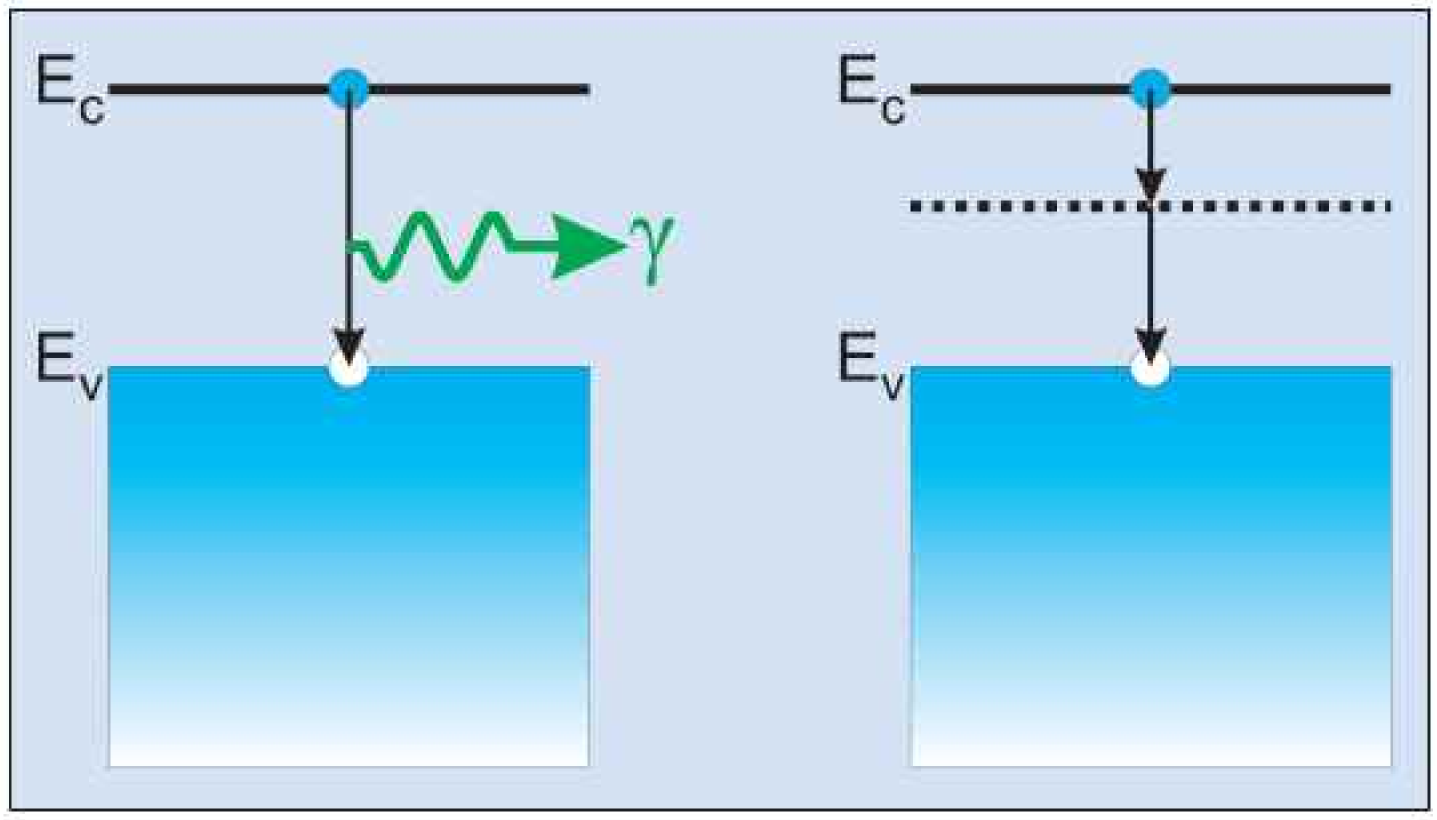

Figure 1. The recombination of an electron and a hole can occur either with the production of a photon (left) or through interaction with an intermediate state (right).

