NanoLEDs, a new breakthrough for the LED industry

Xavier Hugon and Philippe Gilet of HelioDEL and Patrick Mottier of Leti explain how nanowire-based LEDs can improve LED efficiency and cost reduction for solid-state lighting applications.

With close to 20% of worldwide electricity consumption currently devoted to lighting, switching to high-efficiency light sources presents a major opportunity to reduce the production of harmful greenhouse gases.

Long-term electricity consumption models show that the widespread use of LED light sources capable of producing up to 200 lumens per watt (lm/W), could decrease worldwide electricity consumption for lighting by more than 50%, and total electricity consumption by more than 10% (see 'Solid-state lighting: lamps, chips, and materials for tomorrow', Jeff Y. Tsao, IEEE Circuits & Devices Vol 20 No 3 (May/June 2004) pp28–37).

However, a dramatic improvement is needed for LED-based light sources to reach this level of performance.

Significant cost reductions also are needed to facilitate the widespread use of LED light sources. Packaged white LEDs that now cost more than $10 per 1000 lumens (klm) must be lowered to $1/klm. Concurrently, the so-called 'efficiency droop' — a tendency for LEDs' energy efficiency to fall at high drive currents — has to be eliminated if the industry is to achieve its goal of producing LED packages that can sustain 200lm/W in operation.

This seems to be difficult to achieve with conventional gallium nitride (GaN) LEDs, mainly because of the lack of high-quality, high-diameter and low-price bulk GaN substrates. Instead, many manufacturers are relying on GaN epitaxial layers grown onto sapphire substrates. However, due to the physical mismatch between sapphire and GaN crystals, the GaN layers are inherently stressed, which induces dislocations into the epitaxial layers and decreases LED efficiency and lifetime, as well as manufacturing yields.

For similar reasons, large-diameter sapphire substrates also have been difficult to industrialize. Moreover, sapphire substrates' poor thermal properties require them to be removed before LEDs are assembled and packaged. It should be possible to re-use these larger, more expensive sapphire substrates after LED assembly. However, the substrate recovery process is complex and, at least thus far, suffers from low yield. That, in turn, reduces the cost advantage of processing more LED dies at a time.

All these reasons combine to slow the industry's efforts to reduce LED manufacturing costs.

Looking ahead, the task of combining high efficiency and large injection current density also remains challenging, and will pose a further obstacle to the widespread use of LEDs in general lighting.

Those difficulties generate other system-level drawbacks, since the most-likely cost-reduction route is focused on increasing LED brightness enough to allow the use of fewer square mm of material to produce the necessary lumens. As a consequence, thermal extraction and management have become major issues, and are contributing to increased lamp costs. Moreover, from a usage point of view, LEDs' extreme brightness can become so dazzling so that it requires additional optics to diffuse that brightness at the lamp level.

A disruptive technology

To overcome these limitations, the French research institute Leti is developing a disruptive new technology called nanowire-based LEDs (NW-LEDs), or nanoLEDs. Nanowires are thin crystalline structures that emit a broader spectrum of light than conventional LEDs when electrically charged, and can be grown on industry-standard silicon substrates.

Leti has successfully demonstrated the operation of a first NW-LED, as well as the ability to grow nanowires on silicon substrates using metal-organic vapor phase epitaxy.

Each of these nanowires acts as a nanoLED with an axial symmetry (Figure 1). Starting from its axis, this so-called core–shell nanoLED heterostructure consists of a GaN core surrounded by indium gallium nitride (InGaN)/GaN radial quantum wells, covered by a GaN shell.

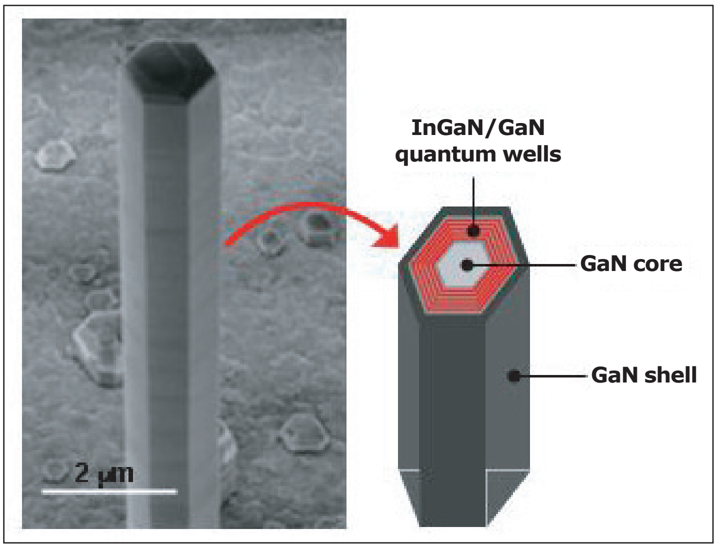

Figure 1. Schematic view of a cross-section of one of Leti's nanowire structures (right), as shown in the SEM image on the left.

