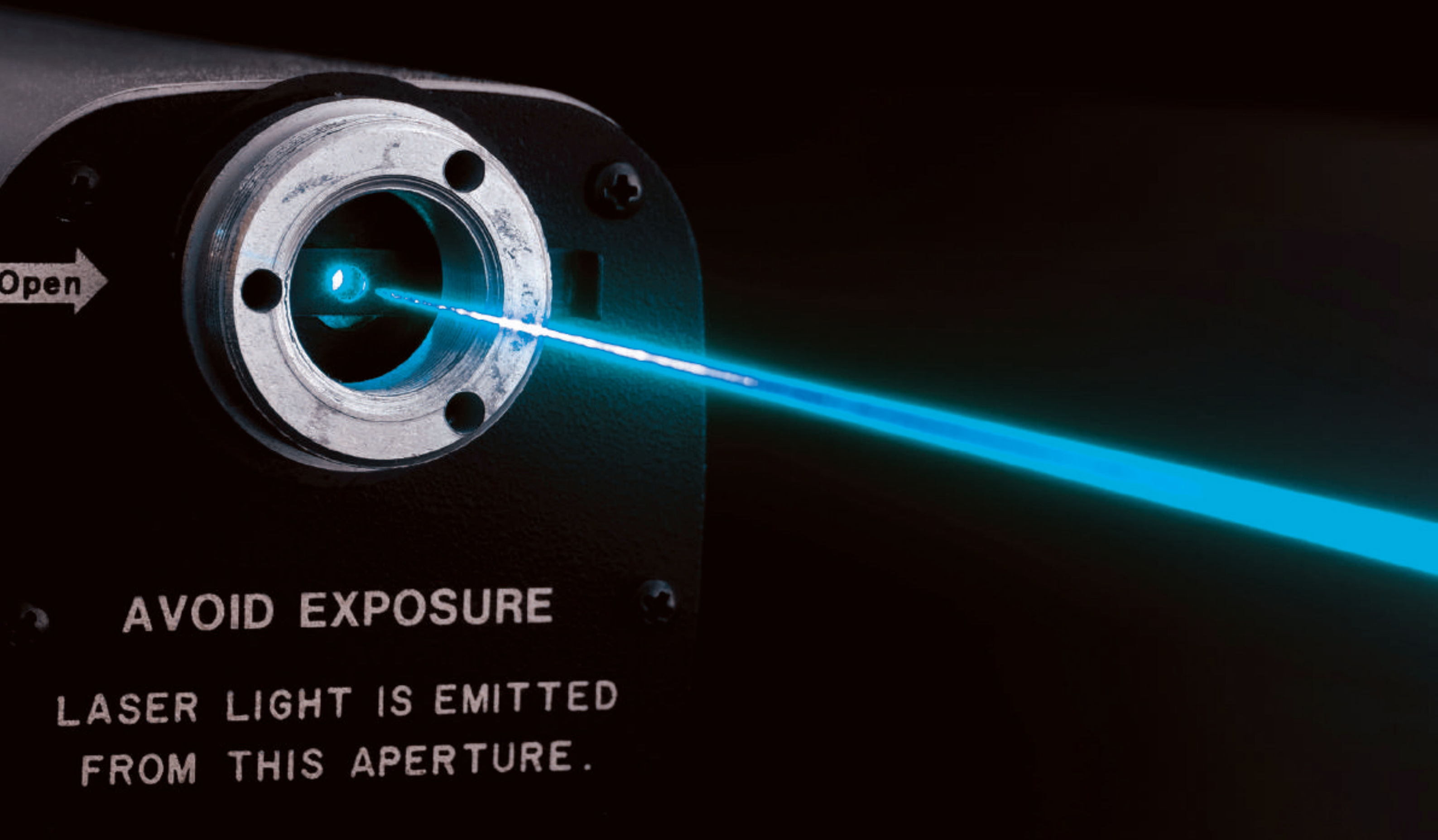
What is to blame for the low energy efficiency of GaN-based lasers?

Why is the power conversion efficiency of the leading GaN lasers just half of that of the best LEDs?

BY JOACHIM PIPREK FROM THE NUSOD INSTITUTE LLC



Back in 2014 Shuji Nakamura received a Nobel Prize for Physics for the invention of the efficient GaN-based blue LED, a device that has enabled energy-saving white light sources. At the time he predicted that this device could soon be usurped by the GaN-based laser. But this is yet to happen – and it's not going to any time soon.

