New-Type LED with G-QD@KSF and Its Application in Liquid-Crystal Displays

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Abstract

We demonstrate for the first time mass-producible quantum dot (QD) LED chips using a traditional dispensing process. The corresponding LCDs are capable of achieving an ultra-high color gamut display. By employing band-gap engineering and applying silica-aluminum oxide coatings to the QDs, our LED devices have a substantial lifespan, meeting the longevity requirements of certain LCD products, including those in the IT sector.

Author Keywords

QD LED; QD on Chip; LCD;

1. Introduction

Based on the working mechanism, the adoption of quantum dots into the display field can be classified into two types. The first is photogenic applications. The second type involves electroluminescent applications, such as quantum dot light emitting diode. However, QLEDs are not yet ready for commercialization due to the limited lifetime of blue light-emitting components. Currently, the most mature application of QDs is in photoluminescent liquid crystal display (LCD) backlighting, which can be categorized into three forms: on-edge, on-surface, and on-chip. QD on-chip technology involves encapsulating quantum dots directly within LEDs, where they bond to blue GaN chips, absorbing blue light and converting it to green or red. While this application requires fewer quantum dots, the direct contact with the GaN chip demands greater stability and more stringent production standards. As a result, no mature products have yet reached the market. QD LED technology, which incorporates quantum dots directly onto LED chips, offers several technological innovations and advantages. One significant benefit is its high color gamut. Compared to conventional white LED backlight technology, QD LEDs can easily achieve an NTSC color gamut of over 110%. Additionally, QD LEDs offer potential cost savings and environmental benefits. Furthermore, QD LEDs are particularly effective in small to medium-sized displays, offering a seamless upgrade from current commercial LED products with standard color gamuts. They maintain the existing terminal display forms while enabling narrow bezels and ultra-thin designs.

2. QD and QD LED properties

2.1. Original QD properties for LED

The green emitting CdSe/ZnS and red emitting CdSe/CdS/ZnS QD utilized in this study were synthesized through the epitaxial growth of a wide band-gap semiconductor layer on a CdSe core. Quantum dots with varying emission peaks were obtained by adjusting the size of the initial CdSe core and the thickness of CdS and ZnS layers. Thereafter, the prepared CdSe/ZnS and CdSe/CdS/ZnS QD were then coated with a $Si_xAl_yO_{2x+3y/2}$ (SiAlO) layer using a modified Stöber method. TEM images of the QD before and after coating are shown in Figs. 1 A-B.

The coating experiments were conducted on quantum dots with four typical emission wavelengths: 535nm, 545nm, 620nm, and 635nm. PL spectra were recorded on a Cary Eclipse Fluorescence spectrophotometer, respectively. As shown in Figure 1E, the coated QD@$Si_xAl_yO_{2x+3y/2}$ (QD@SiAlO) displayed nearly identical PL emission spectral compared to the original QDs. And the UV-vis absorption also barely changed. The PL quantum yields (QYs) of QDs were calculated using an integrating sphere at identical optical densities. According to table 1, the PL QYs of quantum dots remained nearly unchanged before and after SiAlO coating. These results indicate that the SiAlO coating process has negligible impact on the photoluminescence properties of the QDs, and the obtained QD@SiAlO maintains excellent dispersibility without significant aggregation, as shown in TEM image (Figure 1B). Digital images under daylight, before and after coating, are shown in Figure 1C. There is virtually no noticeable change in the luminescence brightness of the QDs before and after coating, which can be attributed to the excellent photostability of our QDs and the fact that the coating process we developed does not alter the optical properties of the QDs.