After processing substrates to create an extremely high number of nanowire structures (Figure 2), Leti researchers diced the wafers into devices measuring a few mm^2, which were then characterized. The devices presented macroscopic electroluminescence coming from multiple quantum wells, with the emitted light centered in the blue spectral range (425nm) and clearly visible with the naked eye.

Single-wire emission measurements led researchers to expect several tens of optical watts emission per cm^2, an output level that already is comparable to conventional LED levels. As will be explained later, the route toward fulfilling general lighting needs could be achieved without increasing brightness. Nonetheless, no physical limitation has yet been identified that would prevent an increase in NW-LED performance above the level of current high-brightness LEDs. As far as we know, this is the first time that such impressive electroluminescence results have been reported.

In summary, these nanowire structures appear to overcome all of the previously mentioned limitations encountered with conventional LEDs.

Substrate cost and size

Due to their small footprint, nanowires can be grown on a wide variety of substrates. GaN nanocrystals, for example, can easily be grown on 8-inch silicon wafers, opening the door to actual mass production, which is a prerequisite if solid-state lighting is to become the world's dominant lighting technology.

In addition, nanowires' high crystalline quality is largely independent from mismatch between materials. Indeed, the strain induced by the lattice mismatch and differences of thermal expansion coefficients between nanowire material and substrate is localized at the base of the nanowires, and thus able to avoid cracks and wafer bowing — a major concern for conventional LEDs. As a consequence, the wafer size possibilities for NW-LED manufacturing are only limited by the handling capability of the epitaxial tool used.

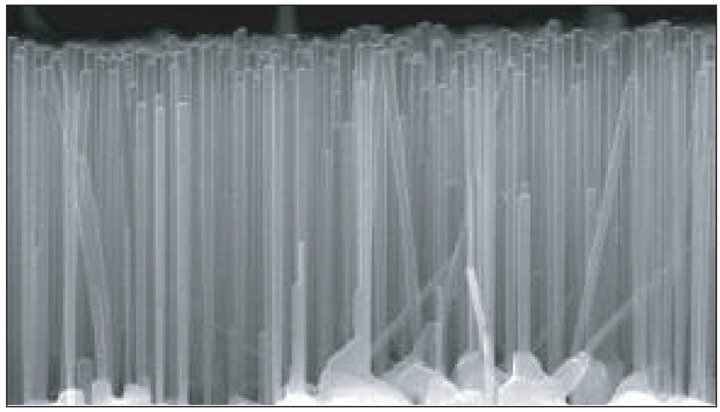

Figure 2. High-density nanowires grown on Si wafer.

New epitaxial technologies could even allow manufacturers to consider using non-silicon, non-monocrystalline substrates, which could potentially be produced using large-volume, roll-to-roll technology, as is already being done with some photovoltaic products.

A simpler process flow

In addition to their wide substrate compatibility, the three-dimensional structures of these new-generation nanoLEDs should allow manufacturers to avoid several process steps that are normally required to produce conventional LEDs. Light extraction from high-index GaN layers, for example, requires additional substrate or LED nanostructuration that comes naturally with NW-LEDs. As a result, NW-LED production is expected to require at least 30% fewer process steps, reducing tool investment as well as processing time and cost.

Solving the efficiency droop issue

The efficiency of GaN-based LEDs decreases when current density increases, resulting in the phenomenon known as efficiency droop. At high current densities, let's say 100 amps per square-centimeter (A/cm^2), conventional LED efficiency decreases by as much as 30–40% compared with the maximum value obtained at low current density (say 35A/cm^2). Specialists don't fully agree on the physical cause of this phenomenon, although the Auger effect is often mentioned as a probable cause.