Although such lasers are being implemented in the headlights of high-end cars, such as BMWs, they are failing to make much impact in the general solid-state lighting market. That's predominantly because the blue LED's power conversion efficiency can hit 84 percent, while that for the laser is, at best, just 43 percent (the power conversion efficiency is defined as the fraction of electrical input power emitted as light output power).

If lasers are to displace LEDs in solid-state lighting, this gap will have to close. And if this is going to happen, efforts must begin with a comprehensive understanding of the physical mechanisms that are behind the low laser efficiency. At the NUSOD Institute we have been trying to do just that: read on to discover our findings.

To uncover a deeper understanding of the efficiency deficit, we have used advanced laser simulations to reproduce and analyse measured laser characteristics. These efforts have focused on a study of Panasonic's 7.2 W laser that emits at 405 nm. It delivers a record-breaking output power, due in part to a novel double-heat-flow packaging technology that trims the thermal resistance to about 7 K W^{-1}.

Another attribute of Panasonic's laser is its minimal internal optical loss (see Figure 1 for vertical profiles of refractive index and lasing mode intensity). Thanks to a small overlap between the lasing mode and the highly absorbing *p*-doped AlGaN cladding layer, the modal absorption coefficient falls to a record-low value of just 2.5 cm^{-1}.

One insight from our numerical analysis is that most of the remaining absorption is caused by free carriers inside the waveguide layers, which are located between the quantum wells and electron blocker layer (this is shown in the dashed line in Figure 1). Triggering free-carrier absorption is electron leakage from the quantum wells, which rises with increasing current injection.

Self-heating of the laser diode is behind the escalation in electron leakage. Despite the device's low thermal resistance, the temperature of the quantum well increases by 120 degrees when the injection current hits 4 A. It is well-known that self-heating is detrimental, reducing gain in the quantum well, so more carriers are required to maintain lasing (see Figure 2 for plots of laser power and carrier density with and without self-heating).

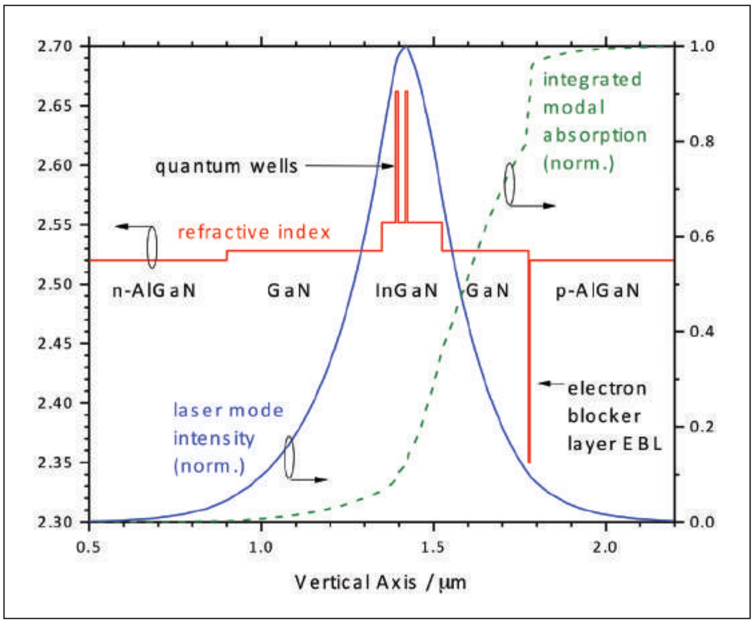


Figure 1. A vertical profile of the refractive index (red), normalized optical mode intensity (blue) and the integrated modal absorption (green, dashed) of the high-power Panasonic laser investigated by NUSOD. The internal optical wave peaks at the two quantum wells (QWs) that transform electrons into photons. But some electrons leak into the *p*-side InGaN/GaN waveguide, between QWs and the electron blocking layer (EBL), where they attract holes and cause free-carrier absorption of the laser light. The light wave suffers some more absorption in the highly *p*-doped EBL and *p*-AlGaN layer.