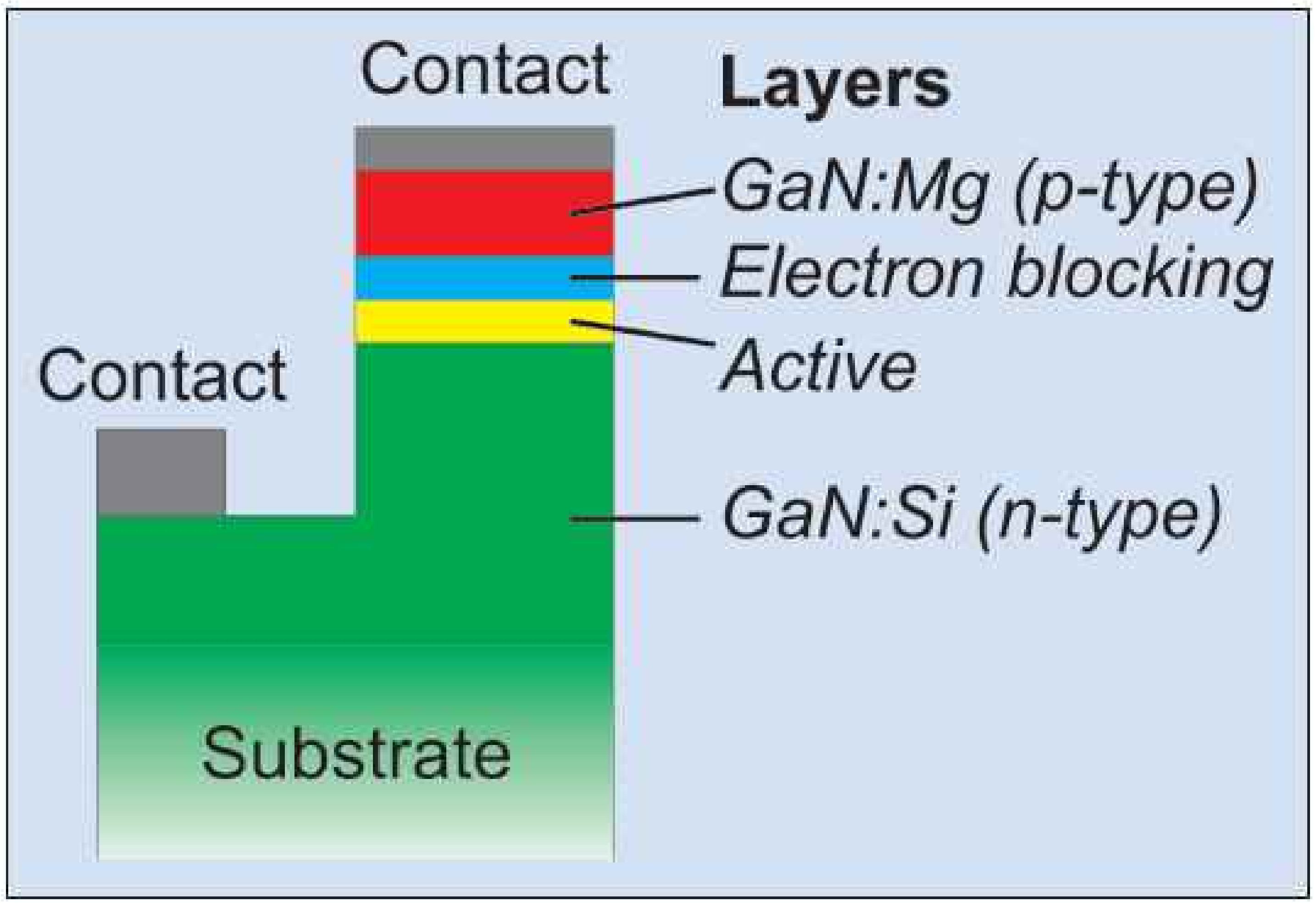

Figure 2. Schematic diagram of a single-layer InGaN LED.

