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How we made the microLED

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Micro-light-emitting-diode display applications are growing quickly as technology companies begin to use them in a range of products. Key to the development of these applications was the miniaturization of gallium nitride light-emitting diodes. Hongxing Jiang and Jingyu Lin recount how this was achieved.

In the late 1990s, blue and white light-emitting diode (LED) technology was making rapid progress and was poised to revolutionize the lighting and consumer electronics industries. At the time, our team at Kansas State University was investigating size and microcavity effects in gallium nitride (GaN) LEDs. During a dinner table discussion, we questioned what might happen if such an LED was reduced to the micrometre scale, and we decided to try to make micro-sized LEDs (microLEDs). We were hoping, in particular, to achieve a higher emission efficiency and be able to tailor the emission patterns.

The team involved in the initial developments included Jing Li, Weiping Zhao, Sixuan Jin and Jagat Shakya, and we had to overcome a number of major obstacles. We needed to ensure low contact resistance and minimize the effects of dry-etching-induced surface damage, both of which become worse as device size decreases. We succeeded, and in August 1999, we were able to observe blue-light emission under a microscope from a microLED of only 12 µm in diameter (Fig. 1). We reported our results at the 1999 Materials Research Society (MRS) Fall meeting in Boston. Meeting attendees were intrigued, but many also asked the question 'what are they for?'.

We realized that GaN LEDs grown on sapphire wafers have a distinct feature compared with other III–V LEDs. The use of sapphire introduces a high misfit dislocation density in blue and green wafers, but it is an excellent insulator. This enables various interconnection schemes between microLEDs. And we showed that an LED consisting of hundreds of microLEDs connected in parallel (called interconnected microLEDs) can provide higher efficiency and brightness than conventional LEDs of the same area due to a reduction in the total

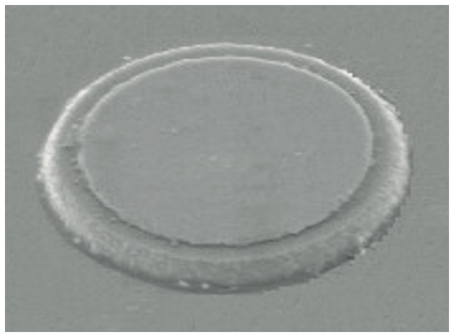

Fig. 1 | The first GaN microLED. Scanning electron microscopy image of one of the first microLEDs, which were based on indium gallium nitride/gallium nitride (InGaN/GaN) quantum wells. The device has a pixel size of 12 µm and p-type nickel/gold (Ni/Au) contact diameter of 10 µm. Figure adapted with permission from *Appl. Phys. Lett.* **76**, 631 (2000), AIP Publishing.

internal reflection. Today, this architecture is used in ultraviolet-C LEDs to enhance light extraction. Connecting isolated microLEDs in series on-chip also creates LEDs that can handle high a.c. and d.c. voltages (called a.c. and d.c. high-voltage LEDs). These are now being commercialized for use as general and automobile lighting.

It subsequently became clear to us that if we could control the microLEDs individually within an array we could create a microdisplay. And in November 2000, we created a 10 × 10 microdisplay by passively connecting the p-contacts of individual microLEDs with bonding pads deposited on the periphery of an array using metal lines (the results were published in *Applied Physics Letters* in February 2001). The system could only display characters. But it exhibited a range of valuable features including self-emissivity, low power consumption, fast operating speed, long lifetime and wide colour gamut, as well as high resolution, brightness and contrast.

From studying focal plane array detectors, we also realized that achieving a true high-resolution microLED microdisplay — with video graphic capabilities — would require an active driving approach in which millions of microLED pixels are individually addressed by a heterogeneously integrated complementary metal–oxide–semiconductor (CMOS) circuit. But no funding agency was willing to sponsor such a development at that time. However, in 2007, a company we founded — III-N Technology (3N) — proposed the active driving microdisplay idea to the Night Vision and Electronic Sensors Directorate of the US Army and received funding.

Integration between a microLED array and a CMOS integrated circuit was achieved by flip-chip bonding via indium pumps. And near the completion of the project, we delivered several blue and green microdisplays in video graphics array (VGA) format (640 × 480 pixels) to the Army, who commented that they had never seen such bright microdisplays; to see the details of the microdisplay, they had to dim them with neutral density filters. We then reported an actively driven microLED microdisplay in *Applied Physics Letters* in July 2011, which led to serious industry attention in the technology.

Working as a husband-and-wife team was a blessing. One of us (H.J.) likes to focus on the big picture, while the other (J.L.) likes to pay attention to the details. When things got less certain, arguments naturally extended to the dinner table. But here we often got new ideas. On one occasion, we tried to identify all possible practical applications for microLEDs. Some of these ideas — such as eyeglass displays, windshield projectors and optical cochlear implants — have since emerged. But other applications that have emerged — such as the use of microLEDs in two-dimensional optical phased arrays and to manipulate neurons in the brain — were beyond our imaginations back then.

One thing we learned from this process is that the path from technology invention to commercialization is very long. Our first microLED patent filed by Kansas State University expired two years ago, and microLED display products are just beginning to penetrate the mass consumer electronics market. But you need to try to enjoy every moment of success — and, if you can, even the moments of failure.

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Competing interests
The authors declare no competing interests.