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Breakthrough and Application of Micro-OLED and Quantum Dot OLED (QD-OLED) Technology in High-Resolution Display

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Abstract. With the continuous progress of display technology, OLED (organic light-emitting diode) technology has become one of the important display solutions in modern electronic products, especially in terms of improving display resolution. In OLED technology, Micro-OLED and quantum dot OLED two core technologies to improve the resolution have been widely concerned. Micro-OLED is a display technology that uses miniaturized OLED (organic light-emitting diode) technology with extremely small pixel size. Because of its miniaturized pixel size, high brightness, self-lighting and other advantages, it is usually used in applications that require high resolution and small display devices such as augmented reality (AR) and virtual reality (VR) devices and smart glasses. Quantum dot OLED (QD-OLED) is an innovative display technology that combines quantum dot technology with OLED display technology. Quantum dot materials can enhance the color and brightness as well as resolution of OLED displays due to their wide color gamut, self-luminous properties, etc. However, OLED technology still faces challenges such as stability, manufacturing accuracy, and production costs. This article will introduce the principles of both techniques, their applications, and how to solve the challenges.

INTRODUCTION

OLED (Organic Light Emitting Diode) is a new type of display technology that uses the self-emitting properties of organic materials when an electric current is passed to display images or videos. Its self-luminous characteristics and the advantages of higher contrast and saturation make it widely used in the display field. The first practical organic light-emitting diode (OLED) was introduced in 1987 [1], after which OLED rapidly developed and became popular in the market. The main reason for the significant improvement in display technology is that the pursuit of display quality is constantly improving, which includes the pursuit of high resolution. In terms of high resolution, Micro-OLED technology and QD-OLED technology have continued to break through in recent years, and have strong potential in the future. Micro-OLED is a miniaturized OLED with extremely high pixel density, good color performance and moderate brightness, appropriate for small screen devices such as augmented reality (AR), virtual reality (VR) devices, smart glasses, etc. Its low power consumption is fitting for portable devices. Quantum dot OLED (QD-OLED) is a technology that combines OLED with quantum dots. It has a high pixel density, vibrant color performance and high brightness, well - suited for large screen sizes. By combining OLED with quantum dots, this technology enables OLED screens to emit purer and fuller colors. It has the advantages of higher brightness, higher contrast, and a wider color gamut. In terms of power consumption, QD - OLED consumes less power than traditional OLED and is more energy - efficient than LED backlight displays. Both technologies have their own merits. Micro-OLED Because it is a miniaturized OLED, its pixel size is very small, so it can be used in space-limited devices. Of course, Micro-OLED also has the self-luminous characteristics of OLED, which does not need to use backlight, can provide higher contrast and deeper black, which makes it can display excellent image quality. Its unique properties make it widely used in small devices. Micro-OLED and QD-OLED each have strengths, QD-OLED is generally used in large displays, its pure color makes it have a unique advantage. Micro-OLED and QD-OLED have a wide range of applications in their respective fields, and the combination of the two may bring further breakthroughs. Embedding quantum dot technology into the Micro-OLED screen, the quantum dot film can be placed directly on the light-emitting layer of the OLED screen, so that the combination of Micro-OLED and Quantum Dot OLED (QD-OLED) technology not only improves the pixel density, placing more pixels in the same area, thus achieving higher resolution. It also improves color accuracy and brightness, so that the Micro-OLED screen has purer colors and higher brightness. In general, by combining Micro-OLED and QD-OLED technologies, color performance, contrast and brightness can be enhanced while improving resolution. Because of the above benefits, the scene in the micro display can be a visual feast and therefore has strong future potential. This combination enables the display to maintain delicate images, rich colors and excellent dynamic performance at high resolution to meet the needs of high-end displays. Of course, both technologies still face some problems. For example, the artifact problem that may occur when Micro-OLED is displayed, and the stability problem of the QD-OLED quantum dot layer. These challenges are what all display devices must face and break through. This article will introduce the basic structure of Micro-OLED and Quantum Dot OLED (QD-OLED) technology to explain the basic principle of their luminescence. Through its structure, it shows how the two technologies contribute to high-resolution breakthroughs, and shows how the two technologies can be combined to make breakthroughs. Finally, solutions to current challenges and prospects for the future will be presented.