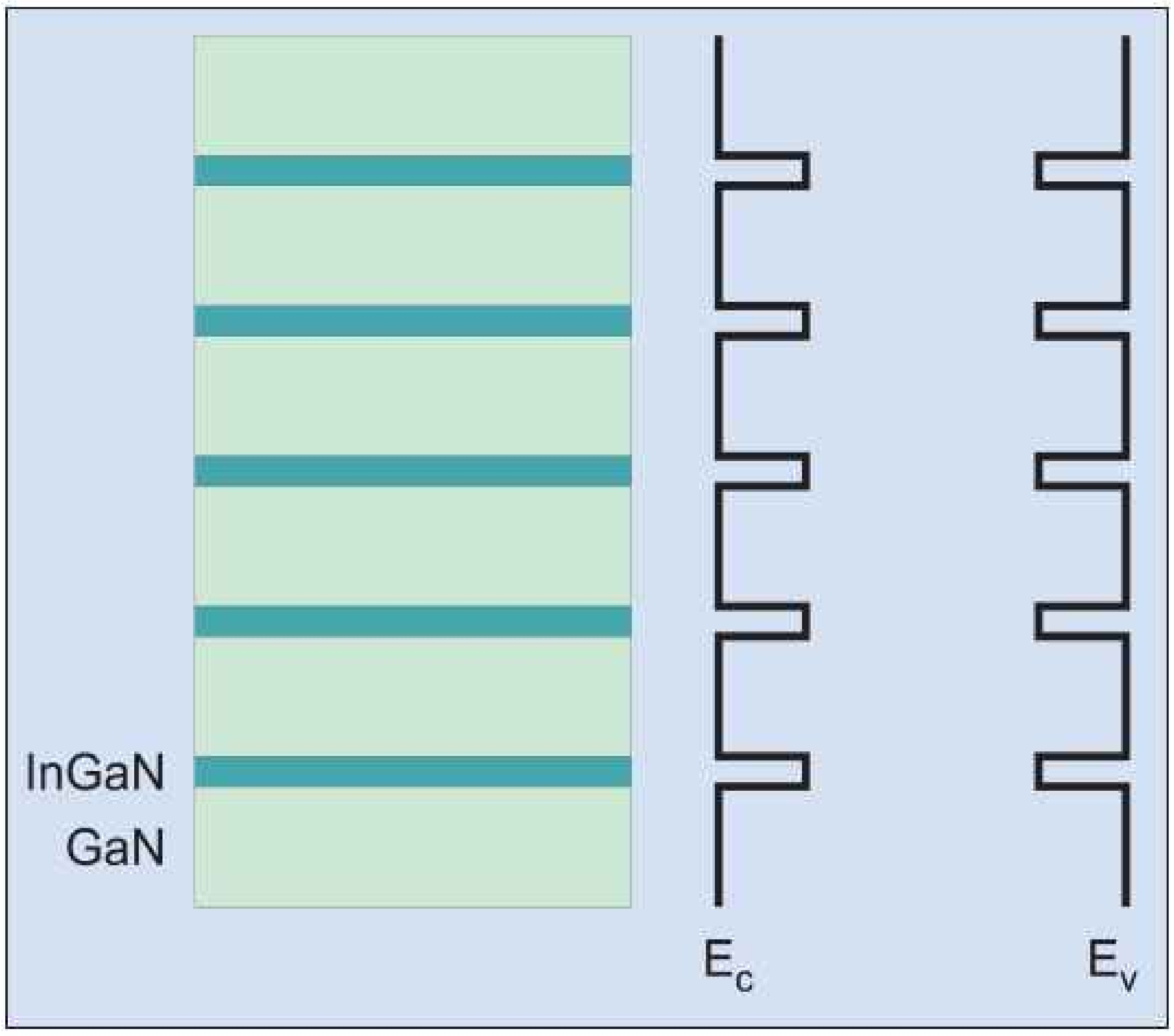

Figure 3. Multi-quantum well structure with an idealized band structure. In reality, polarization fields and other effects drastically modify the potential.

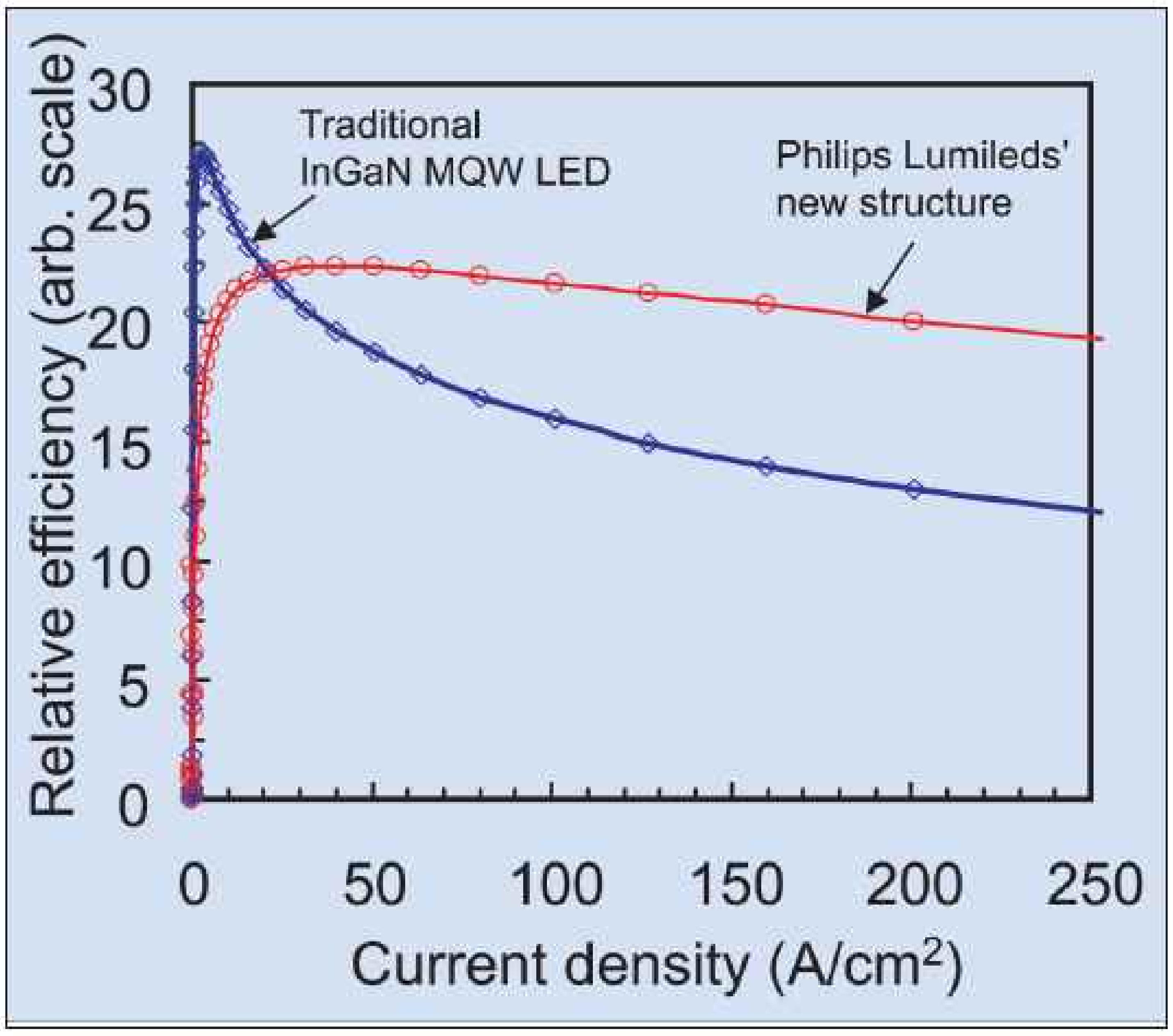

Figure 4. Efficiency versus current density for traditional MQW devices shows a peak and a droop. Also shown is the behavior of a double heterostructure device developed by Philips Lumileds.

Auger controversy

Auger recombination is a third route to recombination that has been proposed as a solution to the puzzle of the efficiency droop. Auger recombination transfers the energy released to another carrier rather than a photon (Figure 5). This third carrier, either an electron or hole, then loses energy to the lattice through a series of scattering events. This sort of process becomes more likely as the carrier concentrations increase. As a rough guide, the Auger rate is expected to increase as n^2p or np^2, where n and p are the electron and hole concentrations. As increased current in a light-emitting device leads to increased carrier concentration in the active region, one expects that Auger recombination will become an important loss factor at some stage.

