Out of the red: how microLED makers are ramping up efficiency

As microLEDs lead the AR/VR charge, the race is on to boost efficiency and lower costs. But which tech will come out on top, asks Ben Townsend

The last thing you want to see when you're swinging your arms around wearing an AR or VR headset is the pixel grid pattern of the screen in front of you. Nor do you want to be standing with your headset plugged into the wall – it's not exactly immersive.

That's where microLEDs come in. Their tiny size (100 times smaller than conventional LEDs) means they can fit inside an AR/VR headset, directly in front of your eyes, without a "screen door effect". Most importantly, they're far more energy-efficient than many current display technologies, which allows them to offer unparalleled resolution, brightness, pixel density, response time, and battery life.

Based on predictions from intelligence provider TrendForce, the value of the microLED chip market will reach $580m in 2027, up from $27m in 2023. This is thanks to new applications such as AR/VR – a market which, by the same year, is estimated to be worth $114.5bn.

These are big numbers, but while the efficiency of microLEDs is one of their main selling points, it's also a weakness. Why? When you scale down an LED to the micron level, efficiency is lost. For blue LEDs this isn't such an issue – they drop from around 90% to 40%. But for the longer wavelengths, it's a different story. For red it is the most significant, with efficiency plummeting from 40% to 1% at the micron level.

Caroline O'Brien, CEO, Kubos Semiconductors, says her company is looking to increase the efficiency of its red microLEDs to 5%

Porotech CEO Dr TongTong Zhu says its 'all-in-one' microLEDs could revolutionise the display and semiconductor industries

Addressing the efficiency gap

While microLEDs still outperform their larger counterparts, such as OLED panels and LCD displays, this efficiency gap is a major setback for AR/VR developers. And it has to do with the materials involved.

"The main problem with current LED technology in the RGB realm is that the red, green, and blue LED emitters are made from different materials," says Ron Mertens, General Director of The MicroLED Industry Association. "The blue and green emitters are made from one material – indium gallium nitride (InGan) – while an InGan red emitter would be highly inefficient."

Traditionally, red was made from a different material, he says. "That's all well and good for lighting, but for displays, where your backplane needs to drive these subpixels very accurately, this complicates matters a lot. Several factors affect the decrease in efficiency as we move from blue to red. Non-radiative surface recombination on the surfaces and sidewalls of microLEDs increases as the size is reduced. In addition, as the wavelength is increased, non-radiative recombination increases due to piezoelectric fields increasing within the quantum wells."

Due to this efficiency gap, the industry is driving towards a single-material solution for red, blue, and green wavelengths, according to Mertens, and it's why many researchers are working on developing efficient, native InGan red emitters.

Steve DenBaars, for example, a Professor of Materials at the University of California, Santa Barbara, is one such scientist

'We see a path to increasing the red efficiency to beyond 20%'

focusing on InGaN alloys. "Currently our microLEDs have 50% blue, 25% green, and 6% red external quantum efficiency (EQE). We see a path to increasing the red efficiency to beyond 20% by employing additional improvements in the materials science of InGaN alloys.

"By increasing the indium content of the quantum wells, the InGaN alloy system is capable of covering the entire visible range from blue to red. Through improvements in the deposition technology of metalorganic chemical vapour deposition, we have been able to grow alloys with 30% indium which emit efficiency in the red to 6% EQE."

Hexagonal or cubic GaN?

GaN is a semiconductor material that has a high radiation compound efficiency, making it ideal for manufacturing light-emitting devices such as microLEDs. But while

Porotech

Porotech technicians holding silicon wafers. The firm claims to have developed a single-microLED chip capable of producing any visible colour from a single pixel, including white light

gallium in its hexagonal phase is most typically used for microLEDs, it doesn't work so well at longer wavelengths.

"Hexagonal gallium is a fantastic solution for blue LEDs, but when you move it up to longer wavelengths such as green, amber, and red, then the efficiency rolls off," says Caroline O'Brien, CEO of Kubos Semiconductors, a spin-out from the University of Cambridge.

But what does 'efficiency' actually mean when it comes to AR/VR technology? O'Brien explains that it has to do with photon distribution: "When you're in AR/VR, you're projecting a head-up RGB display onto your glasses through an optical system. If that's to work, the optics have to be very, very close to the microLEDs But red LEDs today are made using phosphites, which means they can't scale down.

