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Putting microLED technology on display

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After some two decades of advances in manufacturing processes, microLEDs have the quality and capabilities necessary for many display applications.

When the Nintendo Virtual Boy was released in 1995, it was perhaps the earliest consumer product to use LEDs in a display. It used only a 1D row of 224 red-colored pixels for its monochrome, stereoscopic 3D display. The display's oscillating mirror scanned the row of pixels through 384 lines, resulting in a resolution of 384 × 224 pixels.[1] The Virtual Boy, however, was a commercial failure—it is Nintendo's only game console to sell fewer than a million units—and the development of LED display technology stagnated.

LEDs were not traditionally used for displays, lighting, or any of their other modern applications. Rather, they were limited to simple indicator lighting in electronics. The history of LEDs dates back to the 1960s, with red and green LEDs made from the semiconductor materials of gallium arsenide and gallium phosphide, respectively. Higher costs, inefficient energy consumption, and low brightness limited the usefulness and adoption of early LEDs. Color displays need red, green, and blue (RGB) subpixels at varying brightness to combine into single pixels that can cover the color spectrum set by the International Commission on Illumination, an authority on light, illumination, and color.

Blue LEDs were not possible to manufacture with appreciable brightness levels until Shuji Nakamura's invention of them in 1993 and the subsequent vast improvements that he and others made to green LEDs. The advances made it possible to combine all three primary colors to emit light across the entire color spectrum.[2] The pioneering work won Nakamura, Isamu Akasaki, and Hiroshi Amano the 2014 Nobel Prize in Physics (see Physics Today, December 2014, page 14).

After the blue LED puzzle was solved, researchers in 1998 at Kansas State University proposed the idea of LED miniaturization, termed microLED. In a patent, the researchers outlined the potential usage of microLEDs as bright-light elements for making minidisplays and as detectors or sensors.[3] Unlike LEDs, microLEDs range from single-digit microns to 100 microns in size.[4] MicroLEDs emit light when current is injected by applying a positive voltage on the anode and a negative voltage on the cathode. During that process, electrical energy is converted to optical energy by electronic carriers (electrons and holes) that move through the active semiconductor material, where they recombine radiatively and emit photons.

Improvements to microLED technology came in 2001, when the Kansas State group demonstrated a blue monochrome microLED microdisplay.[5] And 10 years later, the same research group, now at Texas Tech University, used indium gallium nitride and gallium nitride in the first blue and green microLED display with a 640 x 480 resolution and video-graphic capabilities.[6] Since then, microLED brightness, efficiency, lifetime, and manufacturing have advanced considerably, primarily driven by improvements in the material qualities of InGaN

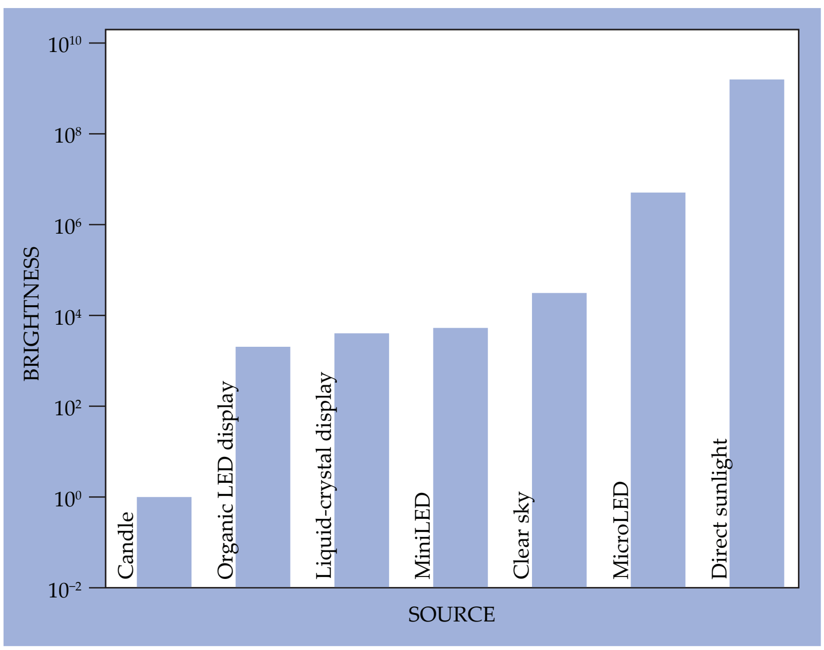

FIGURE 1. MICROLED TECHNOLOGY is brighter than other light-emitter technologies. MicroLEDs are more than two orders of magnitude as bright as clear daylight, which makes them suitable for displays that can be used outside.