Basic Structure and Luminous Principal Light-Emitting Principle of Micro-OLED

In simple terms, Micro-OLED is a miniaturized OLED, and its basic structure is similar to OLED. Its structure is shown in Figure 1 (a). Micro-OLED has the same composition as OLED and is composed of four parts: a base layer, an anode, a cathode, and an organic layer (conductive and emitting layer). The selection of anode material is one of the key factors in determining the performance of Micro - OLED. It can significantly influence the current injection efficiency, stability, and service life of Micro - OLED. Therefore, the anode material must exhibit excellent electrical conductivity to enhance the efficiency of Micro - OLED. In 2019, Y. Chen and Y. Yue et al. tried to use graphene as a transparent electrode for organic optoelectronic devices, and the excellent performance of graphene has promoted the application prospect of graphene in future flexible, foldable electronic and optoelectronic devices [2]. The organic layer is the core of the Micro-OLED, in which the organic layer is divided into three Layers, namely electron transport layer, hole transport layer and luminous layer. Its structure is shown in Figure 1 (b). The hole layer and the electron transport layer transport carrier holes and carrier electrons to the luminescent layer respectively. When electrons and holes are injected into the luminescent layer, excitons are produced, which release energy and emit light. The above part is its luminous structure, which is encapsulated with a film to protect it from moisture and air to ensure its stability [3]. Outside the film package is a color filter and protective glass. Its structure is shown in Figure 1 (c). The outer color filter enables the Micro-OLED to display pure colors. When the current flows through the underlying OLED device, the excitons within the OLED emit white light. The color filter consists of three separate filters that allow only red, green and blue to pass through, respectively, thereby separating the RGB primary colors. Color filters selectively filter the red, green and blue colors in white light, thereby controlling each pixel to present a variety of colors. In terms of brightness, the brightness of each pixel can be controlled by controlling the current flowing through the OLED. This method of controlling color is not the same as traditional RGB OLED, which does not have a color filter, but rather darkens certain colors in the three primary colors by controlling the current. In contrast, this filter design in Micro-OLED can produce more uniform and restorative colors, while also reducing power consumption and improving resolution. In recent years, because red and green light have changed the material into phosphorescent materials, the efficiency and life of organic materials have been significantly improved, but the blue part still uses fluorescent materials, so its life is still very low. In order to improve the service life, C. Kim and J. H. Jung et al. increased the size of blue pixels and proposed a new structure as shown in Figure 1 (f) to improve the service life of OLED [4].