Philips Lumileds is among those that believe that Auger recombination is the source of the efficiency droop effect [1]. To determine the relative importance of Auger recombination, company researchers performed photoexcitation experiments on quasi-bulk InGaN layers rather than quantum wells to avoid complications such as polarization fields and interface effects (more on these below). Assuming equal electron and hole populations, the recombination rate was modeled as a series of powers of the carrier concentration, with the first power being interpreted as SRH recombination, the second being radiative recombination, and the third being the Auger term. The coefficient of the third power was determined to be in the range $1.4–2.0\times10^{-30}$cm^6/s.

The paper comments: "An Auger coefficient of this magnitude provides the dominant mechanism behind the drop in quantum efficiency for a state-of-the-art c-plane InGaN/GaN QW LED at relatively modest current densities."

Philips Lumileds calculations on an InGaN/GaN 2.5nm quantum well with a recombination thickness of ~1nm (less than half the physical thickness due to electron–hole separation caused by polarization fields) suggests that carrier densities of $4–5\times10^{18}$cm^{-3} are achieved at current densities of the order 5–15A/cm^2. At this density level, according to Philips Lumileds, Auger recombination is the dominant recombination path. The carrier density that is used depends on the observed fact [2] that the radiation from MQW devices

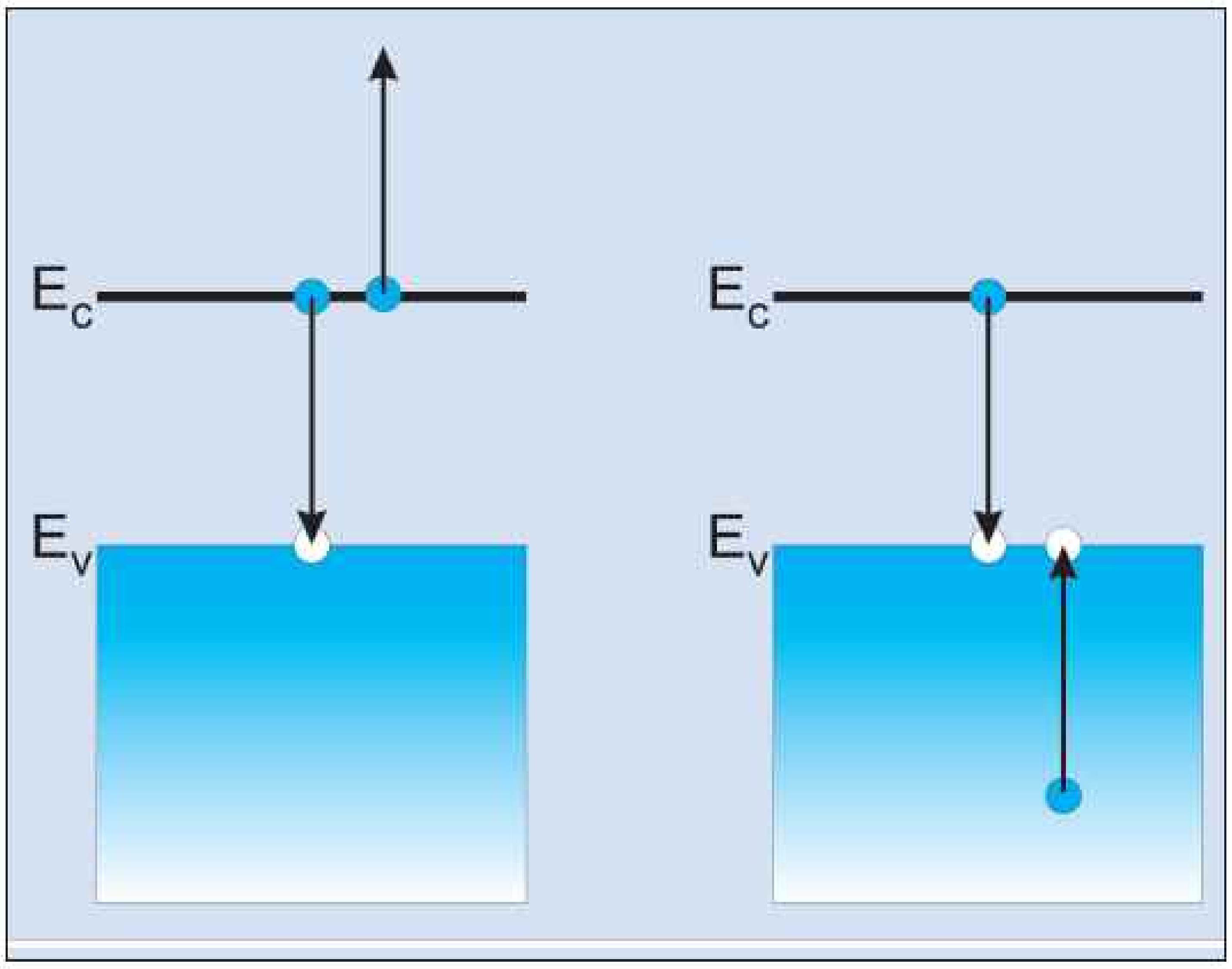

Figure 5. Auger recombination where released energy is transferred to another carrier — either an electron is thrown high into the conduction band (left) or a hole is created deep in the valence band (right).

predominantly comes from the well that is nearest to the p-type region. This means that most of the structure is inactive. So, although the devices are designed as multi-wells, they are effectively operating as single wells, defeating the purpose of constructing the MQW.