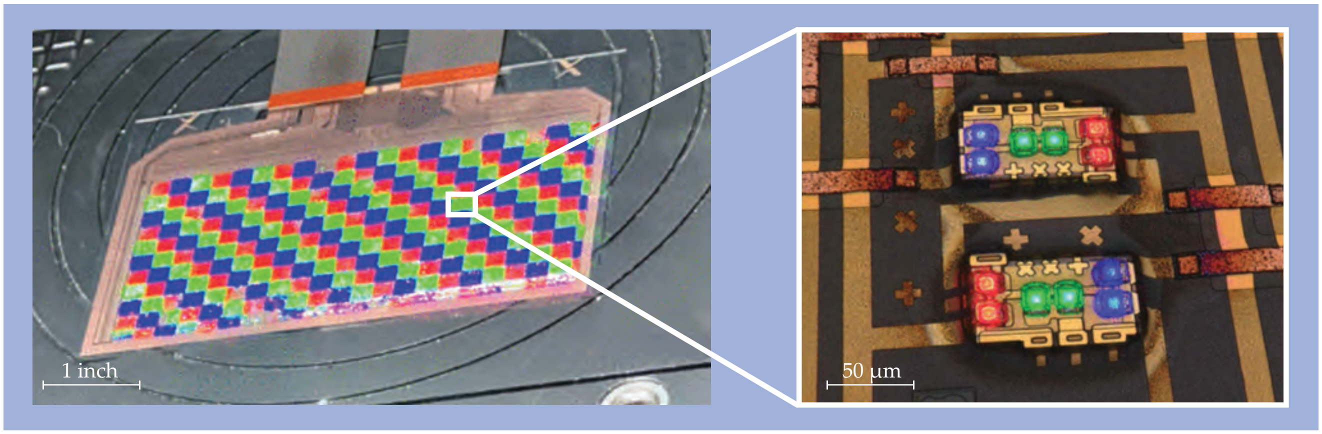

FIGURE 2. THIS RGB DISPLAY, made by X Display Company, is 5.1 inches and has a resolution of 320 × 160 pixels. The inset shows the microLED display's RGB (red, green, and blue) subpixels, which are assembled using an elastomer stamp mass-transfer process. (Adapted from ref. 15.)

and GaN. The display industry is interested in microLEDs because of its growing focus on augmented reality and virtual reality.

Why microLEDs?

The key advantages of microLEDs are their ultrahigh brightness, high efficiency, and long operational lifetimes of more than 100 000 hours.[7] Ultrahigh brightness is particularly relevant for applications in augmented-reality displays that compete with the Sun's brightness in outdoor environments. Figure 1 compares other light-emitting sources with microLEDs, which show brightness capabilities that are three orders of magnitude higher than liquid-crystal displays (LCDs) and organic LEDs (OLEDs). Some of the biggest technology companies, including Meta (with the formation of Reality Labs) and Google (with its acquisition of Raxium in 2022), have put microLEDs at the forefront of next-generation display technology. Other applications include small displays, such as for smartwatches and smartphones; heads-up and infotainment displays in the automotive industry; and pico projectors, which are small, portable projectors that require high brightness.

MicroLED displays are often directly compared with LCDs and OLED displays, but each technology offers its own set of advantages and disadvantages, depending on the specific application. In conventional displays, microLED technology shouldn't be confused with miniLED technology. MiniLEDs provide better contrast and localized dimming zones for traditional LCDs by using many smaller LEDs as backlight sources. MicroLEDs represent a more significant technological leap forward because they offer true self-emission properties. Self-emission microLED displays, like OLED displays, are defined by each pixel intrinsically generating light of its respective color. Self-emission results in true black levels and high contrast ratios because each pixel fully turns off when not in use.

In contrast, LCD technology constantly emits white light and applies color filters to achieve RGB subpixels. Although LCDs are cost-effective, their reliance on a backlight prevents them from achieving high contrast ratios and thin form factors. LCDs and microLED displays are durable and have longer lifespans than OLED displays because they are less susceptible to pixel burn-in. OLED displays, although not as cheap to produce as LCDs, have seen considerable price drops, especially in mobile form factors, and they're still much more cost-effective than microLEDs. Additionally, OLED displays can be built on flexible and conformable substrates for folding and curved displays. Compared with OLED displays and LCDs, microLED displays stand out for their combination of high performance, durability, and energy efficiency.

