How NanoLED Will Enable Next-Generation Displays

NanoLED's promising performance is attracting many researchers looking toward technology and applications that may revolutionize displays.

by **Takeshi Ishida, Yohei Nakanishi, Noboru Iwata, and Makoto Izumi**

QUANTUM DOTS (QDS) HAVE ATTRACTED SIGNIFICANT interest as a new material for display applications. Light-emitting QDs are nanometer-sized semiconductor particles that generally exhibit a narrow emission spectrum with high internal quantum efficiency. These unique properties allow QDs to create a wide color gamut (WCG) and low power consumption when used in displays. With this in mind, we expect to see QD materials' technical application for displays evolve in three major steps (**Fig. 1**). The first step, which began in 2013, is QD backlights for liquid crystal displays (LCDs), where QD sheets are used as wavelength-converting materials to achieve pure RGB white light. The second step, which began in 2022, is the direct-pixel color-conversion method, which converts blue light wavelengths into green and red ones for each pixel in a display. This mainly is being developed in combination with organic light emitting diode (OLED) displays, known as QD-OLED displays. The final step is the self-emissive method of QDs by current injection (hereinafter referred to as nanoLED, as the light-emitting diode structure created using nanoparticles), which is expected as a next-generation display that could replace OLED displays.

The technology up to step 2 has been put into practical use, whereas the technology of step 3 is still in the research and development (R&D) stage. As a strong candidate for next-generation displays, we focus on the nanoLED, in which red, green, and blue (RGB)-emitting layers are patterned directly by photolithography. In this article, we describe the potential applications of nanoLEDs from the perspective of technology and market demand. We also explore the latest developments and challenges for realizing nanoLED.

Compatibility Between Technology and Market Demand

Most of the display methods attracting attention as state-of-the-art technologies have limited applicable products because of manufacturing limitations, such as the ability to make very tiny pixels with high efficiency, very high brightness displays, and the need to use large mother glass-based processes to achieve low unit cost (**Table 1**).

OLEDs are the only self-emissive displays that widely have penetrated the market. They are gaining recognition for their high contrast ratio, thinness, and compatibility with flexible substrates, which are more suited to self-emissive displays. OLEDs broadly are classified into two technologies according to their colorization methods. The first method is direct patterning of RGB emission layers onto each subpixel, where each emitting layer is formed by deposition using a fine metal mask (FMM), or RGB-OLED. The other method is a technology that combines a white OLED layer and color filters (WOLED). Instead of patterning the light-emitting layer for each RGB subpixel, a WOLED layer is formed as a common layer, and color filters are formed for each subpixel to achieve colorization.

RGB-OLED is the most widely applied technology. Because RGB direct patterning loses less energy, RGB-OLEDs are mainly used in wearable devices, smartphones, tablet PCs, and laptop PCs, where performance at low power consumption is important. However, RGB-OLEDs cannot be easily applied to TVs, which require a large screen, or augmented and virtual reality (AR/VR) devices, which require ultrahigh resolution, because of the FMM's size and reso-

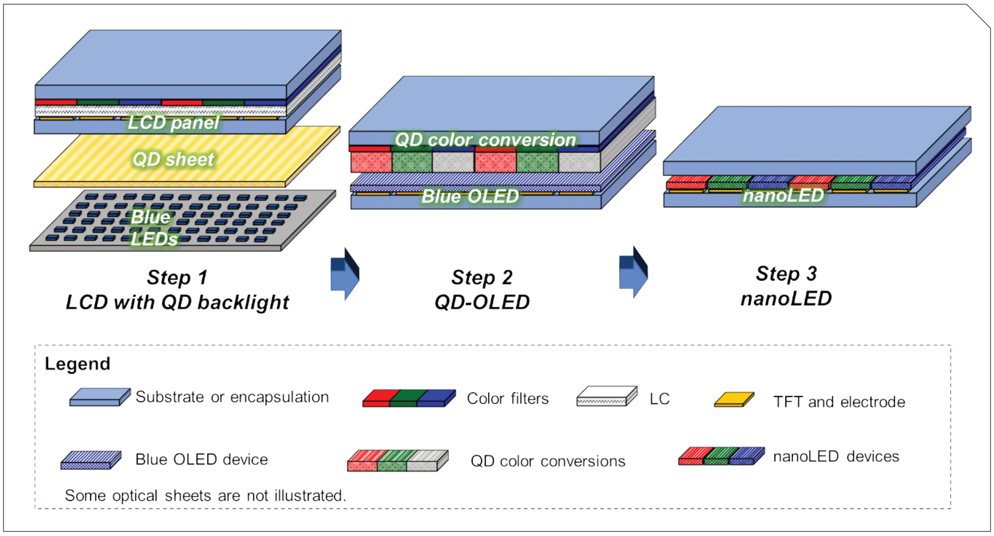

Fig. 1.

