New approaches to efficiency droop in nitride & phosphide LEDs

New ideas and results from simulations and experiment at varying temperature down to 80K are emerging for efficiency droop problem of nitride semiconductor LEDs. Similar experiments on phosphide LEDs also show droop effects even when absent at room temperature. Mike Cooke reports.

While white-light emitting diodes (LEDs) begin to penetrate the mass market for general illumination, the efficiency characteristics of these devices continue to challenge scientists and engineers. The leading concern is 'efficiency droop' where the device efficiency falls off dramatically beyond a certain injection current (often in the tens of milliamps range). Droop limits the amount of light that can be efficiently extracted from one device so that LED-based illumination requires larger numbers of emitters, increasing production cost.

There are a number of approaches to explaining the droop effects. Since light is produced through electron–hole recombination, a natural explanation would be a competing mechanism that absorbs the energy. Auger recombination is such a mechanism, where the energy is transferred to another carrier. However, there is a wide range of alternative explanations such as polarization effects (particularly strong in nitride semiconductors) creating electric fields that separate electrons and holes, and electron overspill from the active region into the p-type hole injection region.

Here, we look at two alternative approaches to droop. One beginning from the perspective of nitride semiconductor LEDs at varying temperature, the other explores droop effects in the more mature red LEDs with phosphide active light-emitting regions. In the past few weeks, the first approach has also been extended to phosphide emitters.

Effect of unbalanced carrier densities

Rensselaer Polytechnic Institute (RPI) and Samsung LED see the unbalanced nature of the n-type (electron) and p-type (hole) injection regions as playing a more important role in droop than previously considered [David S. Meyaard et al, Appl. Phys. Lett., vol99, p251115, 2011].

A major problem in producing light emission from electron–hole recombination in nitride semiconductor devices is the difficulty in producing p-type conduction. Electron (n-type) and hole (p-type) carriers are created through doping with elements that either donate or accept electrons from the conduction or valence bands, respectively. Silicon (Si) has a donor electron level in gallium nitride that is in the range 12–20meV from the conduction band. By contrast, the magnesium (Mg) acceptor level (E_A) is 140–210meV from the valence band.

These values need to be compared with the typical thermal energy available to excite electrons or holes at room temperature (~300K) of ~26meV (k_bT). The silicon level is therefore almost completely ionized, while only a few holes are created through magnesium doping. A simple Boltzmann factor ($\exp(-E_A/k_bT)$) suggests suppression of hole carrier concentrations by 2–3 orders of magnitude, compared with electron concentrations in silicon-doped n-type regions. This asymmetry is worsened by going to lower temperatures. Unfortunately, there is presently no better way to create the p-type material needed for hole injection into light-emitting structures.

The researchers developed their analysis both with simulations and experimental work. The advantage of simulations is that possible effects of the unbalanced carrier densities of reality ($p \ll n$) can be compared with the more difficult-to-achieve balanced situation ($p \sim n$). To simplify the simulation, a single p–n junction in pure gallium nitride was investigated.

The product of the n- and p-type carrier densities was taken as an indication of the amount of recombination occurring, and hence the amount of radiation. With the balanced situation, the peak for recombination moved slightly (1.6nm) towards the p-end as the current increased. With the more realistic unbalanced situation with electron carrier densities on the n-side very much greater than hole densities on the p-side, the shift was more than ten times bigger at 18.3nm.

Another effect of having unbalanced carrier densities is that the high electric field/potential drop occurs not just over the depletion region but also extends into p-type region. Since the mobility of electrons (100–300cm^2/V-s) is much higher than that of holes (1–5cm^2/V-s) in GaN, the effect of this electric field is much higher on electrons. In this case of high-level injection, the conductivity of the depletion region can be comparable to that of the p-type region, due to the lack of majority carriers: both the low carrier concentration and low mobility lead to low conductivity in p-GaN.

Real nitride LEDs are usually constructed with undoped quantum wells of indium gallium nitride (InGaN) sandwiched between n- and p-type GaN layers. However, like in the simulation for unbalanced carrier densities, there has been observed a tendency for the radiative recombination to occur toward the p-end of the heterostructure. It has also been found useful to create electron barrier layers (EBLs) between the active light-emitting region and the p-type region, blocking the overshoot of electrons into the p-type GaN. Such overshooting not only produces non-radiative or parasitic recombination, it also reduces the amount of hole injection into the active region.