To produce colors across the entire visible spectrum, RGB subpixels are spaced closely together and programmed with different intensities. When viewing a display from a sufficient distance, the human eye detects the subpixels as one light source, and the individual colors appear to mix. It is desirable to have all three colored subpixels made from the same semiconductor material to simplify manufacturing. The most commonly used materials for making blue LEDs are InGaN sandwiched between layers of GaN. The LED is grown epitaxially on a sapphire substrate: A crystal layer of each material is deposited one atomic layer at a time on a seed layer with a well-defined orientation in specialized deposition chambers.

One measure of manufacturing success is the improvement in external quantum efficiency (EQE), which refers to the ratio of the number of photons emitted to the number of electrons injected into the semiconductor material. Whereas blue microLEDs' EQE can be high at over 40%, achieving the same efficiency with red and green microLEDs has been challenging when using InGaN for dimensions of less than 20 μm. The difficulty in achieving efficient green emission from InGaN microLEDs, termed the "green gap" phenomenon, is primarily because of the reduced crystal quality of the grown InGaN.

Blue to green to red

Light emission from LEDs depends on the active material's bandgap—the energy difference between the material's electronic states, separated into conduction and valence bands. A material's bandgap is determined by crystal-structure

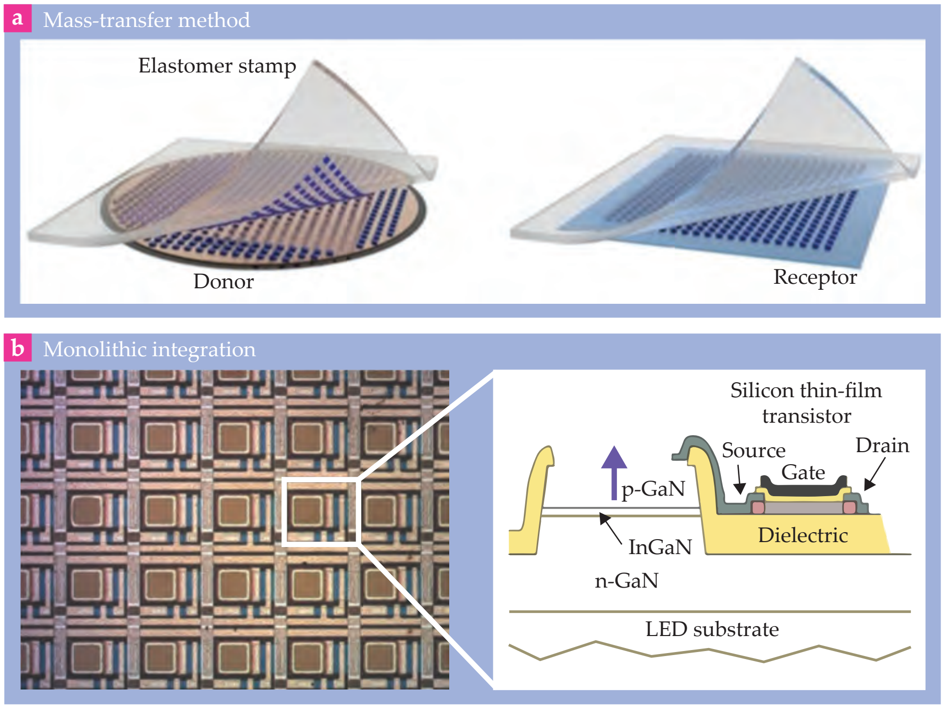

FIGURE 3. FULL-COLOR DISPLAYS made with microLEDs are typically developed with two approaches. **(a)** In the mass-transfer method, an elastomer stamp removes individual microLEDs from a donor substrate and then prints them onto a receptor substrate. (Adapted from ref. 16.) **(b)** For the monolithic-integration approach, a silicon thin-film transistor is fabricated side by side with a microLED onto the same substrate, so no mass transfer is required. The microLED consists of a p-type gallium nitride layer, a layer of indium gallium nitride, and an n-type GaN layer. The purple arrow shows the direction of light emission. The transistor's three terminals—the source, the drain, and the gate—connect to the electronic circuit, and the dielectric layer provides isolation from the GaN layers. (Adapted from ref. 17.)

parameters, such as the lattice constant. The presence of indium in InGaN leads the material to have a higher lattice constant and a smaller bandgap than GaN.