Evolution steps of quantum-dot (QD) displays. TFT: thin-film transistor.

lution limitation. WOLEDs are applied in such instances.

The configurations of these displays are different. WOLEDs for large displays are driven by thin-film transistor (TFT) backplane substrates consisting of indium gallium zinc oxide (IGZO), while ultrahigh-resolution WOLEDs are driven by silicon complementary metal-oxide semiconductor (CMOS) TFT substrates. Also, the OLED element configuration for emitting white light differs between the two methods. Depending on the colorization method, both large-size and high-resolution OLEDs are defined as the same WOLEDs in this article. WOLEDs have no size nor resolution restrictions due to the FMM. However, power efficiency due to light absorption loss at the color filter and reduction of color gamut due to leakage of undesired wavelengths from the color filter are issues. For these reasons, WOLEDs are used only for large displays such as TVs or ultrahigh-resolution displays for AR/VR, wherein RGB-OLEDs are not applicable.

LCDs with QD backlight have been applied primarily in TVs and monitors. QD backlight has contributed to great improvements in color purity. Furthermore, in recent years, the combination of QD and miniLED backlights have enabled reductions in the total thickness of displays, so it also is being applied to some laptops and tablet PCs. MiniLED backlights contain thousands of blue LEDs with a size of several hundred micrometers. By individually controlling the luminance of these blue LEDs, it is possible to greatly improve the contrast ratio, which has been considered a weakness of LCDs. In addition, when combined with a QD sheet, this approach is superior to conventional LCDs in terms of expanding the color gamut. Because of these advantages, it is expected to be widely used in laptops and tablet PCs in the near future. However, the thickness of miniLED-based displays is still too large for smartphones and wearable devices.

QD-OLED TVs and monitors were introduced to the market in 2022. Their WCG and wide viewing angle performance have been well received, and further applications are expected.

Table 1.

Compatibility between technology and market demand.*
*The green bars show applicable product range.

Technology classification		Simplified diagram	Applicable product			
			AR / VR	Smartphone / Wearable device	Tablet PC / Laptops	Monitor / TV
OLED	RGB-OLED	OLED				
	White-OLED	Color filter White OLED				
QD Display	LCD with QD backlight	LC panel QD backlight				
	QD-OLED	QD color conversion Blue OLED				
	nanoLED by inkjet	nanoLED				
	nanoLED by photolithography	nanoLED				

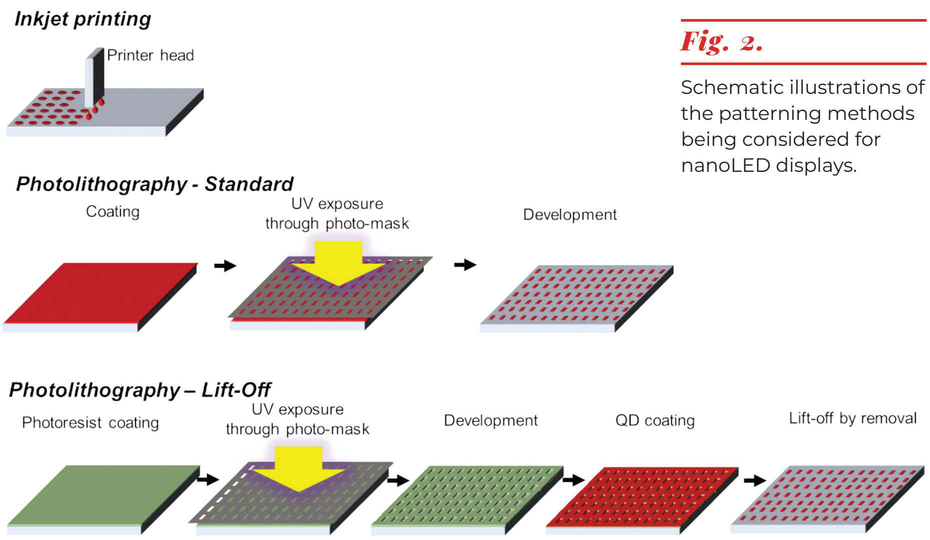

Fig. 2.

