COMPOUND SEMICONDUCTOR

March 2007 Volume 13 Number 2

CONNECTING THE COMPOUND SEMICONDUCTOR COMMUNITY

LED LIGHTING

Lumileds innovation drives market penetration

PORTFOLIO

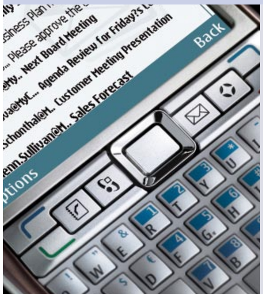
Filtronic and Bookham face some tough decisions p11

TECHNOLOGY

Tuned in; turned on

Syntune develops fabless strategy as demand soars for tunable lasers. p25

HEADLINE NEWS

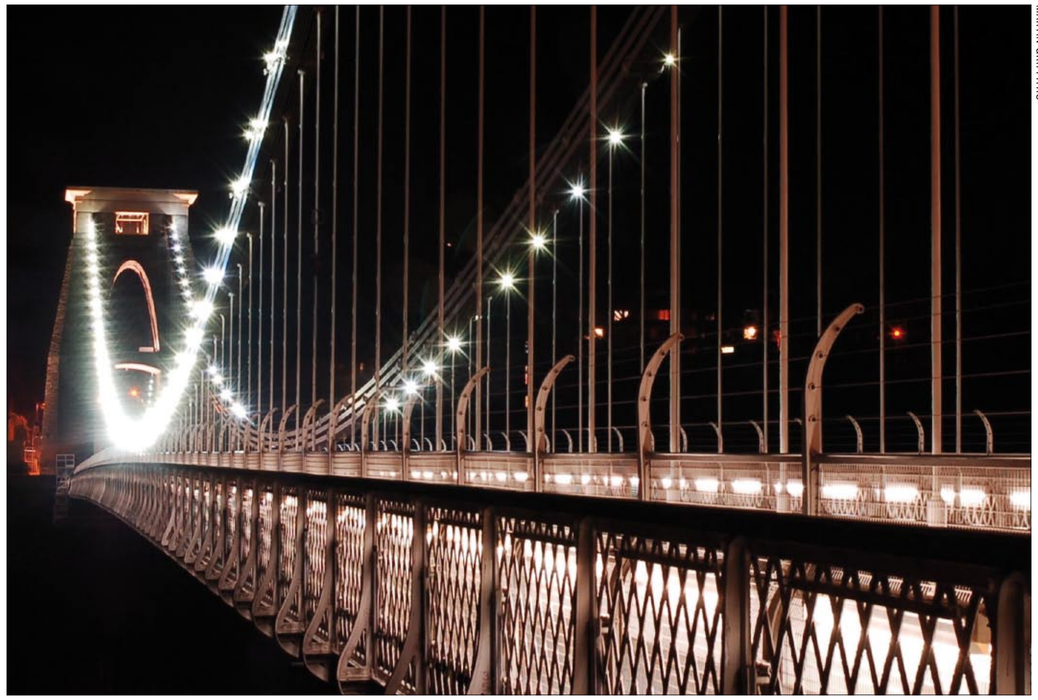


Spanish fever

GaAs grabs the attention as the mobile industry decends on Barcelona. p5

Evolutionary new chip design targets lighting systems

Philips Lumileds has combined its thin-film structure with a flip-chip design. The result, say **Oleg Shchekin** and **Decai Sun**, is a highly efficient device for lighting applications that delivers a better performance than vertically injected LEDs.



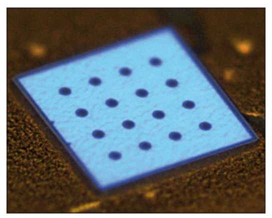
Philips Lumileds' Luxeon LED chips, which incorporate a flip-chip design, already illuminate architectural attractions such as the Clifton Suspension Bridge in Bristol, UK, completed in 1864. The addition of the thin-film technology to Luxeon products will take the performance to a new level and help to initiate penetration into the residential-lighting market.

The performance of commercial white-light LEDs has rocketed over the past few months. Competition has fueled the creation of novel device architectures with improved photon-extraction efficiencies, which have in turn increased the chip's brightness and output power. This has opened up the range of applications for these devices, and brought their characteristics more closely in line with the requirements for widespread deployment in solid-state lighting.

Among the many LEDs available today for these applications is an InGaN/GaN flip-chip (FC) design by Philips Lumileds, which features in our company's Luxeon products. We have now built on this success by uniting it with a thin-film (TF) structure to create a higher-performance thin-film flip-chip (TFFC) LED (see figure 1a).