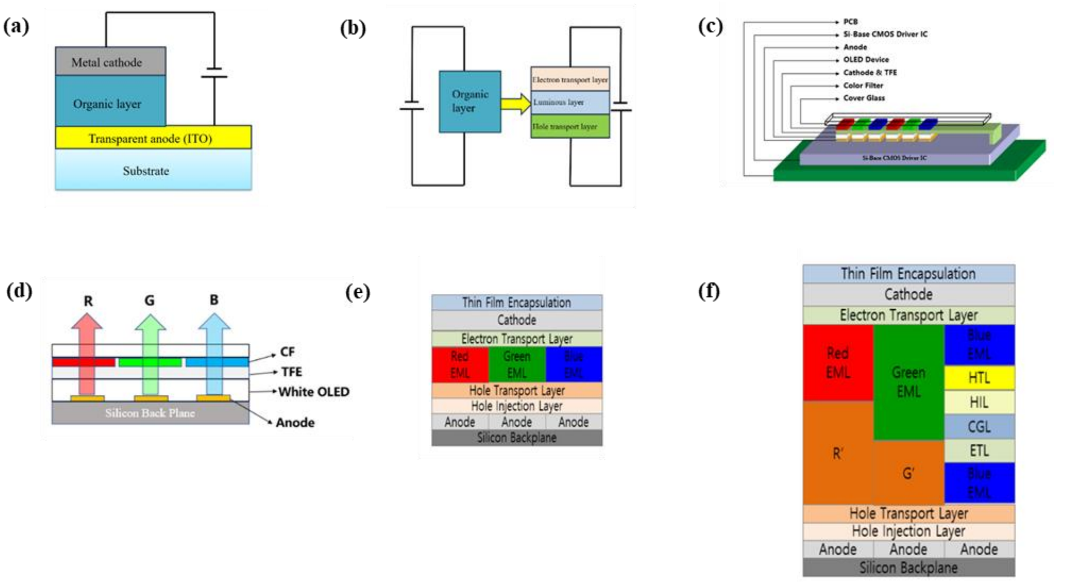

FIGURE 1. (a) The basic structure diagram of OLED. (b) The organic layer structure diagram of OLED. (c) The structure diagram of the Micro-OLED [3]. (d) Schematic diagram of the RGB color filter structure [3]. (e) The structural schematic diagram of a conventional OLED [4]. (f) Schematic diagram of double-stacked OLED structure [4].

Luminescence Principle of Quantum Dot OLED (QD-OLED)

Quantum dots (QDS) are semiconductor nanocrystals between 1 and 100 nanometers in size, typically composed of hundreds to thousands of atoms, whose surfaces are coated with organic surfactant molecules called ligands [5]. These ligand molecules make the electronic transitions of quantum dots appear to be significantly size-dependent, resulting in their unique optical and electronic properties [5]. Because of the extremely small size of quantum dots, the movement of electrons within them is spatially confined. This confinement requires electrons to possess more energy for transitions, thereby increasing the effective band gap. The smaller the quantum dot, the greater the impact will be, resulting in the difference between the energy absorbed and emitted by the quantum dot, resulting in a blue shift in the absorption and emission curves [6]. This is why quantum dots can tune the light color. The structure of QD-OLED is shown in Figure 2 (a), its lower layer is an OLED that emits blue light, and its upper layer is a quantum dot layer. In the quantum dot layer by adjusting the size of the quantum dot to change the wavelength of absorption, so that through the quantum dot to enhance and fine - tune color display. The degradation mechanism of quantum dots (QD) is an issue that has to be considered. Quantum dots (QD) will degrade due to interactions with oxygen and water molecules, and water and oxygen molecules will adsorb on the quantum dots, which may enhance or weaken their optical properties [7].Studies of this degradation mechanism and stability have focused on CD-based quantum dots, where studies have shown that when CdSe quantum dots are exposed to light and come into contact with moist air, their ability to emit light is enhanced, a phenomenon known as light activation, and this process can be reversed by inert gas purgings [8]. When photoexcited QDs are exposed to oxygen, they undergo surface oxidation. This mechanism is called photooxidation [8]. In 2008, Dembski et al. embedded CdSe/ZnS quantum dots into silica colloids and used the photoactivation and photooxidation mechanism of QD to enhance the photoluminescence of QD to 10 times [9]. As for the stability of QD, Moon et al. enhanced the stability of QD by introducing an intermediate shell, binding L-type ligands such as alkyl phosphine (R_3P), alkyl phosphine oxide (R_3PO) and alkyl amine (RNH_2) and X-type ligands such as ligand alkyl carboxylic acid (RCOOH), alkyl mercaptan (RSH) and alkyl phosphonic acid ($RPO\ _3H_2$)to the surface of QD, and coating with over-rapid insertion and removal connectors [10]. Its structure is shown in Figure 2 (b).

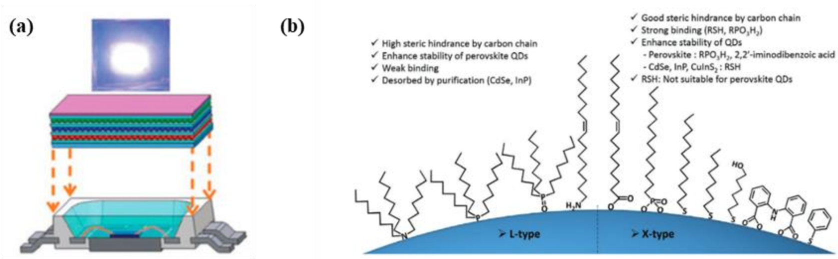

FIGURE 2 (a) The structural schematic diagram of quantum dot OLED [10]. (b) Various ligands for QDs and characteristics [8].