Schematic illustrations of the patterning methods being considered for nanoLED displays.

However, its application may be limited to products with larger screen sizes without further advances. The current approach to QD-OLEDs requires a relatively thick QD layer of ~10 µm to efficiently absorb light emitted from the blue OLED layers and convert it into green and red. QD color-conversion layers are patterned separately by inkjet for each red and green subpixel, but the resolution of the QD-OLED currently is limited to ~200 ppi because of the accuracy of the inkjet patterning. In addition to the low power efficiency of blue OLED, the QD-OLED has an energy loss of the QD color-conversion layer, so energy efficiency remains an opportunity for improvement.

NanoLEDs, sometimes called electroluminescent quantum dot (QD-EL) or QD-LED, are expected to be the next generation of technology that achieves superior performance—high luminance, WCG, and high contrast ratio—for displays. The manufacturing method will determine the product coverage of nanoLEDs. Several methods have been proposed for manufacturing nanoLED based on the QD patterning technology (**Fig. 2**).

Inkjet printing is a major deposition process in which QDs' ink is dispensed to the target position. The required droplet size can be minimized, leading to a reduction of cost with QD ink. This method has a strong advantage. There have been several demonstrations of nanoLED patterns using inkjet printing,[1–3] but some issues are present with high-resolution patterning. As a result, the application of inkjet-printed nanoLEDs will be limited to TVs and monitors, similar to QD-OLEDs, where QDs as color-conversion layers are patterned in the same way.

Photolithography also is a promising technique for QD patterning at high resolution based on two methods. One uses photoresist material, which reacts to UV light to form an insoluble matrix; the other is called the lift-off method, where the photoresist first is patterned, QDs are deposited, then the photoresist pattern is removed with QDs. Both methods have been used for nanoLEDs.[2–8] Manufacturing nanoLEDs by photolithography is more difficult than inkjet printing because of damage to QDs during the process. However, if a process technology based on photolithography can be established, it would have a significant advantage. Photolithography is the most widely used method for manufacturing electronic devices, including LCDs, and it is expected to be applicable—from high-resolution small displays to large displays—without technical limitations, similar to LCDs.

Facilitating Developments in NanoLED Displays

Recently, advances in materials and process technology have enabled several display manufacturers to develop active-matrix (AM) nanoLED displays. TCL introduced a 32-inch AM hybrid display using red and green nanoLEDs combined with blue OLED.[3] BOE demonstrated a 55-inch AM display using RGB nanoLED.[4] Samsung Display fabricated a 6.95-inch AM display using RGB nanoLEDs composed of cadmium (Cd)-free QDs.[5] Cd-containing QDs show excellent luminous performance, but Its toxicity has been suggested to have adverse effects on the environment. The successful development of a display using Cd-free QDs would be a significant achievement toward the practical application of nanoLEDs. Each of these AM displays were manufactured using inkjet printing.

There are few reports on the development of AM nanoLED displays using photolithography, which is technically challenging. Recently, we reported on the successful fabrication of a 6.2-inch AM nanoLED display using all Cd-free QDs patterned by photolithography[6] (**Fig. 3**). We also demonstrated the utility of ultrahigh resolution, one of the features of photolithography.[7] **Fig. 4** shows experimental results of high-resolution patterning of nanoLEDs using a passive-matrix test cell on a Si wafer. Despite the ultrahigh resolution of 3,994-ppi, RGB emissions are observed without crosstalk. This is the highest-resolution self-emissive device created by separately painting red, green, and blue.

Fig. 3.

Full-color image display of a 6.2-inch Cd-free nanoLED patterned by photolithography.

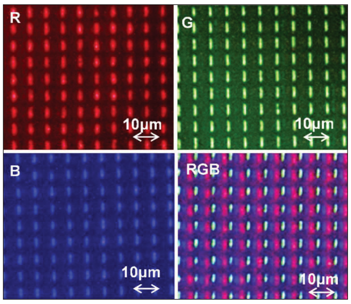

Fig. 4.

◂Micrograph of 3,994-ppi nanoLED pixels patterned by photolithography.