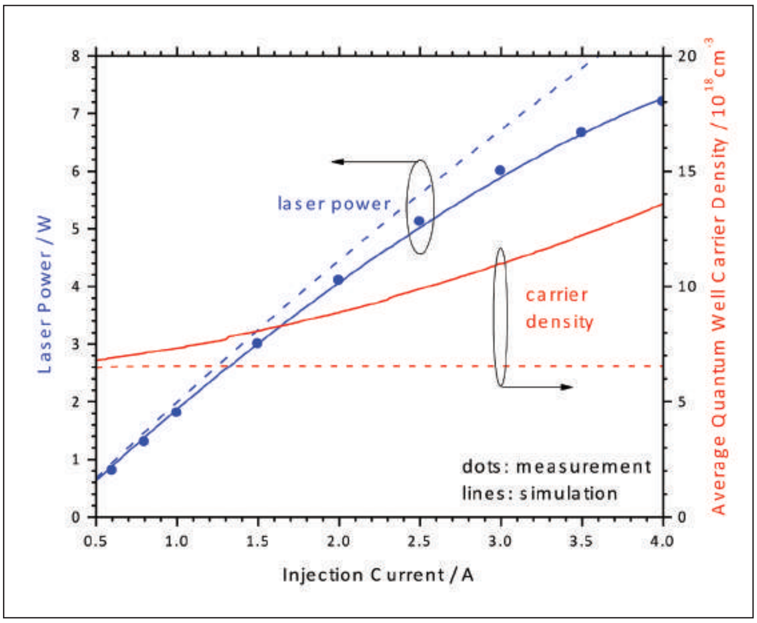


Figure 2. Laser power (blue) and quantum well (QW) carrier density (red) as a function of injection current above lasing threshold. The widely held view that the QW carrier density remains constant is only true if the internal laser temperature is kept constant (dashed lines). But high-power lasers typically suffer from strong self-heating, causing declining QW optical gain. So, QW carrier density must rise to maintain lasing, which eventually leads to a declining lasing power (dots and solid lines).

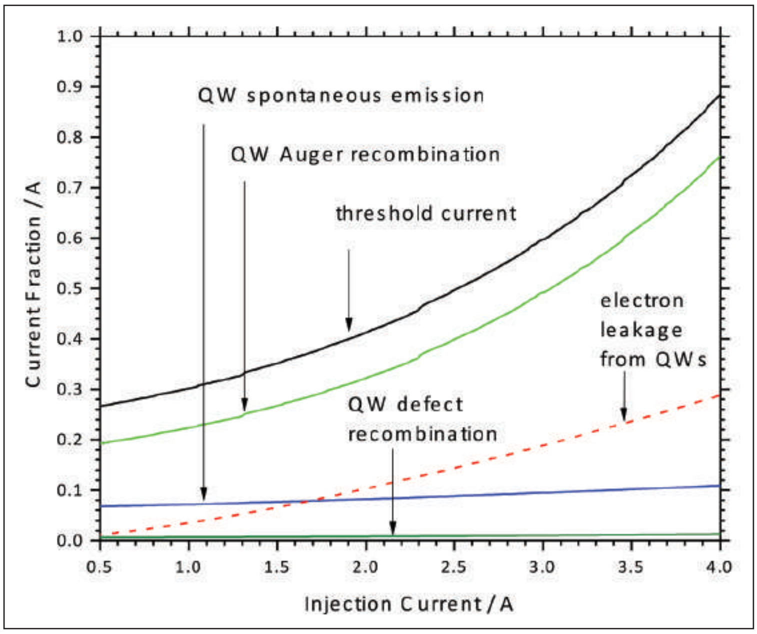


Figure 3. Simulated contributions of different carrier loss mechanisms to the total injection current. The highest loss is caused by Auger recombination (light green line), which rises most strongly with carrier density (see Figure 2). Together with spontaneous photon emission and defect-related recombination, it adds up to the threshold current, which compensates for all carrier losses inside the quantum wells (QWs). Due to self-heating, the threshold current keeps rising above the initial lasing threshold. The leakage current (dashed line) lowers the slope efficiency of the laser.

