Silicon-based LEDs leap from lab to fab

Silicon offers a large, low-cost platform for making nitride LEDs, but realizing high-quality epitaxy is tough due to the stress between the two materials. However, it is possible to produce the crack-free, low-defect-density films demanded by high-power LEDs by turning to a patterned substrate and a multi-layer buffer, says **Lattice Power Corporation.**

LEDs are widely used in displays, automobiles, handsets, notebook backlighting, TV backlighting, and general lighting. The light-emitting films - InAlGaP for red LEDs, and InAlGaN for their blue and green cousins - need to be grown on a carrier substrate.

There is no good substrate to match the GaN material system, in terms of lattice constant and thermal expansion, but it is possible to grow high-quality films on sapphire, SiC and silicon.

Almost all GaN-based LEDs are fabricated on sapphire substrates, and Cree is the notable exception, using SiC substrates instead.

Massive adoption of solid-state lighting requires further advances in large-scale, low-cost manufacturing. Silicon-based GaN LEDs have been attracting researchers in universities and industry for many years, due to their promise of large-scale production and compatibility with the IC manufacturing platform. In comparison, sapphire and SiC substrates are much smaller, and they can't be processed through silicon lines.

The biggest roadblock for manufacturing high-performance GaN-on-silicon LEDs is the material stress that results from a combination of lattice mismatch and thermal expansion mismatch.

But it is possible to use special epistructures, novels substrate designs and sophisticated growth techniques to make GaN-on-silicon structures that lead to high-performance, high-reliability LEDs. At Lattice Power, which is based in Nanchang, China, we have done exactly that, and demonstrated the promise of this approach for making high-performance, lighting-class LEDs.

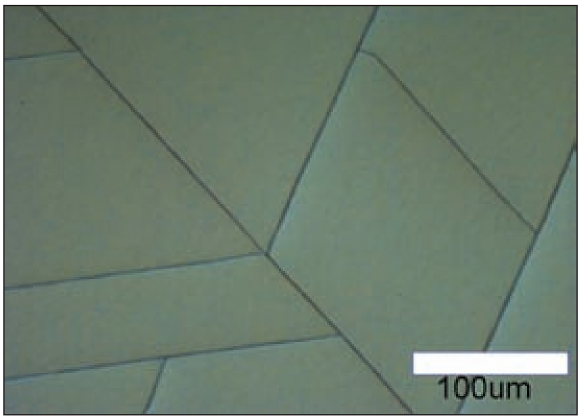

Figure 1: Cracking in GaN film grown on silicon substrate

The substrate used for GaN growth is (111) silicon. Its lattice-constant mismatch to GaN at room temperature leads to a tensile strain of +17%, but it is +40% tensile-strained following pseudo-morphological growth at around 1000 degrees Celcius, due to the thermal expansion coefficient mismatch. This results in more than a 2 µm lattice constant mismatch for a 1mm die. The upshot is that cracking occurs, sometime massively.

However, more often it causes the wafer to bow during growth, yielding wafer non-uniformity and poor device performance. In comparison, when GaN films are grown on SiC substrates, the strain caused by lattice constant offsets that caused by thermal mismatch.

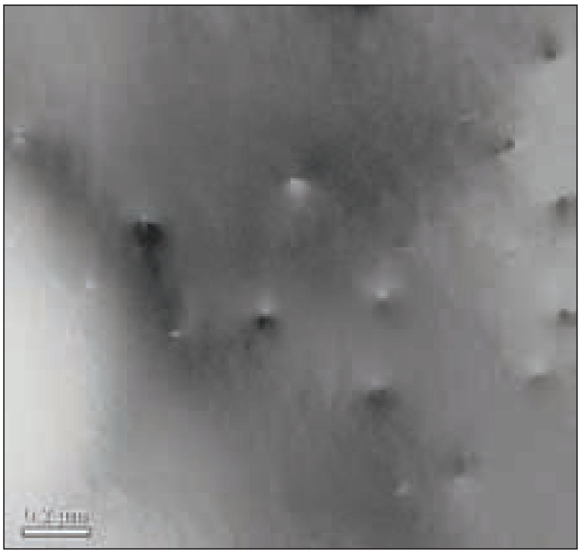

Figure 2: Low dislocation density from a GaN wafer grown on silicon substrate

If sapphire substrates are used, compressive strain in GaN film results from the lattice constant and thermal mismatch, but this does not lead to cracking.

In other words, this highly tensile strained GaN film on silicon substrate presents the biggest challenge for making high-performance, high-reliability LEDs. Figure 1 illustrates a GaN-on-silicon wafer with cracking everywhere.

Managing the stress

Successful high performance LED manufacture demands low-dislocation, crack-free films. Managing the stress is the first hurdle to overcome. Large lattice-constant mismatch between GaN and silicon leads to high dislocation densities, which can be as high as 10^9-10^{10} cm^{-2}.