"One of the fundamental problems is that the recombination times are longer than the diameter of the devices that they're trying to produce in AR/VR because they're so tiny – one or two microns. All of the recombination is kind of going around the edges, so you get edge effects, and you're not getting a uniform distribution of the photons across the device. This basically means it's not efficient because it's not doing its job properly."

Thanks to a £700,000 Future Economy Investor Partnerships grant from Innovate UK grant, Kubos is looking to increase the efficiency of its red microLEDs to 5%, effectively doubling the efficiency currently achievable with other process technologies, the firm says, helping make microLEDs more viable for AR/VR applications.

"Over the last 18 months, we've realised that the AR/VR market is going to take off and it is going to be microLEDs driving it," says O'Brien.

The problem with hexagonal gallium is why Kubos Semiconductors is taking a different approach. To increase the efficiency of long-wavelength microLEDs such as green, amber, and red, Kubos has developed its own method of growing cubic GaN in its cubic crystal phase, which is compatible with the standard microLED growth process.

"It's been long known in the industry that cubic GaN solves many of the issues with hexagonal GaN microLEDs when moving into these longer wavelengths," says O'Brien. "But the problem is, nobody's been able to make it in a compatible and scalable way. We don't have that problem in our material system. We can get to those longer wavelengths more efficiently than current hexagonal GaN microLEDs. Kubos is planning exponential efficiency growth – no jiggery-pokery in terms of adding quantum dots or coatings and so on… we've also calculated we could save hundreds of millions of tonnes of CO_2 emissions."

O'Brien uses carbon as an analogy to describe how Kubos processes its GaN: "Carbon in its natural state is graphite, and it's found abundantly. Now, if you put it under certain temperatures and pressures, you can force it into what's known as a metastable state, which is diamond. We were doing the same thing, but with gallium and nitrogen – we're forcing it into this very stable state.

"People go, 'metastable state – does that mean it's unstable?' Well, does your wife's diamond ring suddenly fall apart?"

She adds: "It's a native material we are producing, we're producing it in a revolutionary way. It's very close to the hexagonal GaN in terms of how you build the stack and how you improve it."

O'Brien goes on to explain that other methods – such as colour conversion – and the materials being used to try and combat the red microLED gap haven't yet demonstrated they can be effective.

"Some of these other technologies are going to take years to come into the market because they can't slot into the existing production lines like [Kubos Semiconductors'] can," she says.

"For example, the material used to do the quantum dot conversion. We've seen lead-based materials, some of which aren't Restriction of Hazardous Substances

→

Kubos Semiconductors

A 150mm wafer of GaN microLEDs under test via wafer probing

Directive (RoHS)-compliant, and we've seen cadmium, which actually gives the best performance, but cadmium is very nasty – it's now a banned substance in the European Union."

She says there is also a problem with many colour conversion methods adding height to red microLEDs, "and then you end up with different heights for different colours. And then you have a challenge to put your optics close to the microLED."

"There are all sorts of real-world problems that we don't have to navigate because we're actually not that much different from the existing material."

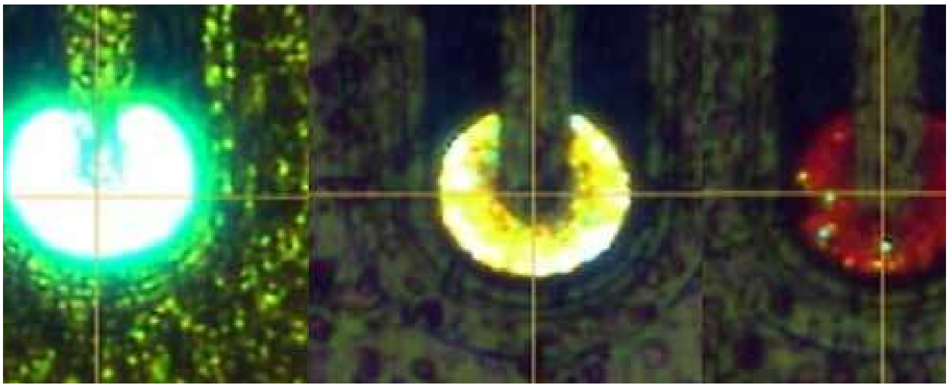
However, O'Brien warns about going too far down the rabbit hole.