However, experimental results show that increasing the active area thickness tends to decrease the efficiency droop. Again, due to the large free surfaces of nanowire LEDs, it should be possible to elastically relax the strain in the quantum well and then increase their thickness, which in turn should decrease the efficiency droop. Moreover, thanks to the much larger emitting area than actual die size in the NW-LED core-shell structure, effective current density through the active

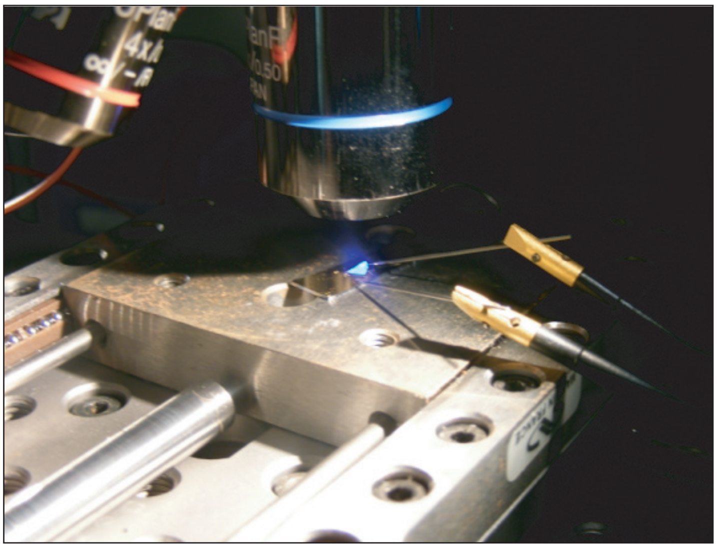

Figure 3. A nanowire LED in operation.

zone is lowered, allowing LEDs to operate in their highest efficiency domain, which should further contribute to reducing the efficiency droop effect.

The green gap issue

For LEDs to emit green light, their indium content must be increased above 20%. However, such a concentration provokes indium clustering or phase separation. In addition, high indium concentration is usually thermally unstable and tends to degrade during the end of the growth cycle. Furthermore, increasing the indium content in InGaN alloy increases its lattice parameter mismatch with GaN, resulting in internal mechanical strain. The strong piezoelectric field induced at the interface between the InGaN quantum wells and the GaN barrier along the c-axis promotes a separation between electrons and holes, decreasing the recombination rate. And that significantly affects the quantum efficiency. Consequently, green LEDs have typically been limited, up to now, to half the quantum efficiency level of blue LEDs. This is the so-called 'green gap' issue.

In nanoLEDs, however, elastic strain relaxation at their free surfaces prevents the quantum well from degrading when the indium content is increased. Furthermore, in the NW-LED core-shell geometry, heterostructures are now grown along m-planes, which are non polar and are therefore free of piezoelectric effects. So, even though it has not been demonstrated yet, core-shell nanowire-based LED technology could offer a way to overcome the green gap issue.

Cost reduction

Besides their substrate quality and size advantages, various other factors are expected to help lower the overall cost of light produced by NW-LEDs. First, because of their three-dimensional structure, the effective light-emitting surface available from a given chip area is significantly larger than that of conventional LEDs. And because manufacturing costs are directly related to the area of chip surface used, NW-LEDs' higher light quantity per chip should contribute directly to lower costs. Second, while current LED technologies require expensive sapphire substrates, the silicon wafers used to fabricate NW-LEDs are much cheaper, especially when used in large diameters. Silicon also is an excellent electrical and thermal conductor, and easier to dice or to remove for re-use. Thus, assembly and packaging costs should be reduced as well.

Novel LED lighting paradigm

Thanks to the great cost-reduction potential shown by NW-LEDs, the high-brightness approach may not be the only route available to the production of more efficient light sources. Depending on the actual cost per cm^2 of die that can be achieved, lower brightness, larger source size and even higher lumen/watt devices may be possible within an acceptable price range for mass-market lighting buyers. That's especially the case when NW-LEDs' drastically reduced thermal management costs are taken into account, as well the decreased need for optics at the lamp level to avoid dazzling users. For many domestic applications, NW-LEDs may be an ideal answer.

Conclusion

The promising results reported here open the way to the development of a new breakthrough in lighting. Indeed, even after the initial LED breakthrough that occurred at the beginning of the century with the emergence of high-brightness white LEDs, and the amazing improvement in performance since then, the general lighting market is still not widely open to LEDs.

NW-LEDs have the potential to greatly extend the performance limits of solid-state lighting. Moreover, the added potential for lower costs will almost certainly help this new technology to make significant market inroads. NW-LEDs are the only credible technology demonstrating sufficient performance at present, as well as the potential for dramatic further improvement needed to meet future market demands.

The implementation of this remarkable technological breakthrough promises to accelerate the process of cost reduction, and to improve LED energy efficiency. ■

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Leti (www.leti.fr) is an applied R&D institute of the French Atomic Energy Commission (www.cea.fr), focused on micro- and nano-technology and located on the MINATEC campus (www.minatec.com), in Grenoble, France.
Hugon and Gilet left Leti to form the start-up HelioDEL.