The researchers tested their ideas by operating nitride semiconductor LEDs emitting at wavelengths around 440nm (blue) under a range of temperatures from 80K to 450K. The 5-period multi-quantum well (MQW) LED epitaxial structure of InGaN with GaN barriers was grown using metal-organic chemical vapor deposition (MOCVD) on sapphire. An electron-blocking layer of aluminum gallium nitride (15% Al) was placed after the MQW structure. The nitride layers were then transferred to silicon substrates by wafer bonding and laser lift-off removal of the sapphire. The exposed GaN N-face was roughened to improve light extraction.

The silicon wafer with flipped nitride layers was then diced into 1mm x 1mm chips. The light-output power was measured using 5μs pulsed currents (1% duty cycle) to avoid self-heating effects.

At the lowest operating temperature of 80K, one expects the p-type conductivity of the magnesium-doped region to be almost completely frozen out, resulting in the concentration of electrons being very much greater than that of holes in the active region. In measurements (Figure 1) one finds the efficiency droop effect to be greatest as the temperature decreases. At the same time, the maximum efficiency is also greatest at 80K, descending as the temperature rises.

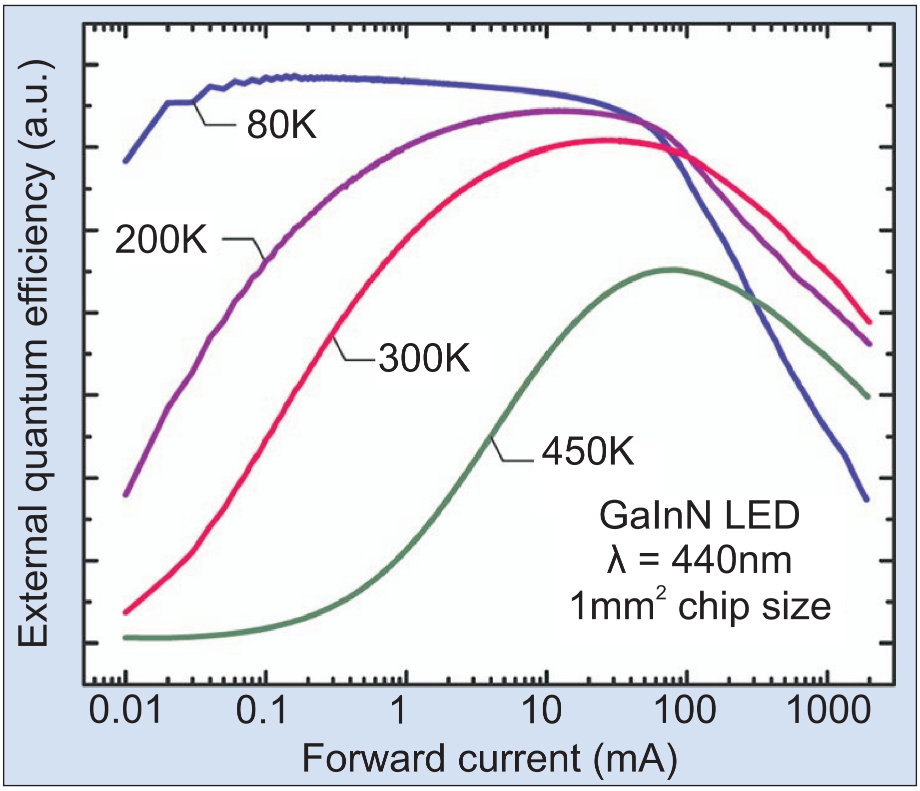

Figure 1. Measured external quantum efficiency of a GaInN LED for several temperatures ranging from 80K to 450K. (Courtesy RPI/Samsung LED.)

The researchers comment: "We propose that this behavior can be explained by the asymmetry in the transport properties of electrons and holes in GaN-based pn-junction diodes. As the temperature decreases, fewer acceptors are ionized. This leads to a large asymmetry in carrier concentration, and therefore an onset of high-level injection conditions at lower currents."