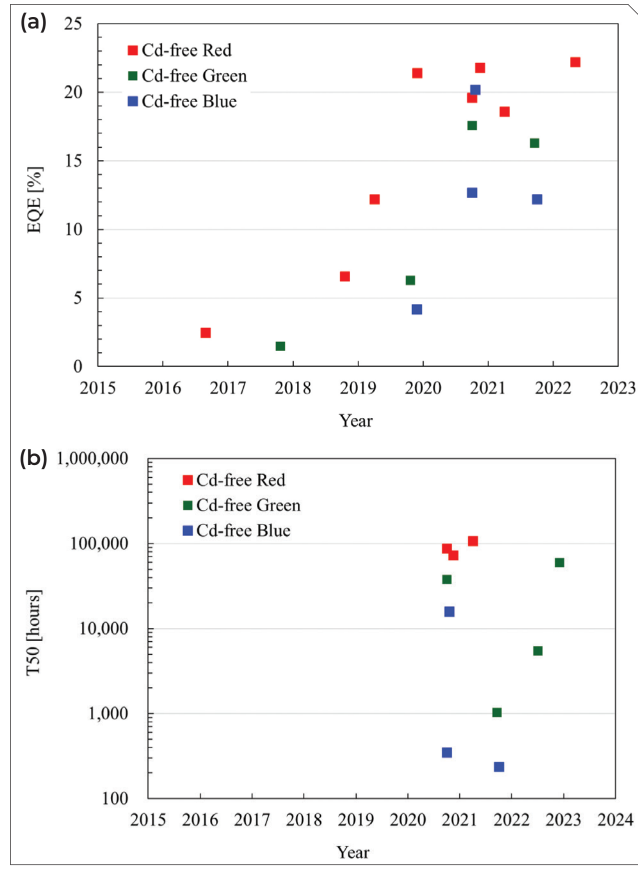

Fig. 5.

▸Progress of nanoLED (a) efficiency and (b) lifetime with Cd-free QDs.

Challenges for Realizing NanoLED Displays

NanoLED technology has shown steady improvement in recent years, but further evolution is necessary for its practical application. To realize nanoLEDs, the most important challenge is to improve the performance of QD materials. Until recently, the most-efficient QD-LED devices used QDs composed primarily of cadmium selenide (CdSe).[8] Cadmium is extremely limited under the Restrictions of Hazardous Substances (RoHS) regulation, making it impractical to use Cd-based QDs in display applications. Consequently, alternative non-toxic QD materials, such as indium phosphide (InP),[9–27] zinc selenide (ZnSe), zinc selenium telluride (ZnSeTe),[18,22,10-32] and others, are under consideration for nanoLED devices.

Fig. 5 shows the progress of nanoLED efficiency and lifetime using Cd-free QDs, making tremendous strides in the past five years (**Fig. 5a**). The highest efficiency of red nanoLED using InP QD reached more than 20 percent,[17,19,21,22] and green nanoLED has reached 17.6 percent.[18] InP cannot be used to realize blue-emitting nanoLED, as such a particle would be too small to reliably synthesize. However, ZnSe or ZnSeTe are suitable alternatives. The best efficiency for blue using ZnSeTe QD has reached more than 20 percent.[31] Thus, the efficiencies of nanoLEDs with Cd-free QDs have improved ~20 percent for all colors. This is the minimum acceptable efficiency for nanoLED to be used as pixels in displays. Efficiency affects power consumption of displays, so this is quite critical, especially for mobile display applications.

The lifetime of Cd-free QDs still needs improvement. **Fig. 5b** plots the lifetime from an initial luminance of 100 nits to a reduction of 50 percent (T50). An improvement for red-emitting nanoLED using InP QD has been reported for achieving both high efficiency—comparable to toxic-based QD-LED—and a lifetime of more than one million hours.[17] This was achieved using a chemical treatment to reduce oxygen formation at the interface between the core and the shell of the QD structure. However, the lifetime of green[18,25-27] and blue[22,31,32] still is less than 100,000 hours, which is insufficient for industrial applications. These lifetimes could be improved substantially in the future to realize nanoLED using all Cd-free QDs.

Journey to NanoLED

Most of the discussed developmental results of nanoLEDs are at the confirmation stage for basic performance as a light-emitting device. However, further refinements are needed. For example, RGB-patterned display devices using Cd-free QDs are ready for demonstration. They just need further improvement through integration of material and process technologies.

The journey to nanoLED is not an easy one, and it will take considerable developmental effort to become an industrial-level technology for display applications. However, its distinguished performance has attracted many researchers, and much research is ongoing. NanoLEDs are on a path to evolve into a technology that will revolutionize the display industry, just as LCDs and OLEDs have done before it.

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