"To me, [focusing on increasing the efficiency of microLEDs] just highlights the problem more than the solution. There is some good work, there's been a lot of investment, but you're looking at a trajectory that's relatively linear in terms of the return over the next couple of years. There's lots of data saying [efficiency] has improved, but nobody quotes any numbers. Honestly, there are so many different ways to define efficiency – take your pick! You've always got to say it's efficient, but the only measure that matters is when it's in a real product or system.

"When you get the right user experience, that's the only thing that matters."

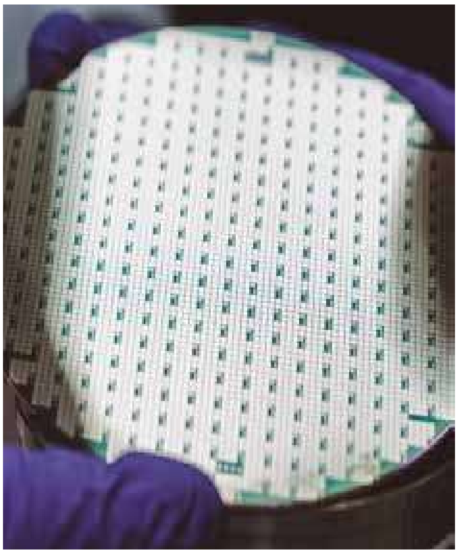
Unlocking 'all-in-one' microLEDs

While Kubos Semiconductors is going back to basics with native, cubic GaN materials, other firms such as Poro Technologies (Porotech), also a spin-out from the University of Cambridge, are developing their own class of GaN altogether. Porotech, co-founded in 2018 after a decade of research and development in GaN-related materials and device applications, has created a new class of porous GaN semiconductor material called PoroGaN. This material led to the development of the firm's latest DynamicPixelTuning (DPT) technology, which it says is the world's first 'all-in-one' microLED.



Kubos Semiconductors

50-micron diameter green, amber and red LEDs from Kubos Semiconductors



Kubos Semiconductors

Kubos Semiconductors has developed what it says is the first commercially compatible cubic GaN growth process enabling more efficient long-wavelength microLEDs

"While researching the use of engineered porosity in GaN to access new material functionalities and properties, Porotech discovered that PoroGaN could be applied to many semiconductor-based applications," says Dr Tongtong Zhu, CEO and co-founder of the firm.

"We developed our new trademarked technology, DPT, for microLEDs, using our proprietary PoroGaN material, which enables a single microLED chip to produce any visible colour from a single pixel, including white light. This technology is set to revolutionise the display and semiconductor industries."

Zhu says PoroGaN addresses key material-related issues "by tailoring the lattice parameter and material properties, which results in high-quality epitaxial growth with fewer defects and enhanced light extraction on the device and system level. The engineered porous architecture allows us to flexibly design the light-emitting region so that the colour of the LED emission can be tuned across the entire visible spectrum range."

He explains that DPT removes the need for RGB sub-pixels, further colour conversion/filtering, and complex stacking architectures, all while enabling colour uniformity and simplifying system design – something he believes will remove the barriers to mass manufacturing.

He adds: "AR/VR displays powered by DPT will have higher brightness with increased resolution, due to the way that DPT pixels are laid out. Without the need for individual RGB subpixels, only one pixel is required instead of the usual three or four sub-pixels to form a colour pixel, expanding the available range significantly; producing both full-colour emission and greatly improved resolution. Additionally, the need for only one material to produce the pixel means that there is a much lower defect rate and less complex manufacturing processes. This breakthrough is of particular interest to manufacturers of small form factor displays that demand higher resolutions.

"In AR/VR technology, these benefits all come together to improve user experience, with higher brightness and increased resolutions resulting in clearer, more immersive images in displays – even against daylight."

Zhu says DPT is an eco-friendly technology that will cut the costs and time involved with mass manufacturing across the wider display industry.

'Our technology enables a single microLED chip to produce any visible colour from a single pixel…this is set to revolutionise the display and semiconductor industries'

"This technology offers a long-term solution to the display industry when it comes to the levels of waste involved in the manufacturing process," he says, "proving that it is possible to do better as an industry to support our environment with long-lasting and durable materials in our devices, as well as cleaner and more environmentally friendly manufacturing operations.

"Additionally, due to the reduced complexity of manufacture, along with the fact that these full colour microLEDs now can be made for the first time using a single material system and tool chain, the cost of manufacture is significantly reduced and the yield can be significantly improved – removing the cost barrier to mass production of microLEDs." EO