On the basis of its work, Philips Lumileds announced in February 2007 that it had 'solved' the droop problem, and that new technology would be implemented in the company's products later last year (Figure 4). From the technical papers issued by the company after this announcement, it appears that this technology is based on using a thicker double heterostructure active layer rather than an MQW to overcome the droop effect [3].

However, not all researchers agree that Auger recombination is the cause of efficiency droop. Theoretical calculations [4] using fully microscopic many-body models find direct band-to-band Auger losses in InGaN MQWs to be negligible. The models use only well-known basic material parameters and describe, within the statistical scatter of the experiments, the performance of more traditional GaAs-based devices applied in the telecom industry.

The paper also points out that the power-law dependences assumed by Philips Lumileds are not those seen in the operating conditions of these devices but rather linear and square dependences for radiative and Auger recombination, respectively.

To show that the model also gives sensible results for GaN-based devices, it is compared with the behavior of InGaN laser diodes, and the results fall within the experimental scatter. Many critics of the Auger hypothesis point to the fact that InGaN MQW lasers need high injection levels for laser action. If an Auger recombination mechanism were important, such devices should not lase at all, they suggest.

Auger supporters retort that the Auger recombination mechanism is one of the few ways to understand the simultaneous high threshold voltage along with high slope efficiency once lasing is achieved. Above threshold, extra injected carriers are quickly converted into stimulated emission, pinning the carrier densities in the active layers and thus pinning the Auger losses as well. Auger supporters also go further and criticize those who adduce carrier injection problems as the source of the droop (see below) by saying that such problems would also afflict lasers, since a large fraction of the carriers would not be available for stimulated emission, because they would not be able to enter the active layer at all.

Auger assistance

Surprisingly, one of the participants in the group behind the work in [4] — consisting of researchers from the University of Arizona, Philipps Universität Marburg and Osram Opto Semiconductors — has been reported as supporting Philips Lumileds' views on the efficiency droop [5]. The apparent turnaround came during a presentation by Osram Opto Semiconductors' Matthias Sabathil at the 2008 International Workshop on Nitride Semiconductors (IWNS). On the basis of "an extensive number of experiments", Osram has come to the conclusion that any presently known physical effect other than an Auger-like loss can be ruled out as the dominant mechanism for the high-current droop of InGaN LEDs.

The LED efficiency droop mechanism proposed is not direct Auger recombination, since that is ruled out by [4], but is rather phonon-assisted — i.e. it taps into energy from lattice vibrations. The experimental work suggests an Auger-like cubic term being responsible for the non-radiative losses. However, theorists on the team have only recently started work on whether a phonon-assisted effect can fully explain these results.

One of these theorists, Jörg Hader of the University of Arizona and Nonlinear Control Strategies Inc of Tucson, comments: "Early indications are that these phonon-assisted losses can be larger than the classical direct ('intrinsic') Auger effect, but we cannot say yet whether they might really be important for the droop.

"I believe that we also have to look into the possibility of density-activated defect-related processes. One idea is based on how lasers operate: at low densities the radiative recombination occurs in high-quality crystal regions, but at higher densities carriers start to spill over into the grain-boundary regions where defect recombination is higher. This density dependence (no loss up to a given density and then a strong linear or higher-power increase for higher densities) might well fit the dependence observed at Philips Lumileds and others. So far, all of this is just a hypothesis."

Easing hole navigation

Virginia Commonwealth University is among those criticizing the Auger hypothesis [6] on the basis of [4], InGaN laser diode behavior, and from the behavior seen in their work. The Virginia group believes that the problem instead arises from the difficulty that the heavy-mass holes have in navigating the MQW structure. In GaN, the (heavy) hole has an effective mass of about 1.4 times that of an electron in a vacuum (m_0), but the electron effective mass is ~$0.2m_0$.

Virginia's most recent work [7] focuses on creating the conditions for a more even spread of holes through the MQWs, thus increasing the effective active region, for example by reducing the thickness of the barrier ($In_{0.01}Ga_{0.99}N$) from 12nm to 3nm, allowing better hole penetration. The $In_{0.14}Ga_{0.86}N$ wells measure 2nm. The current density of the peak external quantum efficiency shifts up from 200A/cm^2 to 1100A/cm^2 for the thinner barrier (Figure 6). The photon wavelengths produced were in the range 400–410nm.