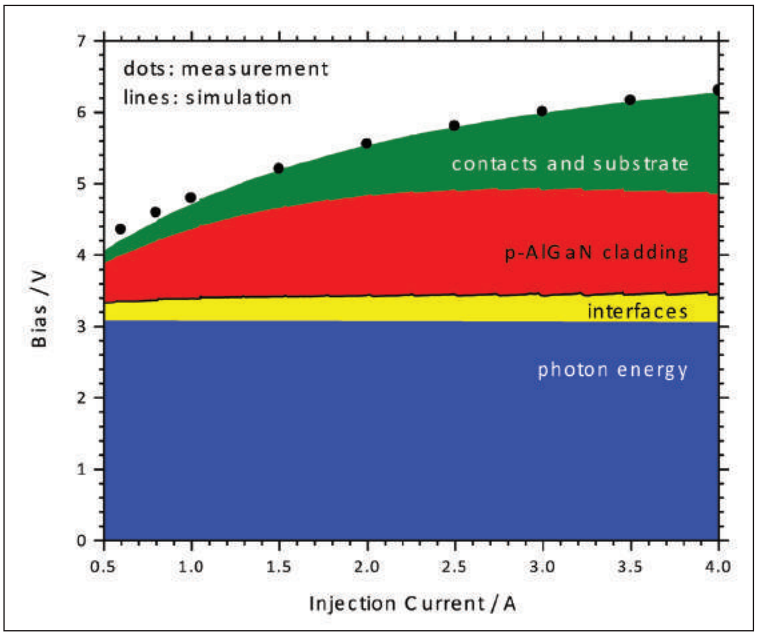


Figure 4. Contributions to the total laser bias, part of which is consumed by the photon energy of the laser light (blue area). The remaining bias is considered excess bias, attributed to the series resistance of the diode, which is dominated by the poor conductivity of the *p*-AlGaN waveguide cladding layer (see Figure 1). Simulations at NUSOD reveal that the *p*-AlGaN contribution is actually shrinking with higher current, because the higher temperature activates more free carriers from the deep magnesium acceptor levels. Hetero-interfaces create a relatively small resistance (yellow area). The remaining excess bias (green area) is mainly caused by the *p*-side contact resistance.

It is often assumed that the carrier density in the quantum well is constant. However, this cannot be the case when the temperature in the well changes. If it rises, the density of carrier increases. In turn, there is an increase in carrier losses inside the quantum wells via Auger recombination, defect-related recombination, and spontaneous photon emission. Of these three, Auger recombination rises the fastest, because it is proportional to the third power of the carrier density.

When carrier losses escalate, fewer carriers are available for stimulated photon emission, a fundamental process for laser emission. However, the threshold current compensates for all carrier losses inside the quantum wells (see Figure 3 for plots of the current components, as well as the resulting threshold current as function of the total current). Unfortunately, such a rise in threshold current is usually neglected in the efficiency analysis for high-power lasers. This has led several groups, including that of Nakamura at UCSB, to incorrectly assume that Auger recombination is irrelevant at high lasing powers.

We have also investigated the need for a high bias for GaN laser operation. For Panasonic's device, the 7.2 W output requires a 6.3 V bias – that's high, considering that only about half of this value is needed for the emitted photons (see Figure 4). So where does the rest go? It is consumed by the high series resistance, which is primarily attributed to the extremely low electrical conductivity of the *p*-type AlGaN cladding layer.

A high electrical resistance should be expected, given that hole conduction in *p*-doped layers has always been a problem in GaN-based devices. Due to the large magnesium acceptor ionization energy, the density of free holes is only about 1 percent of the acceptor density at room temperature, so magnesium has to be incorporated at a very high density. That diminishes hole mobility.

However, our numerical analysis reveals that the contribution of the *p*-AlGaN cladding layer shrinks at higher current (see the red area in our simulation results in Figure 4). This stems from the strong self-heating of the laser, which enhances conductivity by activating more free holes. In addition, there is significant contribution to the excess bias from the *p*-side contact and substrate, and a small contribution from the hetero-interfaces (see the green and yellow areas, respectively, in Figure 4).

To summarise the results of our efficiency analysis, we have plotted the contributions of the various mechanisms as a function of the drive current of the laser (see Figure 5). Device efficiency peaks at 39 percent at a relatively low current near 1.5 A, and falls as current increases. At the peak power output, 7.2 W, efficiency is less than 30 percent.

Another way to look at this is that at a drive current of 4 A, more than 70 percent of the electrical input power is wasted by various loss mechanisms. The greatest villain is Joule heating, caused by high series resistance. Second on this list is carrier losses inside the quantum wells (mainly Auger recombination), which dominate the power budget at lower currents. Additional power losses come from electron leakage and optical absorption.

What can we do about the high excess bias, which is mainly behind this high energy loss? Well, one solution, recently demonstrated by Nakamura and co-workers from UCSB, is to replace the majority of the *p*-doped waveguide cladding layer with a tunnel junction and a highly conductive *n*-doped layer (see Figure 6 for the energy band diagram of a tunnel-junction laser). With this architecture, electrons are injected from the right-hand side contact into the conduction band – and the tunnel junction transforms them into holes traveling in the valence band to the quantum wells, where they meet the electrons injected from the left-hand side, as before.