The higher peak efficiency at lower temperature is explained as being due to minimization of the competing non-radiative electron–hole recombination, as expected from the temperature dependence of the Shockley–Read–Hall (SRH) mechanism.

The researchers also studied high-level injection, which occurs when the diode's current–voltage (I–V) behavior deviates from the exponential of simple Shockley theory. It was found that, soon after the current started falling below the low voltage exponential, the peak light emission efficiency was reached (Figure 2).

The researchers comment: "We propose that the onset of high-level injection results in the buildup of an electric field in the p-type region, resulting in stronger electron leakage and a shift of the recombination location into the p-side".

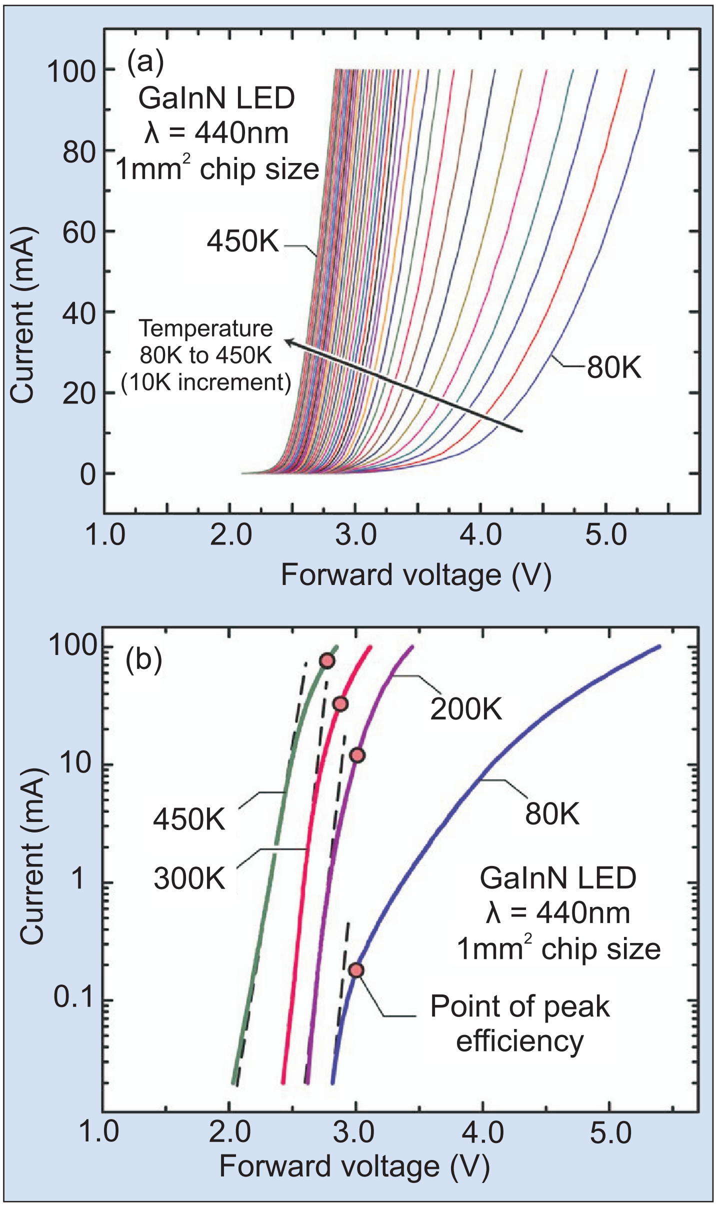

Figure 2. (a) Measured I–V characteristics of the GaInN LED at different temperatures. (b) Measured I–V on a logarithmic scale, showing the onset of high-level injection and series resistance as well as the current at which the efficiency is maximal. (Courtesy RPI/Samsung LED.)

As the temperature increases, the number of holes increases, and the onset of high-level injection is delayed, shifting the peak efficiency to higher current, resulting in less electron spill-over and lower series resistance.

The team also believes that its results are inconsistent with an Auger recombination explanation of droop, since the Auger mechanism "is a high-carrier-concentration phenomenon that would not be expected to increase at low temperatures".