Resolution Breakthrough Micro-OLED Breakthrough in the Field of High Resolution

As a miniature OLED, Micro-OLED itself has the characteristics of small size, and the smaller size enables it to have a higher pixel density to achieve higher resolution. In addition to the basic advantage of its very small size, it can be further improved by a number of other techniques. Sub Pixel Rendering technology (SPR) is a core technology that can make Micro-OLED have higher resolution. Subpixel rendering improves the display of text, graphics or images by using the subpixel structure of each pixel in the display to improve the apparent resolution. This technique enhances the sharpness and detail of the image by refining the presentation of each pixel, especially in high-resolution displays, which can significantly improve visual quality [11]. The technology allows each pixel of the Micro-OLED to be divided into three sub-pixels. These three pixels can display different colors of light. The color of the subpixel is generally red-green-blue (RGB). In addition, other primary colors such as red-green-blue-yellow (RGBY) or red-green-blue-white (RGBW) also exist, and they are designed for specific purposes. By controlling the sub-pixels within each pixel, sub-pixel rendering technology triples the number of individually controllable elements, thereby enhancing the display resolution [11]. However, while sub-pixel rendering may improve apparent resolution, it may result in local color imbalance or "color edge artifact [11]. This artifact forms because only one or two pixels are turned on at the edge of some pixels. The even arrangement of red, green, and blue colors results in a jagged appearance of the image, which is indicative of its low resolution. ClearType is used, so that each pixel can borrow sub-pixels from neighboring pixels, which leads to the fact that red, green and blue are not the same amount, and some pixels only light up one or two of the three sub-pixels of red, green and blue, thus generating artifacts. To reduce this color artifact can be optimized through energy sharing. Specifically, the energy of a single subpixel is shared with its two neighboring subpixels, rather than concentrating all of the energy entirely within it so that the "energy" of each subpixel is propagated to it and its two neighboring subpixels by applying a tri-frequency [1/3,1/3,1/3] color channel filter.

Changing the arrangement method can also improve the resolution. The Delta arrangement is one of the most widely used arrangements. Delta arrangement is a technique that improves the display by changing the arrangement between pixels. Unlike common rectangular or square arrangements such as RGB arrangements, Delta arrangements use different triangular or asymmetrical arrangements. In this layout, the sub-pixels are arranged in a triangular geometry, which can effectively use the space of each pixel to reduce the visual gaps generated in the traditional rectangular arrangement, thereby improving the display resolution and reducing the screen door effect (obvious gaps caused by insufficient pixel density of the display device or excessive gaps between pixels). This arrangement can better show irregular curves in the image, and has a higher opening rate, more suitable for displaying natural scene images [12]. In addition to the above methods, the current commercial pixel patterning technology for mobile OLED uses the fine metal mask selective deposition (FMM) method, but this method faces certain challenges in improving resolution. In order to improve the resolution, the mask holes must be made very small and dense, and the thickness of the metal plate needs to be reduced accordingly to reduce the impact of the shadow effect. In addition, the metal mask must also be light enough to avoid sagging. However, the high production cost of this technology limits the manufacturing of ultra-high resolution OLED display [13]. In order to solve the limitations of FMM, Shtein et al proposed organic gas phase jet printing technology in 2004, which avoids the droplet diffusion or overflow problems that may occur during the injection process of liquid ink [14]. In addition, Hirano et al. proposed the laser-induced Pattern sublimation (LIPS) technology in 2007, which precisely patterned OLED materials from glass donors to substrates by scanning laser beams and fabricated 27.3-inch active matrix (AM) OLED display [15].