This device combines the manufacturing merits of both approaches, and is produced by taking an FC-LED chip that has an anode and cathode on the same side and bonding it to a submount or package using gold interconnects (see figure 1b). An excimer laser removes the sapphire substrate before photo-electrical-chemical etching of the top GaN layer roughens the chip's surface with an ultraviolet lamp and a dilute potassium hydroxide solution. This texturing disrupts wave-guiding in the high refractive index epitaxial layers, increases light output and dramatically boosts the LED's external quantum efficiency.

The TFFC LED architecture produces excellent device characteristics. We show below that the output power, for example, is higher than that of vertically injected thin-film (VTF) chips (see figure 1c). This design was proposed more than a decade ago and has been implemented recently by several chip manufacturers.



Philips Lumileds' thin-film flip-chip LED technology will start appearing in Luxeon products during the spring.

The problems of vertical structures

The downsides of the VTF design are a consequence of its construction. It is usually produced by depositing a high-reflectivity metal contact onto the p-side of the epiwafer, and then bonding this structure to an intermediate conductive substrate to maintain device integrity throughout the remaining processing and packaging steps. Laser-assisted lift-off removes the sapphire before photoelectrical-chemical etching roughens the exposed GaN surface, and a mesh-like metallic n-contact is added that includes wire bonds.

The resulting structure has two major drawbacks compared with a TFFC design. The first is that the intermediate substrate increases the thermal resistance of the package. It has to be carefully chosen to match the thermal expansion coefficient of GaN, otherwise device failure can occur through thermal cycling. The other weakness of the VTF design is a lower light output. The patterned n-contact reduces the chip's effective emitting area, while the wire bonds obstruct light emission. These wire bonds are particularly irksome in the tightly packed chip arrays used in projection displays and some illumination systems, as they increase the distance from the surface of the LED to the primary optic. The greater distance either increases the size, weight and cost of the optic, or it decreases the system's efficiency (see figure 2). In contrast, our flip-chip architecture permits close packing of LEDs, as electrical connections are removed from the light path.

We have compared the performance of our TFFC LEDs with FC and VTF chips produced

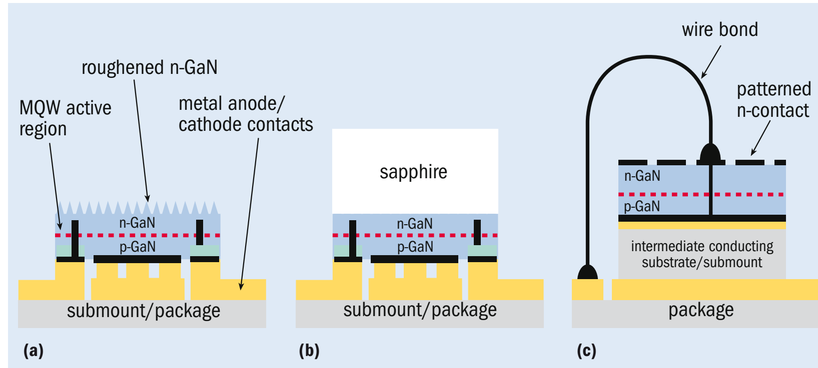


Fig. 1. Philips Lumileds has developed a thin-film flip-chip (TFFC) LED **(a)** that offers better performance than the flip-chip structures **(b)** currently employed in its Luxeon products. The TFFC LED also offers a higher light output and greater efficacies than vertical thin-film chips **(c)**.

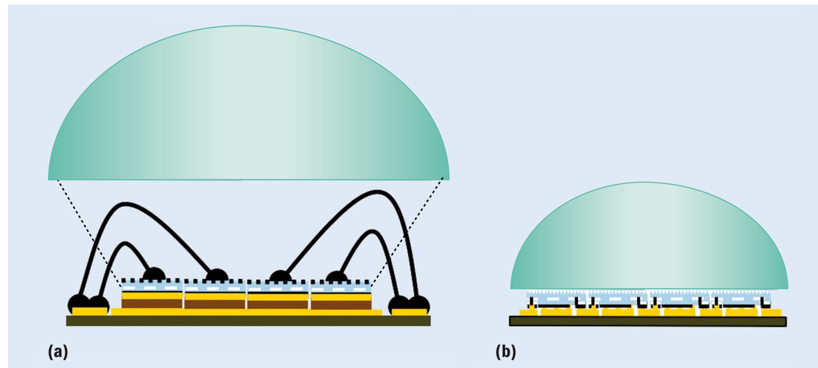


Fig. 2. LED arrays based on vertically injected thin-film (VTF) LEDs require a wire bond for each device **(a)**. These wires block some of the emitted light and force the primary optic that is used in projection displays and illumination systems away from the emitting surface of the LED. Greater light coupling efficiencies are produced with Philips Lumileds' TFFC design **(b)**, which eliminates the loss in light output caused by wires and reduces the distance to the primary optic.