Even though the GaN-based LED is far less sensitive to high dislocation densities than its GaAs or InP cousins, such a high dislocation density still causes low internal quantum efficiencies. This prevents the realization of high-power, high-reliability LEDs. But we can address this issue by introducing patterned substrates that isolate the stress caused by cracking, and a special AlGaN/AlGaN multilayer buffer structure that manages internal strain. We have found that patterned substrates are effective in containing the strain and limiting cracking propagation. The width, depth and shape of the trench are crucial levers to minimizing the stress and limit the cracking. In order to contain the stress and eliminate cracks, a deep trench is implemented, which leads to a free-standing GaN film. If there is cracking in one post, it will not propagate to next.

With this approach it is possible to realize a manufacturing yield of more than 95 percent of chips without cracking, for a chip size is 1mm or smaller and a GaN thickness exceeding 4.5 μm. A dislocation density as low as $5\text{x}10^8/\text{cm}^2$ can be routinely achieved for a GaN film on a silicon substrate.

Figure 2 demonstrates low dislocation density from a GaN wafer grown on a silicon substrate. Figure 3 shows a high quality GaN-on-silicon chip without cracking.

High performance LEDs must also have high internal quantum efficiency. For GaN-on-silicon growth, thick n-GaN layers have always been a problem, because as the epilayer gets thicker, stress increases and the wafer tends to bend and crack. We address this with a multiple special buffer layer.

The AlN layer tends to provide a good buffer for controlling the stress. We are being able to design and grow our epistructure with a 4-5 μm n-GaN layer. Figure 4 shows SEM pictures of the epi layer and quantum well design.

Preventing silicon absorption

Silicon absorbs visible light. So in order to have efficient LED operation, the silicon substrate must be liberated from the device, a thin-film, vertical structure. Figure 5 illustrates the silicon-based thin film process. GaN is grown on a prepared, patterned (111) silicon substrate.
A metal contact is deposited on the p-side of the GaN film. This acts as a light reflector adding further benefits to the device.
A bonding metal is then deposited on top of the p-metal, subsequently bonded on a carrier substrate (pre-deposited with a bonding metal). The substrate can be silicon, germanium or a metal plate. The bonding metal can be gold or one of its alloys, depending on different process designs for different applications.

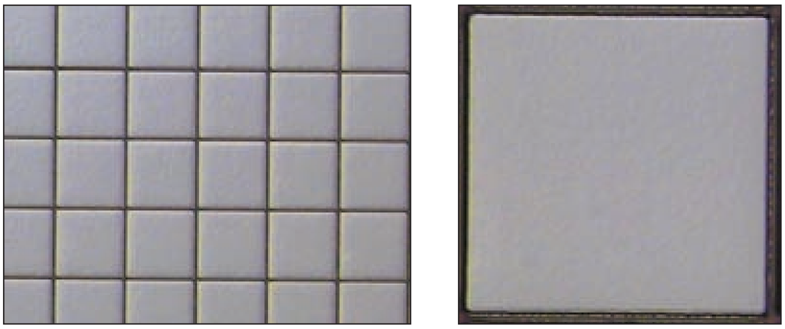

Figure 3: high quality GaN on silicon chips without cracking

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We can produce LED chips with various sizes on silicon substrates. Low operating voltage and high output power are demonstrated, and we have launched reliable products for display applications (small die), LCD backlighting (mid size die) and general lighting (large die)

The original (111) silicon substrate is then removed by wet chemical etching, followed by n-contact metal deposition. For high power devices, we will implement a surface roughening process. The LED emits through the n-GaN side. Figure 6 are actual 500 µm and 1 mm LED chips made from GaN on silicon.

We can produce LED chips with various sizes on silicon substrates. Low operating voltage and high output power are demonstrated, and we have launched reliable products for display applications (small die), LCD backlighting (mid size die) and general lighting (large die). Figure 7a is an example of a 450 nm, 1 mm chip emitting 480 mW when driven at 350mA.

Output corresponds to 100-110 lm cool-white flux at 350mA. The typical quantum efficiency as a function of current for a GaN device on a silicon substrate is shown in Figure 7b. Characteristics are no different from GaN LEDs on sapphire or SiC substrates.

This shows the GaN-on-silicon material quality is as good as that on sapphire or on SiC, and demonstrates that this class of LED is a very promising candidate for large-scale, low-cost production.

Reliability concerns?

The GaN-on-silicon substrate is highly stressed, so there are genuine concerns regarding its long-term reliability. We have conducted a long-term reliability test at three times normal operating current and a 75 degrees Celcius board temperature (approximately 110-120 degrees Celcius junction temperature).