The smaller bandgap results in the emission of lower-energy light, or longer wavelengths. As more indium is added and the bandgap narrows, the color of emitted light shifts from blue to green and eventually to red. The larger lattice-constant mismatch with the underlying GaN layer creates a compressive stress in the active InGaN layer, which causes crystal defects and decreases the efficiency of the light emission from the material. Recent methodologies involving InGaN and GaN nanowires have demonstrated a remarkable closing of the green gap by achieving an EQE that exceeds 25% for green microLEDs.[8]

Similar challenges exist in achieving red emission from InGaN. Compared with green microLEDs, red microLEDs require a higher indium content, which causes an even more significant lattice mismatch. To incorporate more indium into the InGaN layer, the fabrication temperature must be lower, but that leads to higher defect densities and decreases the overall efficiency of the microLEDs. Red microLEDs made using the AlGaInP—rather than the InGaN—material system are more efficient but still undergo nonradiative recombination, in which electrons and holes recombine but do not exhibit light emission. Nonradiative recombination emits energy thermally, and the increased device temperature can further reduce the efficiency of microLEDs if they're not properly heat-sinked.

The efficiency of red microLEDs made from InGaN has improved in recent years. Researchers have achieved an EQE value of about 8% for red microLEDs by employing nanowires of InGaN and GaN, and that improvement has started to close the performance gap with blue microLEDs.[9] Although red microLED efficiency has not yet reached the level of blue microLEDs, research is ongoing, and several technologies—including nanowires, strained quantum-well growth, and double quantum-well technologies—are showing promising improvements.

Given the reduced efficiency of green and red microLEDs and the integration challenges of combining three materials in one display, researchers have developed color-conversion technologies as an alternative solution to achieving full-color displays. One such technique uses quantum dots to obtain green and red colors from blue microLEDs.[7]

Quantum dots are tiny semiconductor particles, typically 2–10 nm in diameter. They are so small that they have unique optical and electronic properties that differ from those of larger particles because of quantum mechanical effects. One of the most critical properties of quantum dots is their ability to emit light of different colors depending on their size, thus making it possible to achieve green and red emissions. (For more on quantum dots, see Physics Today, December 2023, page 16, and the article by Dan Gammon and Duncan Steel, Physics Today, October 2002, page 36.)

Another color-conversion technique uses phosphors. The luminescent substances generally consist of two materials: a host material of wide-bandgap oxides or sulfides and an activator material of transition metals. Phosphors emit light of longer wavelengths when exposed to a radiant energy of shorter wavelengths. Exposing the phosphors to a UV or a blue light source excites the electrons in the material to a higher energy state. The excited electrons emit light of a specific color when they return to the lower energy state. The choice of the activator in the phosphor material determines the wavelength of the light emitted.

For displays, both color-conversion techniques use highly efficient blue microLEDs and down-convert the wavelength to