from the same GaN-on-sapphire epiwafers. Measurements of the best encapsulated blue-emitting 1 mm × 1 mm chips for each type of device reveal that the TFFC structure produces the highest output as expected (see figure 3). At a 1000 mA drive current, the output of the best performing TFFC LED is 46% higher than that of the FC device and 17% higher than the VTF chip.

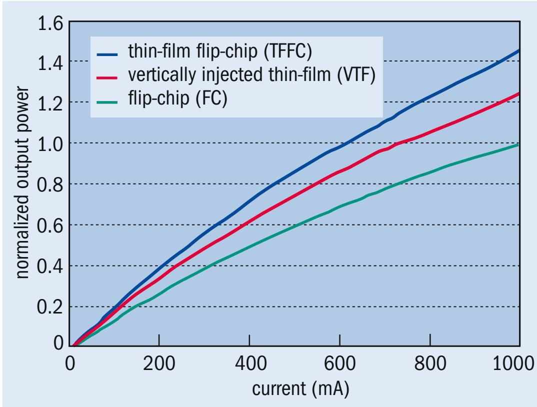
Patterning the top metal contact of the VTF device was not fully optimized in this demonstration, but it is impossible to boost the extraction efficiency and the high-current performance simultaneously. If the dimensions of the top contact are minimized for the greatest light extraction, current crowding increases, which cuts the electrical input power.

The efficacy and light output of our TFFC blue- and white-emitting LED chips at 25 °C and under direct-current conditions are shown in figures 4 and 5. The metallization and contact geometry of both devices have been optimized to provide a low dynamic resistance of 0.8 Ω at 350 mA and 0.4 Ω at 1000 mA.

Our 425 nm blue LED has a maximum external quantum efficiency (EQE) of 61% and a wall-plug efficiency (WPE) of 56%. At 350 mA the chip produces 566 mW at an EQE of 56% and a WPE of 44%, and at 2000 mA its output rises to nearly 2 W. This efficiency is among the highest ever reported for blue devices at these current densities.

The encapsulated white-light TFFC LED, which incorporates a YAG:Ce phosphor, has a peak luminous efficacy of 147 lm/W at 10 mA. At 350 mA it delivers 88 lm/W and at 1000 mA it produces 56 lm/W (see figure 5). These efficacies are far higher than those produced by halogen sources, which typically emit 25 lm/W, and will enable manufacturers of lighting systems to deliver greater electrical efficiencies.

Luminance mapping across the surface of one of our non-encapsulated 1 mm × 1 mm white LED chips reveals a peak luminance of 58.8 Mnit (Mcd/m^2) and an average surface brightness of 50 Mnit (figure 6). This brightness makes the chip a strong contender for projection displays and automotive headlights. The average brightness of LEDs, which is delivered at a luminous efficacy of 40 lm/W, is much higher than that of a halogen source (15–30 Mnit at ~30 lm/W) and not far behind the average effective brightness of high-intensity discharge lamps (60–80 Mnit at ~100 lm/W).



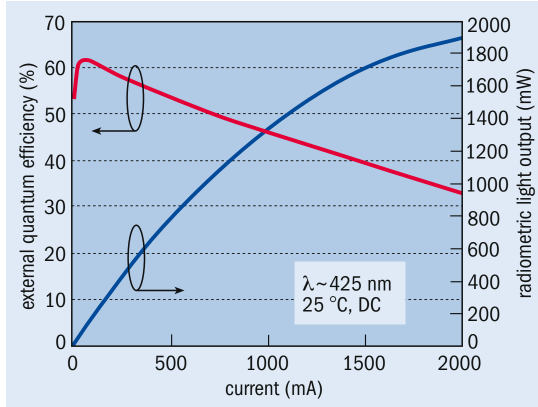
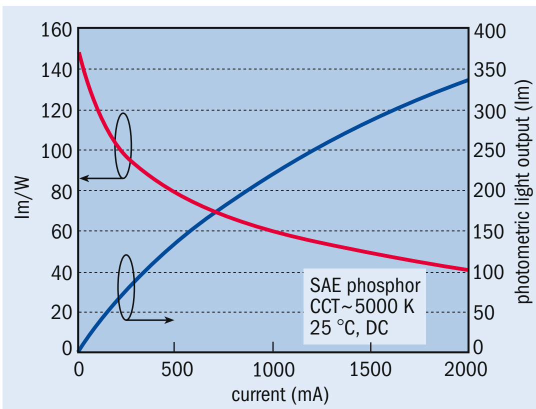