Figure 8 details the results of 0.5mm (at 200mA) and 1mm (at 900mA) chips under a highly stressed reliability test. They show no or very little power degradation. Similar reliability is seen in GaN material grown on sapphire.

Up until now, more than 95 percent of GaN-based LEDs are made on sapphire substrates, with the majority of the remainder grown on SiC. We have been marketing silicon-based LED products for close to two years. Initial production had many issues, mainly related to production line yields.

Customers had many issues too, such as handling and packaging, which resulted from the brittle carrier material of the thin film structure. However, thanks to process

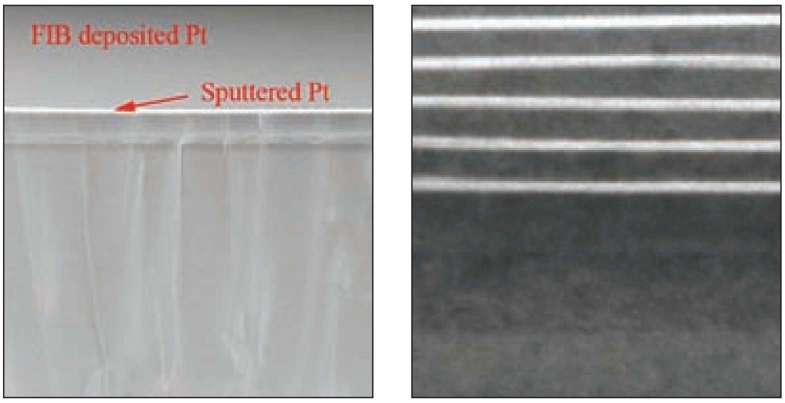


Figure 4: SEM pictures of the epi layer and quantum well design

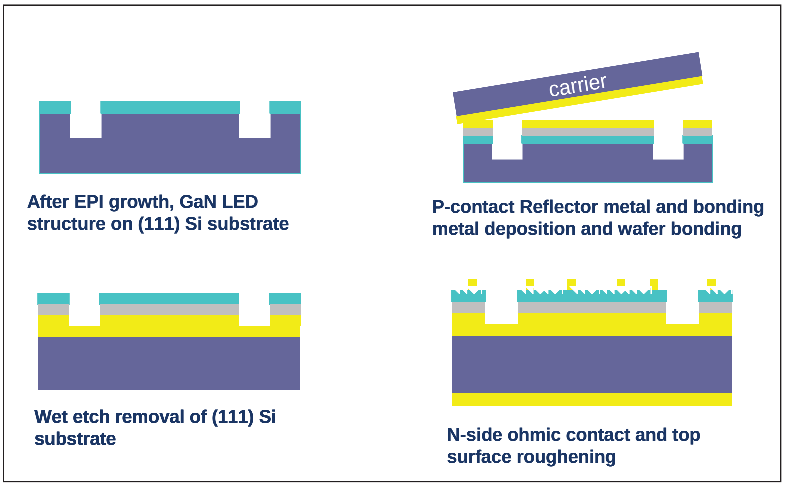


Figure 5: Lattice Power's silicon based thin film process

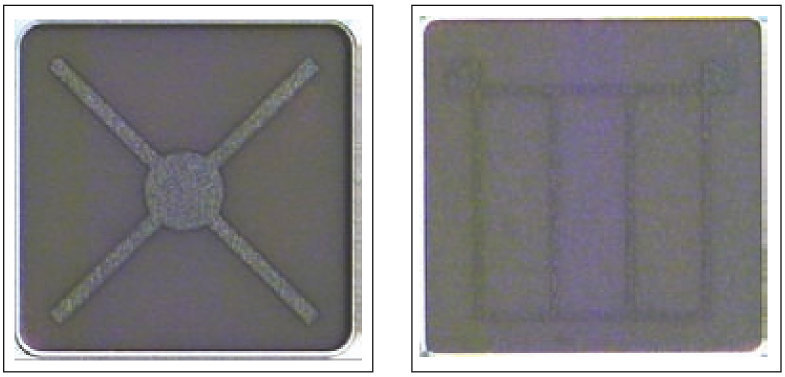


Figure 6: High-performance 500 µm and 1 mm chips made from GaN-on-silicon substrates

Figure 7a: Right) 1mm, GaN-on-silicon chips are capable of producing cool-white LEDs with a flux of 110 µm.

