# Development of 326ppi High-Resolution 1.39-in. Active-Matrix NanoLED Circular Display Using Low-Cost and Low-Permeability Sputtered AZO Thin-Film Encapsulation

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## Abstract
***We report and discuss the challenges to realize a nanoLED based display from the perspective of materials and processes. Additionally, we report on a 326 ppi high resolution 1.39 inch active-matrix nanoLED circular display using low cost and low permeability sputtered Aluminium Zinc Oxide (AZO) thin film encapsulation.***

## Author Keywords
QD-LED, QD-EL, electroluminescence, quantum dot, active-matrix, nanoLED, AZO, thin film encapsulation

## 1. Introduction
In recent years, there has been growing attention to the development of displays using quantum dot materials. Quantum dot materials exhibit the following excellent characteristics to improve display performance.

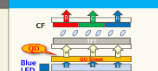
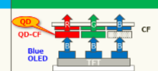
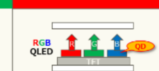
1. The ability to choose any wavelength by controlling the size of the nanoparticles.
2. High internal quantum efficiency.
3. Possession of a narrow half-width, resulting in a sharp emission spectrum, allowing for high color purity.
4. The capability to disperse nanoparticles in a solvent, facilitating handling through a solution process.

These features make quantum dot materials suitable for achieving a wide color gamut, as required by BT2020, low power consumption, and for environmentally friendly solution processes that do not require high-vacuum equipment.

There are two major approaches to applying quantum dot materials in display technology. One is the method employing photoluminescence, and the other is the method employing electroluminescence (Table 1.).

The photoluminescence method is also referred to as the color conversion method. For instance, quantum dot materials exhibiting red or green luminescent properties can be practically applied in LCD and OLED displays. In LCDs, a practical approach involves using a QD sheet and a Blue-LED backlight, achieving a wide color gamut through the narrowed spectrum of QDs. However, challenges persist in areas such as contrast and flexibility. In OLED displays, a practical implementation involves combining QD color filters (QD-CF) with Blue-OLED, realizing both the high color gamut characteristic of QDs and the flexibility inherent to OLED technology. Nevertheless, challenges remain in achieving higher brightness, higher resolution, and cost reduction.

**Table 1.** Expected performances of displays using quantum dots.

| | Photoluminescence | | Electroluminescence |
|---|---|---|---|
| Technology | LCD + QD Sheet | OLED + QDCF | nanoLED |
| Structure |  |  |  |
| Brightness | ★★★ | ★★ | ★★★ |
| Contrast | ★★ | ★★★ | ★★★ |
| Resolution | ★★★ | ★★ | ★★★ |
| Thickness (Rollability, Flexibility) | ★ | ★★★ | ★★★ |
| Cost | ★★★ | ★ | ★★★ |

The electroluminescence method is known as a so-called self-emission method. It involves generating excitons by injecting holes and electrons into quantum dot materials, leading to luminescence. We refer to this self-emitting type, the Quantum Dot Electroluminescence (QD-EL) method, as nanoLED. We believe that nanoLED being of the self-emitting type, has the potential to combine the advantages of LCD and OLED displays, potentially achieving high brightness, low power consumption, high contrast, flexibility, cost-effectiveness, and leading candidate for the next-generation display.

To manufacture a self-emitting type of display, it is necessary to pattern each RGB pixels. Three main methods for RGB patterning have been proposed thus far: contact printing, inkjet printing, and photolithography patterning. A deposition method for precisely placing red, green, and blue QDs in each pixel should be developed to make a full color nanoLED display. This method should allow to form high resolution patterns typically of microns scale of QD film of thickness in the range of 10-30 nm and of single color. Several patterning methods have been reported as shown in Figure 1.

Contact printing is the simplest method and uses stamps to pattern QDs onto a substrate. This method has already demonstrated a high-definition nanoLED display successfully but the display size is limited to the size of the stamp[2-5].

Inkjet printing is an excellent manufacturing method and has been implemented in the display industry. The ink is dropped exactly where it is required and with the desired quantity. This results in less ink waste and therefore reduces the bill of materials. Inkjet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process is suitable for low resolution displays. When this deposition technique is applied for smaller size of the pixel to achieve higher resolution, a so-called coffee ring effect occurs which causes nonuniformity of the QD thickness in the pixel and hinder the external quantum efficiency of the QD-LED[6-13].