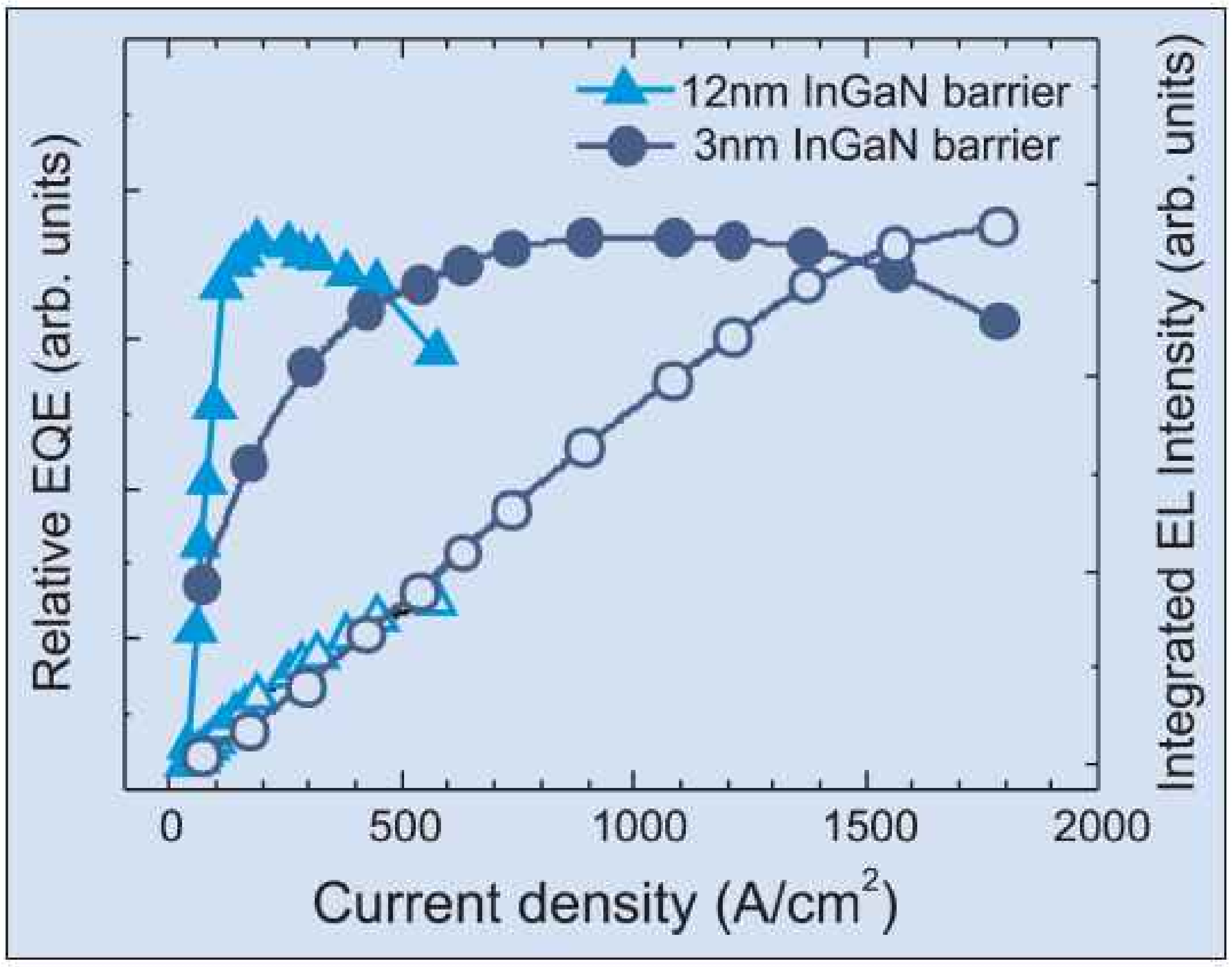

Figure 6. Efficiency (closed symbols) and integrated electroluminescence intensity (open symbols) versus current density for Virginia Commonwealth University devices with 12nm and 3nm barriers.

One notices that the droop current densities quoted by Virginia, even for its comparison device, are an order of magnitude higher than the tens of A/cm^2 quoted by other groups. Professor Hadis Morkoç, leader of the Virginia group, attributes this to the use of an electron-blocking layer. In testing the devices, a 10μs pulsed current (1% duty cycle) is used to avoid effects from the heating up of the device. Thermal effects reduce the peak current density. Many of the other groups also use pulsed currents in their testing for the same reason, however.

While some of the Virginia devices with 3nm barriers drooped after 1100A/cm^2, others maintained their efficiency at a nearly constant value up to 2000A/cm^2. It is thought that a degraded top ohmic contact was responsible for the early decline in some of the devices. With proper optimization of the contact, the researchers believe that efficiency droop effects could be pushed beyond 2000A/cm^2.

Model calculations on the thick-barrier structure suggest that the hole concentration near the p-type top layer is around seven orders of magnitude higher than that near the n-type side for the thick barrier (Figure 7). For the thinner barrier, the holes become much more evenly distributed through the structure.

Previous work at Virginia involved the creation of five blue-light emitting InGaN MQW structures [6], which explored various designs to increase the hole concentration throughout the MQW, such as lowering the barriers by using $In_{0.01}Ga_{0.99}N$ rather than GaN or by doping the barriers with Mg to spread the holes more evenly through the device. Although the MQW with doped barriers showed the highest EQE peak, it is not really a suitable structure for producing high-brightness LEDs, since the Mg in the barriers tends to diffuse into the wells, killing the luminance.