Another effect of reducing the operating temperature was to increase the LED turn-on voltage. The large shift between 1V and 2V was explained as being due to the temperature dependence of the junction voltage.

Current crowding effects as a cause of droop

Ukraine's Lashkaryov Institute of Semiconductor Physics and Russia's Scientific Research Institute of Semiconductor Devices have been exploring current crowding (CC) effects that lead to droop in 625nm (red) LEDs based on the more mature aluminum gallium indium phosphide (AlGaInP) compound semiconductors [V. K. Malyutenko et al, IEEE Photonics Technology Letters, v23, p1745, 2011]. Such devices have reached internal quantum efficiencies of nearly 90%, compared with the 70% level for the best nitride devices.

The LEDs of Malyutenko et al were made from commercially available epitaxial structures grown on 200μm-thick n-GaAs substrates. The p- and n-type cladding layers were AlGaInP. The active light-emitting region consisted of multi-quantum wells (MQWs). A 1.7μm distributed Bragg reflector (DBR) made of AlGaAs was grown first, between the substrate and n-cladding. The DBR was designed to reduce light absorption in the chip. The device was capped with a 12.4μm-thick transparent p-GaP layer, designed to spread the current evenly across the chip.

The top p-contact metal structure of gold-zinc alloy and gold was patterned (Figure 3). A 1.4mm x 1.4mm reference device with intense CC had a 700μm circular p-contact (LED1). LED2 and LED3 were 1mm x 1mm with more complicated patterning that included a 100μm circular central region and rectangular grids. The bottom n-contact consisted of continuous unpatterned layers of gold-germanium-nickel alloy and gold.

The contact areas were 0.385mm^2 (19.6%), 0.3mm^2 (30%) and 0.14mm^2 (14%) for LED1, LED2 and LED3, respectively. Pulsed currents were used to avoid self-heating effects. The devices were also soldered to massive heat-sinks.

Maximum light output power is achieved for LED2 at high current due to its more distributed contact shape (Figure 4). For all the devices a decrease in power conversion efficiency (PCE) was seen beyond a certain injection current. The peaks came at 35mA for LED1, 70mA for LED3, and 150mA for LED2. The droop at 500mA from the peak values was 66% for LED1, 32% for LED3, and only 12% for LED2. Removing the effect of series resistance gave lower droop impacts of 61.5% for LED1 and 18% for LED3. The efficiency degradation for LED2 became negligible.

The researchers believe that much of the PCE degradation in other devices comes as a result of CC and electrical power lost by series resistance of about 17%, but not a decrease in internal quantum efficiency. CC also impacts the near-field light distribution, causing thermal non-uniformity and catastrophic degradation at hot spots as the current increases. The ideality factor is also driven well above its theoretical value. The researchers comment: "The results presented are significant as they indicate that CC gives a remarkable contribution to the efficiency degradation in AlGaInP LEDs with non-optimized p-contact shape".

The researchers also analyzed the emission pattern using a charge-coupled device (CCD) microscope. At a low current under 1mA, the device emissions are uniform but, as the current increases, current crowding becomes evident in non-uniform emission patterns. At 250mA, the ratios of local power output intensity between the near-contact and peripheral regions are 21, 2, and 13 for LEDs 1–3, respectively.

For LED1, the current spreading length from the contact was estimated to be 425μm at low current, but decreased to 75μm at 250mA. One difference between LED1 and LED2 is that only about 5% of the former device's area can be considered to be effectively emitting. By contrast, the researchers comment, "practically the whole contact-free area in LED2 remains active at high currents, as the distance between the contact stripes forming the p-contact remains less than double the current-spreading length".

The researchers see their results as having application beyond red AlGaInP/GaAs LEDs. Non-uniform current injection and high series resistance are features also of vertical and lateral blue and green nitride semiconductor LEDs, which also suffer from lower power conversion efficiency.

Malyutenko comments that his group's work concentrates on the efficiency droop in AlGaInP/GaAs LEDs that has rarely been mentioned since 2002. Up to now this effect has been neglected due to the low efficiency droop that resulted from very high red LED quality.