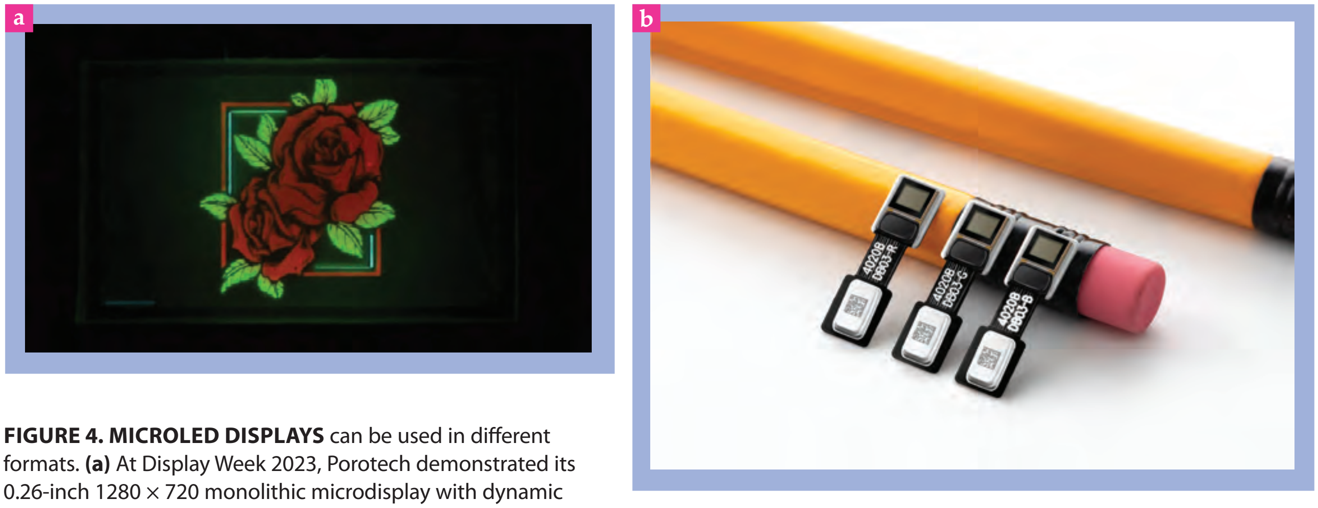

FIGURE 4. MICROLED DISPLAYS can be used in different formats. **(a)** At Display Week 2023, Porotech demonstrated its 0.26-inch 1280 × 720 monolithic microdisplay with dynamic pixel tuning, which enables a full-color display without the need for three distinct subpixels.[14] (Courtesy of Porotech.) **(b)** Jade Bird Display showcased 0.13-inch 640 × 480 monochrome microdisplays. The exceptional brightness is advantageous in augmented-reality and virtual-reality applications. It won a Society for Information Display 2023 Display of the Year award. (Courtesy of Jade Bird Display.)

emit green and red light to achieve full color. Integrating quantum dots or phosphors with displays, however, adds more manufacturing steps and complexity. The overall efficiency of color conversion with quantum dots is diminished—by as much as 50%—because of optical loss caused by inefficient photon travel.[10] Color-conversion techniques can also be limited by cross talk to adjacent subpixels, which leads to color inaccuracies and blurred images.

Full-color integration

Manufacturing a display out of micron-scale light sources requires assembling millions of pixels on a backplane—the electronic circuitry for the logic and the driving current. A full, high-definition, 1920 × 1080 display needs about 6 million microLEDs. But the display technology is unforgiving: Even a single dead pixel is visible to the end user, so an exceptionally high yield is required to make a fully functioning display. The method for assembling microLED displays should be both fast and accurate on an industrial scale. With those factors in mind, the industry has developed two approaches: mass-transfer technology and monolithic integration, both of which have their advantages and challenges.

Mass-transfer technology is more suitable for larger mobile displays, computer monitors, and digital signs. Individual RGB subpixels are picked up and transferred from the native donor substrate to a target substrate. The method provides the freedom to choose a substrate more suitable for the driving backplane. Using different donor substrates enables the use of different material systems for RGB subpixels such that each subpixel is matched to its most efficient microLED material. That approach eliminates the need for color-conversion layers, such as quantum dots or phosphors.

Perhaps the most successful approach to mass transfer uses a stamp to move RGB subpixels to a driving backplane.[11] Figure 2 shows a microLED display fabricated using the mass-transfer method. MicroLEDs are first fabricated on top of a sacrificial layer that is subsequently dissolved, which leaves the microLEDs suspended above an air gap and held to the substrate via thin, breakable tethers. A transfer mechanism—such as an elastomer stamp or printhead—uses van der Waals forces, suction, or adhesives to remove the microLEDs batch by batch from their donor substrate.

The stamp or printhead then moves the microLEDs to the target substrate, where they are aligned and attached at the desired location. The target substrates establish electrical contact with the transferred microLEDs through the use of metal layers that are deposited with conventional lithography processes. Researchers have implemented robotic pick-and-place and roll-to-roll techniques to achieve high-resolution displays with yields that are good enough for industrial scales, although the costs may still be high.[1]

Another method for mass transfer uses fluidic self-assembly.[12] It's a process in which microLED subpixels are assembled onto the target substrate under the influence of fluidic forces. The concept is based on the principle that complementary components will spontaneously assemble into stable structures when they are brought into contact with each other in a fluid environment. Researchers have used the process to assemble GaAs LEDs onto a silicon backplane.[11] The method is simple to implement, low cost, and scalable, but obtaining high yields and assembling each of the RGB subpixels together into one pixel is challenging. Figure 3a shows a schematic of the elastomer stamp technique.