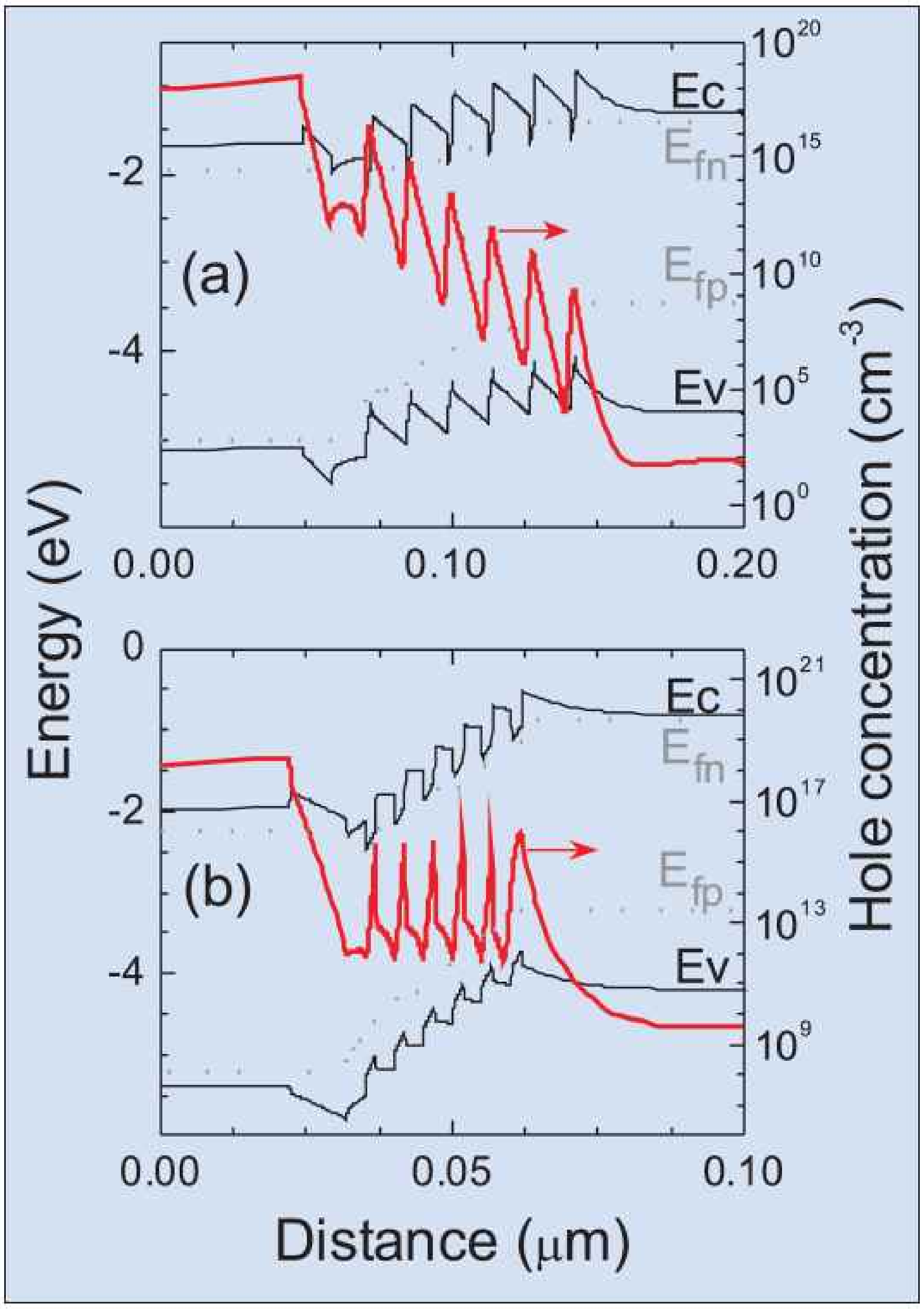

Figure 7. Model calculation of energy band structure and hole concentration distribution for MQWs with 12nm (top) and 3nm (bottom) barriers, as used by Virginia Commonwealth University.

Like Philips Lumileds, Morkoç also sees thicker-layer double heterostructure LEDs as another route to better InGaN LEDs.

Other groups believe that electron transport is the problem. Rensselaer Polytechnic Institute (RPI) and Samsung Electro-Mechanics researchers point out that the interfaces between the AlGaN commonly used as an electron-blocking layer and the GaN barriers between wells have a positive sheet charge [8]. This charge reduces effective barrier heights for electrons. The RPI–Samsung group has compared the performance of GaInN/GaN and GaInN/AlGaInN well–barrier structures with AlGaN electron-blocking layers.
The quaternary AlGaInN LED is designed to reduce polarization charges throughout the structure.
The efficiency peak of the traditional structure is less than 5A/cm^2, while that of the quaternary device is at 22A/cm^2. While the peak efficiency of the quaternary device is less than 70% of that of the traditional structure, its fall-off at higher currents is far less steep, and beyond 50A/cm^2 its efficiency is greater for the region out to 300A/cm^2.