Malyutenko's group was the first to demonstrate large current (and heat) crowding effects combined in blue LEDs [V. K. Malyutenko, et al, Proc. SPIE, vol5941, p59411K, 2005]. Since that time, Malyutenko has considered current crowding as one of the major reasons for low nitride LED performance. He is also critical of efforts to explain droop effects while assuming uniform carrier injection.

Malyutenko also points out that any thermodynamic engine, such as an LED, has only one practical figure of merit: power conversion efficiency (PCE), defined as the ratio of output and input

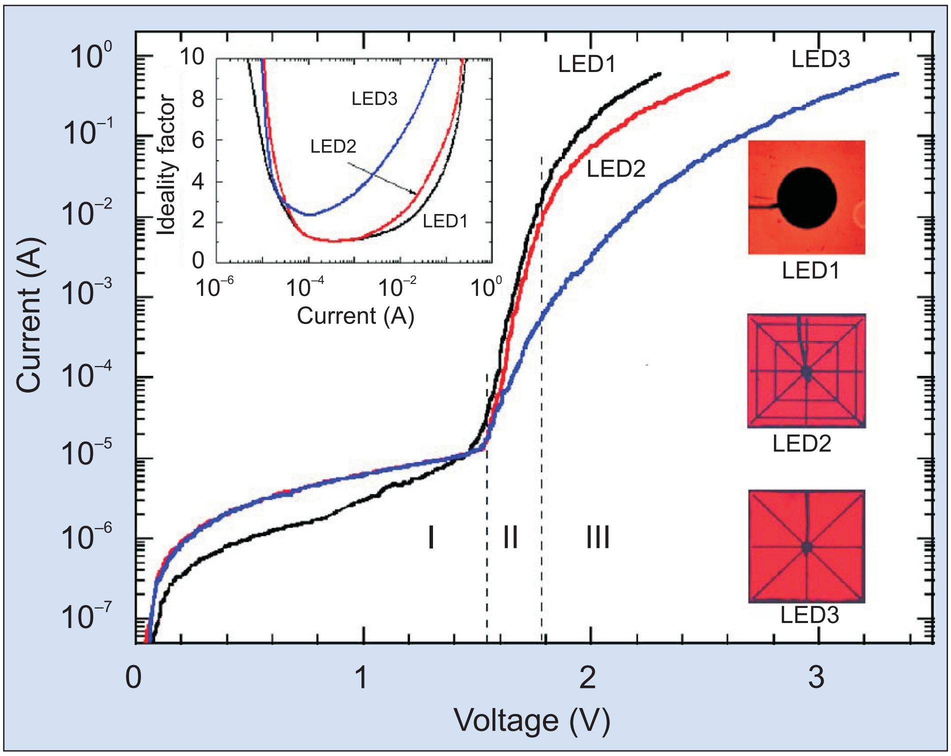

Figure 3. Experimental dependencies of forward-biased LEDs having three regions. Inset: ideality factor as a function of current. Also shown are micrographs of chips under low current injection. (Courtesy Institute of Semiconductor Physics/Institute of Semiconductor Devices .)