QD-OLED Breakthrough in the Field of High Resolution

The optimization of the pixel structure of QD-OLED enables it to break through the resolution. QD-OLED operates by controlling the size of quantum dots in the quantum layer. This manipulation alters the energy absorbed by the quantum dots, enabling them to convert blue light into various colors of light. Each pixel of traditional OLED emits light independently, and each pixel of OLED emits light unevenly, resulting in a gap between each pixel. QD-OLED uses blue OLED as a light source and conducts color conversion through the quantum layer. This conversion process is highly efficient, thereby reducing unnecessary energy losses. In other words, the brightness and luminous efficiency of each pixel are improved, which leads to a more compact and efficient work of each pixel. Therefore, higher pixel density and resolution can be presented in a limited display area, so that the picture is more detailed and the color is more realistic. The improvement of QD-OLED for screen resolution is not only the increase of pixel density, but also the optimization of brightness and contrast. Since QD-OLED is a light-emitting mode combined with blue OLED and quantum dot layer, the screen cannot lose brightness and can show more pure colors due to the regulation of quantum dots. The stability of QD-OLED quantum dot layer has to be considered. In order to enhance the stability and optical performance of quantum dots, scattering particles such as titanium dioxide (TiO_2) can be added to the ink, which has the effect of scattering and reflection [16]. In 2017, Li et al. increased the efficiency of solar cells to an unprecedented level of ~ 19% under standard lighting test conditions by using a novel carbon QD/TiO2ETL combined with a planar n-i-p heterojection [17]. TiO_2 is a material with a high refractive index that scatters light efficiently. When it is added to quantum dot ink, TiO_2 can change the propagation path of light by way of light scattering, increasing the propagation time of light in the ink, thereby improving the light absorption efficiency of the quantum dot. Another important role of TiO_2 in quantum dot inks is to improve the long-term stability of the ink. As a kind of nanomaterials, quantum dots are easily affected by environmental factors (such as humidity, temperature, light, etc.), leading to performance degradation, and the addition of TiO_2 can play the role of a physical barrier to protect quantum dots from interference from the external environment. Its high chemical stability and oxidation resistance help to extend the service life of the ink. In addition to achieving high-resolution full-color displays, in 2011 researchers at the Samsung Institute of Advanced Technology (SAIT) developed a dynamically-controlled transfer printing technology that shows fewer voids and cracks and results in low leakage currents and improved charge transfer. Finally, a 320-inch full-color flexible display with 4 × 240 pixels was successfully demonstrate [18].

Combination of Micro-OLED and QD-OLED

In addition to the improvement of pixel density in essence, optimizing color to improve color details to improve the look and feel is actually a way to indirectly improve the feeling of resolution, although it does not really improve the resolution. For color optimization in 2015, Han et al. [19] for the first time used aerosol jet printing technology to spray RGB QD on the surface of a UV-mu-LED array to achieve a full-color mu-LED display. Since micro-LEDs can be combined with quantum dots, it can be inferred that micro-OLEDs can also be combined with quantum dots. The realization of miniature OLED full-color display based on QD mainly depends on the RGB chip prepared by the method of QD color conversion. Like QD-OLED, the micro-OLED at the bottom emits blue light and then converts the color through the quantum dot layer. Since quantum dots are applied to miniature OLEDs, their size can be smaller to achieve higher resolution density, and then through the color conversion of quantum dots to achieve better colors to improve the audience's resolution perception. One of the problems that must be faced in the process of using QD is how to completely remove the blue laser. To solve this problem, a distributed Bragg reflector (DBR) structure can be used on top of the QD layer to avoid blue light leakage [20], and of course, color filters can be printed. But the easiest way is to start with the QD layer itself. The quantum dots themselves can absorb blue light, and the thickness of the QD layer is a key factor. In 2019, Osinski and Palomaki reported that at a film thickness of 5 microns and a certain volume fraction, red and green QD can achieve 99 percent blue light absorption [21]. Table 1 shows the effect of different colors of QD on blue light for a QD layer with a thickness of 10 microns. From this figure, it can be seen that red and green QD films absorb more than 95 percent of blue light. Thus, different QD film thicknesses can be obtained, and the degree of anti-blue light leakage is different, so the optimal film thickness needs to be considered when using QD layer in the future to achieve complete elimination of blue light.