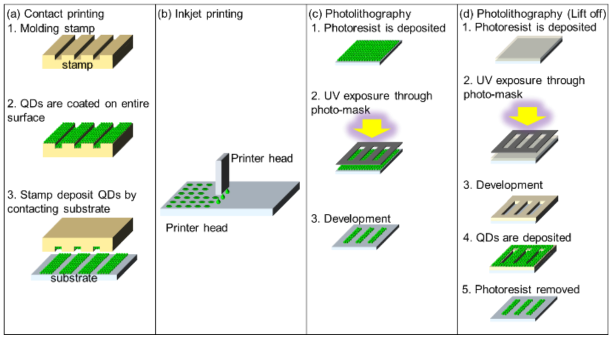


**Figure 1.** QD patterning methods considered for QD-LED displays

Photolithography is a widely used technology in the manufacture of electronic devices and flat panel displays industry such as in the fabrication of backplanes. It can also be an effective technique for QDs patterning, considering that the manufacturing equipment is already installed in display factories. Several photolithographic QD patterning process have been proposed. One is a method of directly curing QD with ultraviolet rays (UV). Ko et al. have used QD with UV cross-linkable ligand[14], and Nakanishi et al. developed a UV curable resin containing QDs[1]. Other method is lift-off process. Photoresist is patterned to form a mask on a substrate. QDs are then deposited over the photoresist mask and photoresist is removed leaving QDs at desired area on the substrate[15-17].

We have been developing RGB patterning using photolithography, which has fewer restrictions on substrate size and resolution. In SID2022[18-20], we demonstrated ultra-high-resolution nanoLED panel and world’s first 6.24” active-matrix nanoLED display with cadmium free QDs patterned by photolithography process, 12.3” active-matrix nanoLED display patterned in the atmosphere in SID2023[21], and 30” 4K active-matrix nanoLED display patterned by photolithography in the atmosphere in SID2024[22].

These our demonstrated nanoLED displays adopted glass encapsulation technique. Encapsulation to prevent penetrating water is a very important issue in self-emitting device like QD or OLED, because general self-emitting material is highly damaged by water vapor. So, such self-emitting device requires highly developed encapsulation technique to prevent water vapor penetrating. The glass encapsulation technique is conventional and easy method, and thin film encapsulation (TFE) technique is also used because its various advantages such as lightness, thinness, flexibleness, and stiffness. Generally, TFE is consists of inorganic/organic/inorganic (IOI) thin film layers and its inorganic film is formed by vapor deposition technique. The key characteristics of this vacuum deposition process are low damage to self-emitting device, high deposition rate, and high coverage. Therefore, this process generally employs CVD (Chemical Vapor Deposition). However, CVD equipment is very huge and uses gases with explosive properties. So more affordable methods are being sought.

In this paper, we report and discuss about 326 ppi high resolution 1.39” active matrix nanoLED circular display using low cost and low permeability sputtered AZO (Aluminium Zinc Oxide) thin film encapsulation.

## 2. Results and Discussion

We have fabricated 1.39 inches RGB active-matrix nanoLED circular display with resolution of 326ppi. (Figure 2). We used Generation 4.5 size mother glass as backplane substrate and divided into Generation 1 size to deposit nanoLED. It consisted of a layer of anode electrode, a hole injection layer (HIL), hole transport layer (HTL), QDs emissive layer (EML), electron transport layer (ETL) and cathode electrode. HIL, HTL, EML and ETL are deposited in the atmosphere and RGB patterned using photolithography. After making the nanoLED device, IOI thin film encapsulation is formed on the nanoLED device. Sputtered AZO film is used for inorganic layer and acrylic resin is used for organic layer. The thickness of the AZO film is set to maximize light extraction efficiency. This sputtered AZO film shows very low value of water vapor transmission rate (WVTR), and we also confirmed no moisture permeability of the film by a deuterated water penetration test. The coverage capability of the AZO film is excellent, and no cracks are observed even in areas with a large taper angle. The damage to the nanoLED device during the AZO film deposition is not found. There is no change in the IV characteristics of nanoLED device before and after the AZO film deposition. The transmittance of the AZO film in the visible light region is over 93% and the refractive index of the AZO film is 1.76@633nm. This IOI encapsulation shows very high sealing ability and reliability of nanoLED display is improved. There is no observed degradation in brightness after 500 hours of storage reliability testing at 40℃ and 95% humidity.

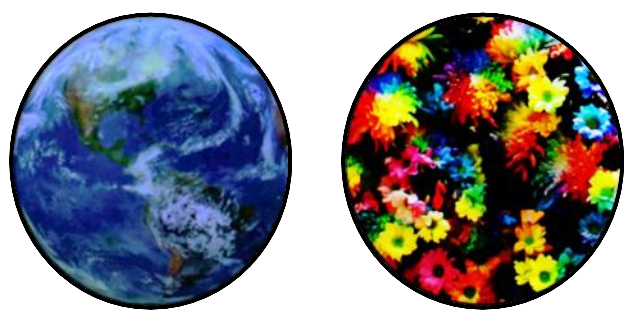

**Figure 2.** 1.39” active-matrix nanoLED circular display

## 3. Conclusion

Our challenges to overcome for realizing nanoLED display from the perspective of processes requirements have been discussed. We have reported that we have succeeded in developing a 326 ppi high resolution 1.39” active-matrix nanoLED circular display having high reliability using low cost and low permeability sputtered AZO thin film encapsulation. We expect that nanoLED will evolve as a technology that will revolutionize the display industry, just as the previous generation of LCDs and OLEDs did.

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