Homegrown pixels

Rather than move microLED pixels from one substrate to another, monolithic-integration techniques address microLED pixels directly on their native substrate. The driving circuitry—that is, the electronics used to manipulate the display pixels—are made available to the native LED substrate without any need for transferring individual pixels. MicroLED pixels with sizes as small as a few microns can make extremely pixel-dense microdisplays, with more than 5000 pixels per inch. Three major approaches are available to implement monolithic integration: microLED epitaxial growth on silicon, transistor fabrication on a microLED epitaxially grown on sapphire, and flip-chip bonding of a microLED substrate to CMOS chips. Figure 3b shows a monolithic-integration method that involves the fabrication of a thin-film transistor alongside the microLED pixel, all on a single substrate.

Although microLEDs that are grown on their native substrates produce the most efficient light emitters, they can also be grown on silicon substrates, and efficient blue LEDs can be color converted to obtain other colors. MicroLEDs grown on silicon are ideal for backplane fabrication because of the maturity of transistors built around silicon materials.[13]

The quality of microLEDs grown on silicon and their emission efficiency has traditionally been poor because of the large lattice mismatch. Using buffer layers such as AlN between GaN and silicon has improved their efficiency. But until microLEDs grown on silicon exhibit efficiency improvements that match that of their native substrate counterparts, they will not be tenable for product deployment. Another strike against microLEDs grown on silicon is that other techniques, such as selected-area epitaxy and strained quantum wells, can produce RGB pixels natively on one substrate without the need for color conversion.

For microLED displays on sapphire substrates, the driving circuits—which are needed for selecting desired pixels in a sequence, also known as pixel addressing—are implemented by fabricating thin-film transistors on microLEDs. Materials such as amorphous silicon and indium gallium zinc oxide are used as the semiconductor layer for fabricating the necessary transistors. But it remains challenging for researchers to achieve uniform electrical characteristics that are as good as those made with CMOS technology. Additionally, such displays are inherently monochromatic or require color-conversion techniques to achieve RGB pixels as complex as the ones typically made with blue microLEDs.

Recent progress in porous GaN technology has paved the way for creating dynamically tunable pixels. With porous GaN, formed by electrochemical etching, higher amounts of indium can be incorporated into the InGaN crystals of the microLEDs because of a decrease in the strain of the lattice. That enables efficient red emission with material systems such as InGaN and GaN. A pixel that's tuned for color with porous GaN technology emits a spectrum of wavelengths ranging from blue to IR. Color tuning eliminates the requirement for multiple subpixels of distinct colors to be grown and subsequently transferred. At Display Week 2023, the company Porotech demonstrated, using porous GaN, the first monolithically integrated, single-panel, and full-color microdisplay.[14]

Another approach for integration is fabricating GaN on sapphire and then bonding it to a conventional CMOS backplane by using such techniques as flip-chip bonding and thermocompression. Flip-chip bonding uses metal bumps to connect two electronic devices. It's appropriate for small-size displays with higher pixel density, such as smartwatches and augmented- and virtual-reality displays.

For active-matrix addressing—in which the individual pixels are connected to a transistor and controlled by applying voltages to it—each pixel needs a bond site on the microLED terminal and another on the CMOS backplane. It's effective for high-resolution displays, but the increased complexity of the bonding methods makes it less suited for mass-scale production. The simpler passive-matrix addressing connects pixels in rows and columns and then applies the voltage directly to the entire structure. That setup is easier to fabricate but lacks the high refresh rate needed in high-resolution displays. Still, passive-matrix addressing is useful for lower-resolution displays, which makes it a popular method to implement in academia for demonstration purposes.

What's next for microLEDs?

In addition to the scaling, packaging, and driving challenges, another issue microLEDs face is the relatively high cost of the source materials and of their subsequent fabrication processing. One solution is to move to larger wafer sizes. GaN is often grown on sapphire, which yields reasonably high LED performance but does not scale to substrate areas larger than about 200 mm. Significant recent work has been applied to the growth of high-performance GaN microLEDs on silicon substrates, which allows for 300 mm wafers to be built and processed.

The higher production efficiency per unit area in LED growth and semiconductor processing offers a road map: A significantly improved cost per LED can help lead to mass-market applications for microLED technologies. Figure 4 shows some microLED displays for different formats and uses that have been made at an industrial scale.

Although microLED displays are in their infancy, many of the technology's technical advantages, such as luminance, lifetime, color quality, and device scaling, have been demonstrated. As one would expect in a maturing technology, the commercial challenges have now transitioned to issues of cost and of scaling the manufacturing process to industrial levels. The future for microLED technologies is bright, and soon we expect to see microLEDs in many display applications, including augmented- and virtual-reality headsets, smartwatches, and smartphones.

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