Merits of this design included the elimination of much of the *p*-cladding resistance and the high *p*-contact resistance. Thanks to this, excess bias plummets (see Figure 7). Reducing the resistance is highly beneficial, because it lowers self-heating. Consequently, fewer quantum well carriers are required for lasing, and Auger recombination falls. The upshot is that the maximum lasing power is now almost three times higher than before (see Figure 7).

With the introduction of the tunnel junction, power conversion efficiency increases to nearly 60 percent at low current – but it is only about 35 percent at peak power (see the blue area in Figure 8). Joule heating now consumes less than 30 percent of the input

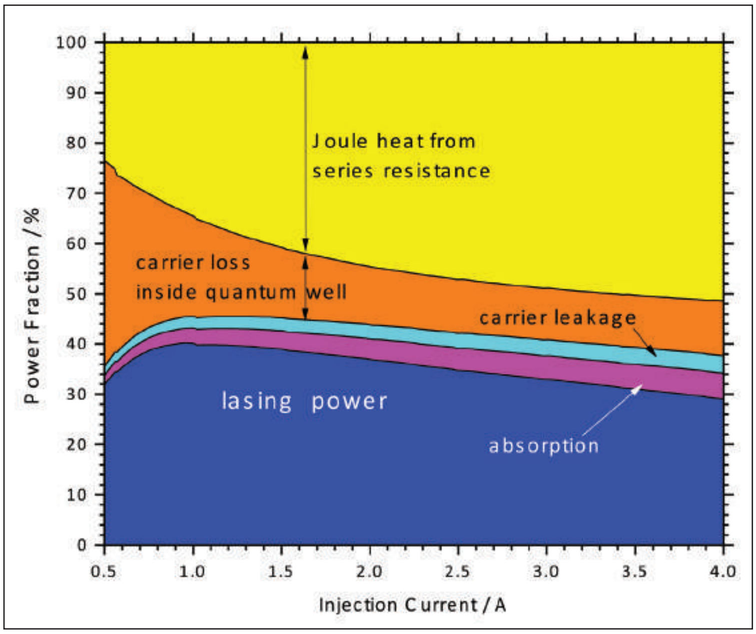


Figure 5. Relative power consumption by different mechanisms above lasing threshold. The power conversion efficiency of this laser remains below 40 percent (blue area). At low current, carrier losses inside the quantum wells consume most of the power (orange area). With increasing current, Joule heating takes over as the leading power loss mechanism (yellow area). Carrier leakage and internal absorption are less important in this case; however, other GaN-lasers exhibit much higher absorption.

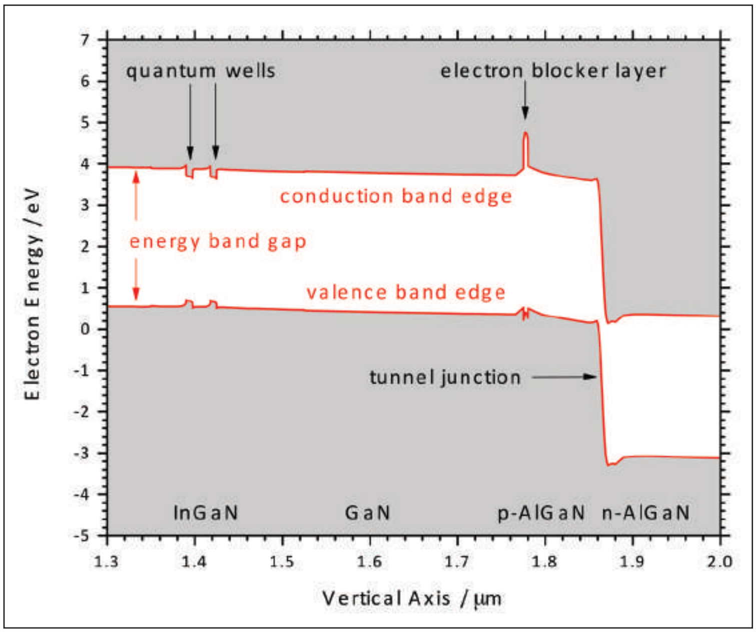


Figure 6. An energy band diagram of the simulated tunnel-junction laser. The *p*-doped AlGaN cladding layer is partially replaced by an *n*-doped AlGaN layer that exhibits a much higher electrical conductivity and a much lower contact resistance. The *p*/*n* interface is highly doped to form a tunnel junction. It allows *n*-AlGaN electrons in the conduction band to become *p*-AlGaN holes in the valence band, which eventually generate photons inside the quantum wells by recombining with electrons injected from the left-hand side.