Fig. 3 (left). A split-wafer study of blue LEDs reveals that the TFFC design delivers a higher light output than VTF and FC equivalents at all drive currents up to 1 A. To ease comparison, light output has been normalized to that of an FC-LED at 1 A. The VTF-LED used in this test has a conventional design, with a reflective p-contact evaporated onto the p-doped side of the device and a GaAs intermediate substrate. Deposited aluminum forms the mesh-like n-contact and the wire-bond pads, and typically 50% of the top surface emits light. To minimize light occlusion effects, the resistivity of regions beneath the mesh contact has been increased with hydrogen-ion implantation. **Fig. 4 (right).** The encapsulated 425 nm blue TFFC LED can deliver a light output of almost 2 W at 2 A. The test was carried out under direct current conditions, with heatsinks used to maintain an operating temperature of 25 °C.



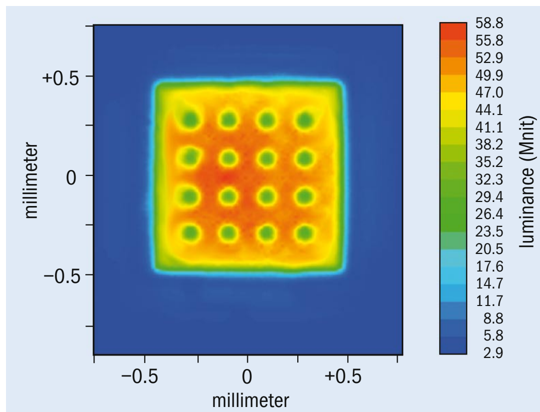
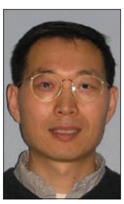


Fig. 5 (left). Coating the blue TFFC chip with a YAG:Ce phosphor produces a white-light device with a maximum efficacy of almost 150 lm/W. **Fig. 6 (right).** The surface of the non-encapsulated white LED chip has an average brightness of 50 Mnit at a 1 A drive current. In comparison, halogen sources and high-intensity discharge lamps produce 15–30 Mnit and 60–80 Mnit, respectively.

About the authors
Oleg Shchekin (left) is a staff scientist at Philips Lumileds Advanced Laboratories. **Decai Sun** (right) is a section manager in the R&D department of Philips Lumileds. Contributing authors from Philips Lumileds are: Henry Choy, Walter Daschner, John Epler, Mari Holcomb, Mike Krames, Ojin Kwon, Tal Margalith, Paul S Martin, Rajat Sharma, Dima Simonian, Dan Steigerwald, Charlene Sun, Melissa Taub and Ling Zhou.

Our devices also have a significant advantage over these two alternatives: a relatively uniform, tightly controlled emission surface. This eases the design of secondary optics and boosts utilization efficiency, advantages that are particularly attractive for automotive forward lighting. In fact, programs are now underway to install devices in production cars. Monochromatic LEDs, which have a very high surface brightness, are also reaching the point where they can compete directly with ultra-high-pressure projection bulbs because they do not require color filtering.

Reliability, another key parameter for commercial success, has been examined with in-house high-temperature reliability testing using direct current conditions and a 1 A drive current. Light output power drifted by at just a few percent during a 1000 h white-light LED chip test at 110 °C and a 7000 h blue-light device test at 85 °C.

We have also combined this TFFC design with other technologies developed by Philips Lumileds to produce a 1 mm × 1 mm demonstration chip that delivers 115 lm/W at 350 mA, 61 lm/W at 2 A and a maximum light output of 502 lm. This LED has a correlated color temperature of 4685 K, which is lower than that of many chips produced by our competitors and closer to the wishes of our customers.

Product roll-out

The various technologies that feature in this record-breaking chip will be united in our products over the next 12–18 months. However, in the meantime customers will be able to purchase our first TFFC LEDs, which offer an unmatched combination of performance and versatility. These devices, which will be launched this spring, will deliver a reliable, high light output and brightness, and will be suitable for use in various lighting systems from projection to general lighting. We expect that this device platform will provide LED customers with a greater value than ever before, and establish a sound basis to proliferate solid-state lighting.