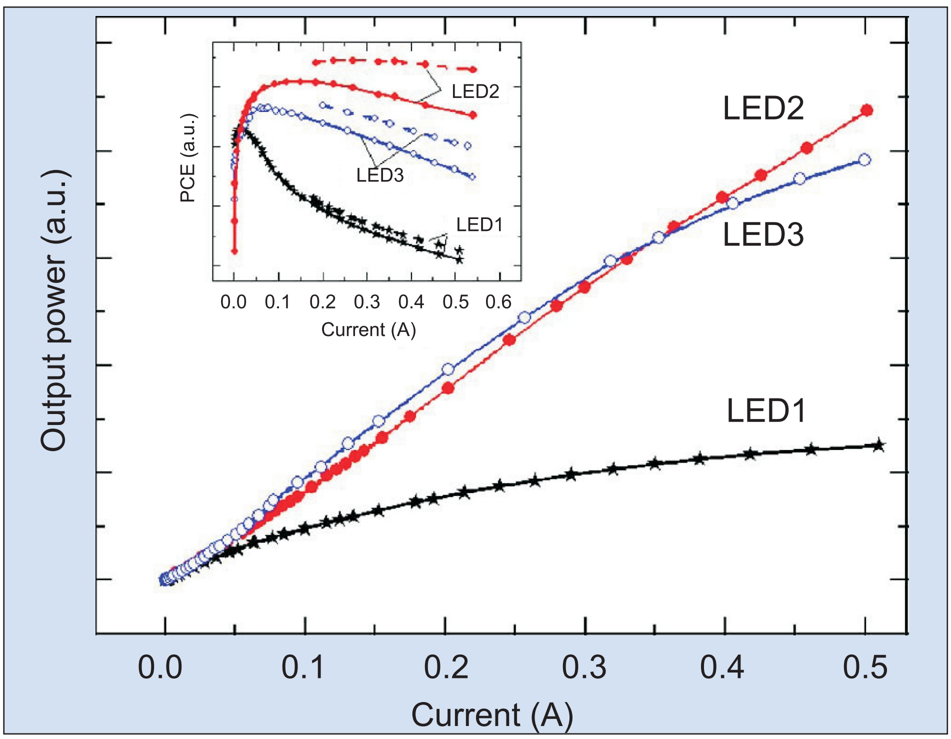

Figure 4. Measured output power versus drive current for different LEDs. Inset: power conversion efficiency as a function of current calculated for input power (solid lines) and power consumed by the junction (dotted lines). (Courtesy Institute of Semiconductor Physics/Institute of Semiconductor Devices .)

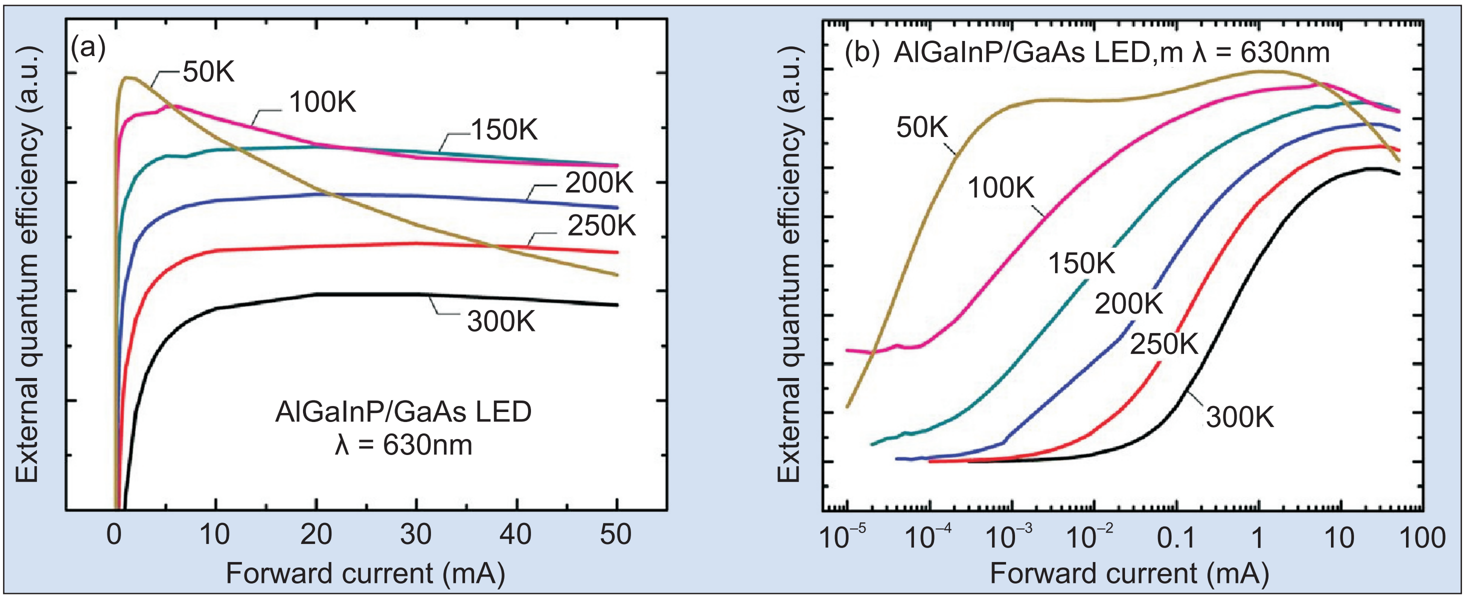

Figure 5. External quantum efficiency versus current of Hanyang/RPI/Samsung AlGaInP LED for different temperatures using (a) linear and (b) logarithmic abscissa.