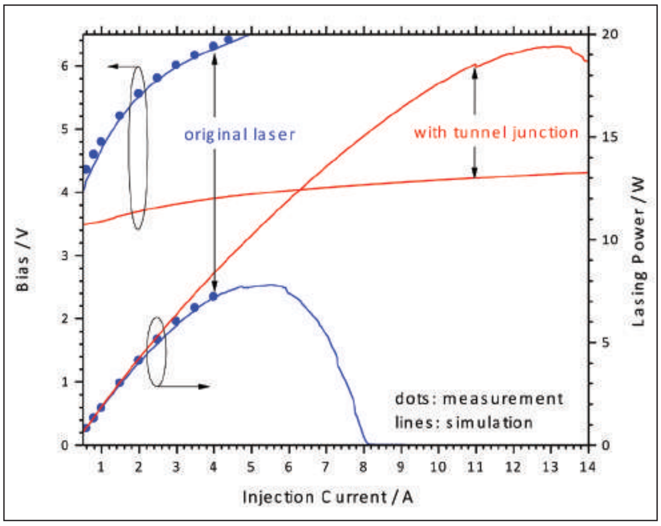


Figure 7. Performance of lasers with and without a tunnel junction. The proposed tunnel-junction laser is represented by the red lines and exhibits an almost three-times higher peak lasing power than the original device. This improvement is mainly attributed to the smaller series resistance, which lowers the Joule-heating and thereby reduces the rise of carrier density (compare with Figure 2) and threshold current (compare with Figure 3).

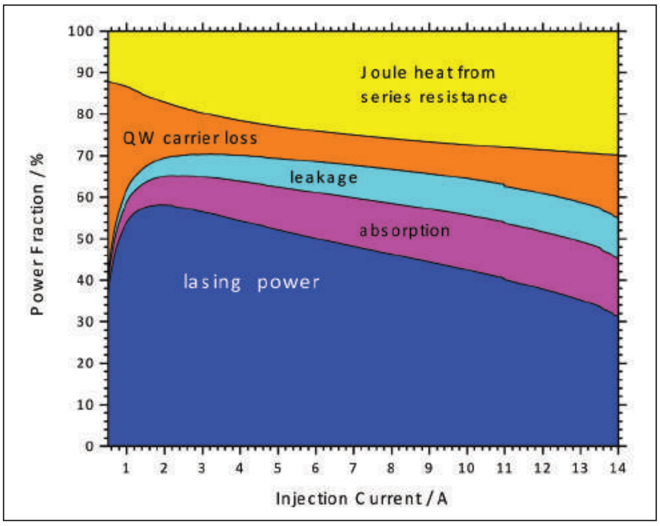


Figure 8. Relative power consumption by different mechanisms in the tunnel-junction laser above lasing threshold. Power conversion efficiency of the laser (blue area) reaches almost 60 percent at low current, but drops to 35 percent at the peak lasing power (13 A). With this design, Joule heating consumes less than 30 percent of the input power. However, due to the high doping of the tunnel junction, absorption loss has increased (pink area). Carrier loss inside the quantum wells (orange area) and electron leakage from the quantum well (cyan area) add up to about 20 percent power loss at the lasing peak.

power, but absorption loss has increased, due to the high doping of the tunnel junction. At the lasing peak, about 20 percent of the loss now comes from the wells, where carrier loss and electron leakage occur.

It is important to note, however, that lasers are usually operated well below the peak power. If this tunnel-junction device is operated at 8 A, it produces an output of 15 W at 46 percent efficiency. That's much more than the conventional device. So, while it's likely that GaN lasers will never get close to the very high efficiencies of GaN LEDs, significant improvements over today's best devices can be expected with the introduction of tunnel-junction contacts.

Further reading

J. Piprek, IEEE J. Quantum Electron. **53** 2000104 (2017) and references therein

NUSOD Institute web site http://www.nusod.org/inst

NUSOD blog at https://nusod.wordpress.com/author/piprek/