➤

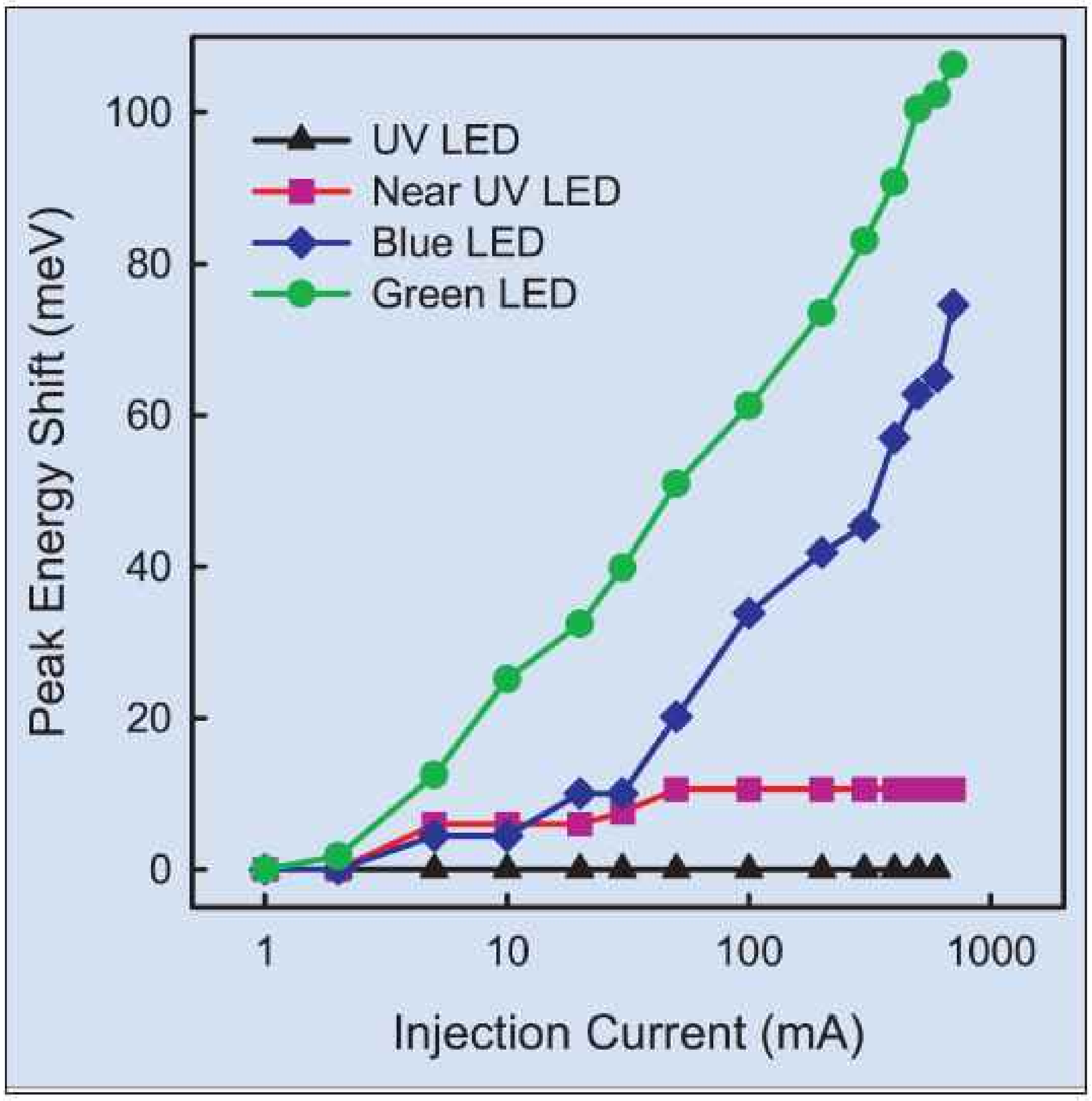

Figure 8. West Virginia University finds that there is a blue-shift in the photon emission for LEDs containing $In_xGa_{1-x}N$ wells with x values of 0.28, 0.17 and 0.09, giving green, blue and near-ultraviolet emission. The UV device had indium-free AlGaN wells.

Indium variation

Researchers at West Virginia University [9] have varied the indium content of MQW LEDs. The peak efficiency current is found to decrease as the indium content increases. At the highest indium concentration, the peak came at $1.4A/cm^2$. The $In_xGa_{1-x}N$ wells had x values of 0.28, 0.17 and 0.09, giving green, blue and near-ultraviolet emission. The GaN barriers were silicon doped. The group also performed measurements on an AlGaN MQW LED that showed saturation of efficiency, but no droop as current increases. As the indium content grows, there is a greater blue-shift and broadening of the spectral peak for photon emission as the current increases (Figure 8). By contrast, the UV LED hardly changes its spectral peak as current increases. Pointing to a weak dependence of Auger recombination on material composition [10], the researchers reject this mechanism as the source of the droop.

The West Virginia group interprets the spectral shift as being indicative of localization effects as being the key non-thermal source of the droop in InGaN devices. The emission is seen as taking place in indium-rich regions but, as the local bands fill up when the current increases, the extra electrons go into the conduction band and move to nearby defects where they recombine non-radiatively with holes, killing the radiative efficiency. The researchers see the blue-shift as supporting this conclusion. As the local band fills up, the energy gap between the electron and hole levels increases. UV LEDs radiate through band-to-band transitions and do not have such localization effects.

Growing LEDs on GaN rather than sapphire showed increased efficiencies but continue to demonstrate a droop. This suggests that dislocations are not responsible for the droop. The researchers believe that the defects responsible for the droop are misfits in the wells and at the well/barrier interfaces. The increased indium content creates phase separation and lattice mismatches between the underlying substrate and the quantum well layers, it is believed. ■

References

[1] Shen et al, App. Phys. Lett., vol.91 (2007), 141101
[2] e.g. by Philips Lumileds' own team: David et al, App. Phys. Lett., vol.92 (2008), 053502
[3] Gardner et al, Appl. Phys. Lett., Vol.91 (2007), 243506
[4] Hader et al, App. Phys. Lett., vol.92 (2008), 261103
[5] "Osram sides with Lumileds' droop theory", Compound Semiconductor, online news, 14 October 2008
[6] E.g. in Xie et al, App. Phys. Lett., vol.93 (2008), p121107
[7] Ni et al, App. Phys. Lett., vol.93 (2008), 171113
[8] Schubert et al, App. Phys. Lett., vol.93 (2008), 041102
[9] Cao et al, J. App. Phys., vol.104 (2008), 093108
[10] As found in Philips Lumileds research for x = 0.09-0.15, [1, 3]