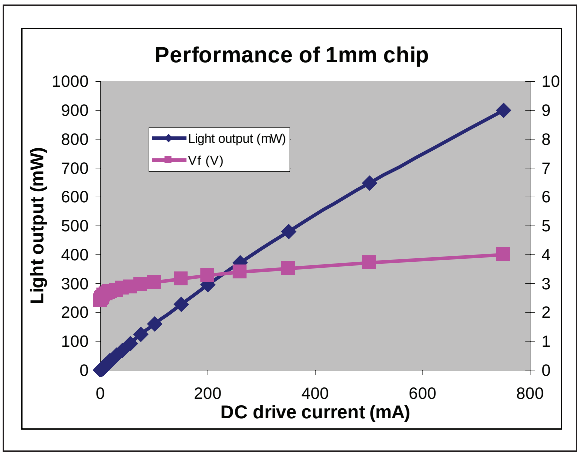
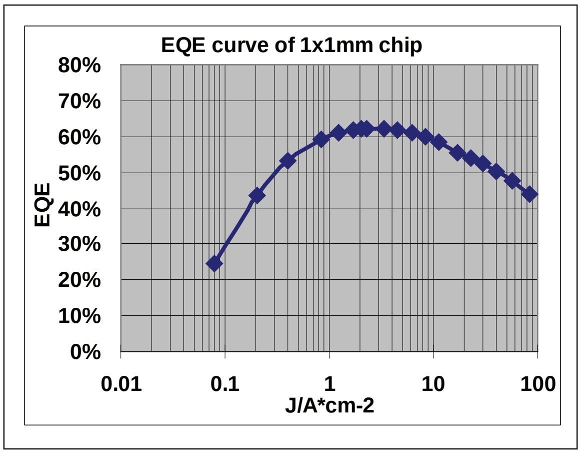


Figure 7b: (Far right) External quantum efficiency vs. current



refinement and better control, silicon-based products are now finding more and more applications and customers.

Due to the vertical thin-film structure, silicon-based devices can be made smaller than similar performance equivalents based on sapphire. 200 µm by 200 µm devices for display application are in high demand, and they now have proven long-term reliability. What's more, the production yield can be on a par with its sapphire sisters currently in use.

To put it simply, the GaN-on-silicon LED is no different from any sapphire or SiC-based LEDs. Its application ranges from displays, backlighting and general lighting. Figure 9 is a full color display featuring our GaN-on-silicon blue and green LEDs. In this particular application, the chip size is 170 µm by 170 µm, and the blue output power is close to 10 mW at 20 mA.

Our current 2-inch GaN-on-silicon process has proved that it is possible to mass-produce this class of device, which combines high performance with high quality and high reliability. The real benefit for GaN on silicon will only be realized at far larger diameters, such as 6 inches and above. This will lead to higher capacity and utilization of standard IC processing tools and equipments, but getting there will require overcoming issues related to these large diameter platforms.

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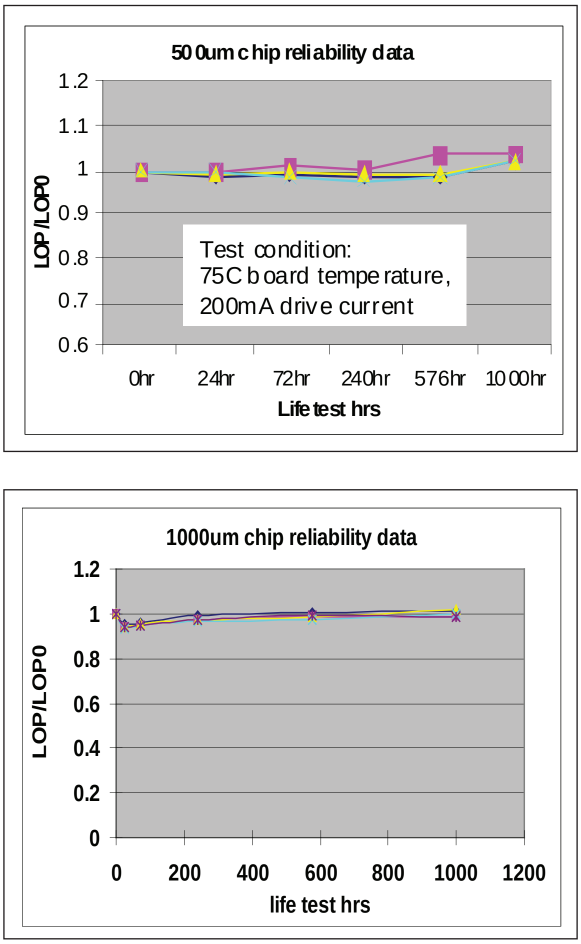

Figure 8: reliable operation of GaN on silicon LED

Figure 9: A high-density LED full color display that features blue and green GaN LEDs grown on silicon substrates

FURTHER READING

ICNS-8, Session H: Epitaxial Growth I, L_1006: "High power InGaN LEDs grown on Si substrate by MOCVD", October 18-23, 2009, ICC Jeju, Korea.

SPIE OPTO: SPIE paper number 7617-48, "High-power GaN-based Blue LEDs grown on Si substrate by MOCVD" Optoelectronic Materials, Devices and Applications, 23-28 January 2010