TABLE 1. Data graph of the absorption effect of 10-micron QD layers of different colors on blue light [22]

	Peak Wavelength (nm)	FWHM (nm)	Blue Transmission
Blue	449.2	20.5	30.4%
Green	546.4	40.0	0.4%
Red	640.6	39.1	0.2%

Challenges and Future Opportunity

Micro-OLED is a self-luminous display technology that has been widely used in small displays (such as smart glasses, AR helmets, etc.), and its high contrast ratio, fast response and excellent black performance make it have significant advantages. Although the brightness of existing μOLED displays can reach 3,000 to 5,000 nits, it still cannot meet the brightness requirements for AR headsets that require a large field of view and are worn for a long time [23]. Future μOLED technology will have to increase brightness in order to accommodate these application scenarios (such as augmented reality). Usually high brightness results in shortened life. Therefore, it is necessary to develop OLED with higher brightness and lower voltage and longer life in the future. Prof. R. Forrest demonstrated the properties of Universal Display Corporation (UDC) OLED materials at the March 2018 American Physical Society (APS) meeting, as shown in table 2 [24]. Continuing research on the material may be the key to future breakthroughs in brightness and longevity. In terms of high resolution, Micro-OLED needs to reduce artifacts, which has been mentioned in this paper that can be optimized using energy sharing and changing the arrangement, but a better optimization scheme may be found in the future, which needs to be continued research. For the FMM technology that is widely used today, the size of the mask hole and the thickness of the metal plate need to be reduced to reduce the impact of the shadow effect, and the metal mask must also be light enough to avoid sagging. However, this technology is expensive to produce. The organic gas phase jet printing technology proposed by Shtein et al., 2004 [14], and the laser-induced thermal imaging (LITI) technology proposed by Wolk et al., 2004 [15], solved part of this problem. Continued exploration of these two technologies holds the potential for significant advancements.

TABLE 2. Universal Display Corporation (UDC) OLED material performance [24]

	PhOLEDs		Fluorescent OLED	
	1931 CIE coordinates	T_{50} [h]	1931 CIE coordinates	T_{50} [h]
Red	(0.64, 0.36)	900 000	(0.67,0.33)	160 000
Green	(0.31, 0.63)	400 000	(0.31, 0.63)	200 000
Blue	——	<100	(0.14, 0.12)	11 000

For quantum dot OLED, heavy metals such as cadmium are widely used in the production of quantum dot layers because of their excellent luminous properties, but the impact of these heavy metals on the environment is huge. The common methods for the treatment of heavy metals are adsorption and repair. Regarding adsorption techniques, nano-carbon materials, nano-metal particles and polymer-supported nanoparticles are effective adsorbents for removing heavy metal ions from wastewater [25]. Remediation techniques can use aquatic organisms and beneficial microorganisms to remediate water pollution such as pseudxanthomonas, Halomonas and Methanococcus [26]. Beyond these two approaches, the search for alternative materials to replace heavy metals in quantum dot OLED production represents a crucial area of future research, as it offers the potential to fundamentally address the pollution issue and drive technological progress.

CONCLUSION

This article provides an in - depth introduction to the basic structures of Micro-OLED and quantum dot OLED, explores the breakthroughs these two technologies have achieved in high - resolution display, and discusses strategies for combining them to attain superior performance. Finally, it presents some of the current challenges and future development directions of the two technologies. Micro-OLED has extremely high pixel density, excellent color and moderate brightness. The sub-pixel technology, unique arrangement method and the improvement of FMM technology have enabled it to break through in the high-resolution field. Quantum dot technology significantly enhances color accuracy. By adding titanium dioxide to further enhance its optical performance and stability, it makes the realization of large-sized, flexible and high-resolution displays possible. The combination of the two technologies can not only increase the display density, but also have more color details at a higher resolution. In conclusion, QD-OLED and Micro-OLED technologies have shown great potential in improving resolution, color accuracy and display performance, and they are two key technologies that will continue to be broken through in the display field in the future.

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