powers. Ignoring losses in driver circuits, the PCE of LEDs is composed of four factors: electrical, injection, radiative and external efficiencies. Studies of efficiency droop tend to take only injection and radiation losses into account. However, the electrical factors become more significant at higher currents and, if current crowding occurs, the electrical loss is even more catastrophic.

In recent weeks, Hanyang University, RPI and Samsung LED have applied the RPI/Samsung asymmetric carrier transport analysis to AlGaInP LEDs [Jong-In Shim et al, Appl. Phys. Lett., vol100, p111106, 2012]. In particular, the researchers carried out cryogenic measurements and found efficiency droop effects at lower temperatures (Figure 5). The devices had active regions consisting of 38 quantum wells and 39 barriers of AlGaInP. The injection regions consisted of p- and n-type AlInP (Figure 6). The layers were lattice-matched with the GaAs substrate used. Due to the mature, well established growth technique and the material properties of AlGaInP, the droop cannot be attributed to factors such as polarization electric fields or threading dislocations that feature prominently in discussions of nitride semiconductor devices.

Instead, the researchers use a similar approach to the earlier RPI/Samsung paper described above. As the temperature is reduced, the holes are frozen out, creating asymmetric high-level injection effects such as the conductivity of the depleted active region becoming comparable to that of the p-AlInP cladding. As with nitride semiconductors, AlGaInP doping for p-type conductivity has a higher activation energy and lower mobility compared with n-type doping. Typical mobility figures are $100cm^2$/V-s for n-AlInP and $7cm^2$/V-s for p-AlInP. However, the activation energy is lower than for p-GaN, allowing non-droop behavior at room temperature. The reduction of peak efficiency as the temperature increases is attributed to the increase of the non-radiative Shockley–Read–Hall recombination mechanism. ■

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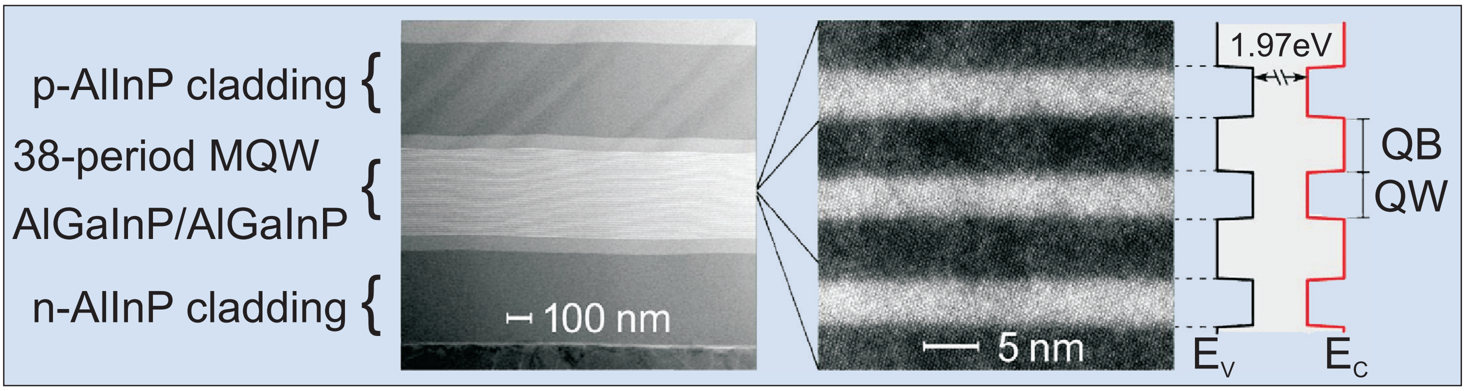

Figure 6. Transmission electron micrograph of the active region of Hanyang/RPI/Samsung AlGaInP LED.