Table 1. The photoluminescence variations before and after coating

Material	PL before	QY before	PL after	QY after
G2-QD	535nm	92.3%	534nm	90.4%
G3-QD	545nm	90.4%	544nm	89.6%
R1-QD	625nm	85.6%	625nm	83.9%
R2-QD	631nm	80.7%	630nm	78.6%

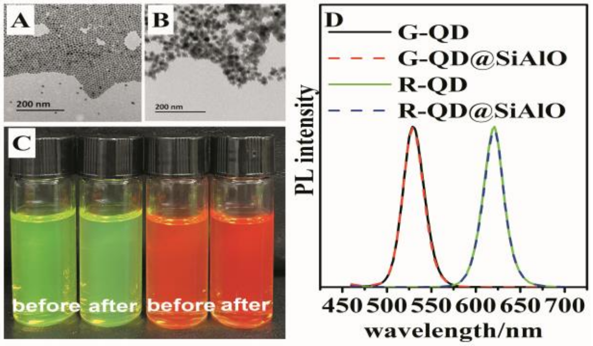

Figure 1. TEM images of CdSe/ZnS quantum dot (A) and QD@SiAlO (B). (C) Digital images of quantum dots before and after coating SiAlO. (D) PL emission spectra of QD in solution and the derivative QD@SiAlO in solution.

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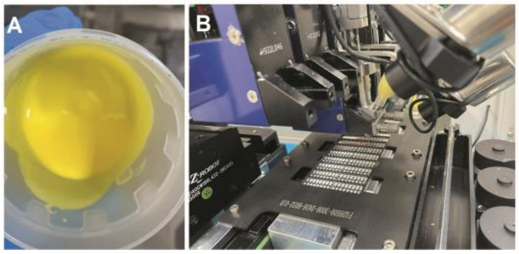

Figure 2. (A). Quantum dot glue; (B) glue dispenser and dispensing process.

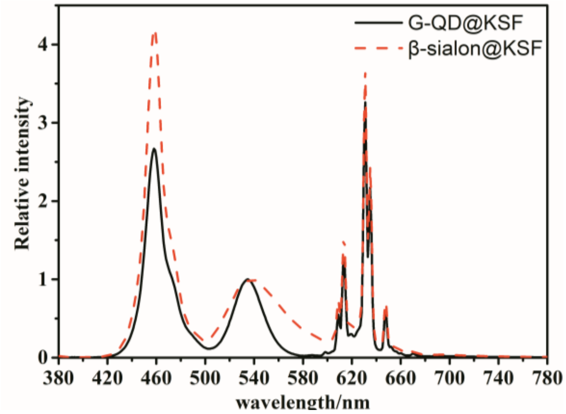

Figure 3. PL curves of G-QD@KSF or β-sialon@KSF based 3006 chips.

2.2. QD LED Properties

The encapsulation of SiAlO-coated QD into LEDs utilizes a processing technique similar to that of commercial white LEDs. A mixture was prepared by blending green-emitting and red-emitting QDs (or commercial KSF) into heat-curing silicone using a glue mixer, resulting in QD glue (Figure 2A). As shown in Figure 2B, the QD glue was then precisely dispensed onto the LED chip using a glue dispenser to form a uniform layer. In some cases, the LED chip needed to be centrifuged to achieve a smooth surface. The chip was then cured in an oven for several hours to form a quantum dot white light chip.

QD LED devices were manufactured using a 3006 package structure, which is a specific design commonly used in the industry. Although the optical characteristics of red QD and KSF are not significantly different, and red KSF can sufficiently meet color gamut requirements, this paper opts for green QD over green phosphor to achieve a wider color gamut. For comparative purposes, commercial wide-gamut LED chips utilizing green β-sialon were also fabricated under identical conditions. Figure 3 shows the photoluminescence curves of LED with G-QD@KSF and β-sialon@KSF. The G-QD@KSF LED benefits from a narrow full width at half maximum (FWHM) at the green wavelength, resulting in a wider color gamut compared to the β-sialon@KSF LED, which covers a smaller color gamut.

Optical stability is a critical requirement for QD applications. The extremely challenging operating conditions, such as high temperatures and intense blue light exposure, present significant obstacles for QD on-chip technologies. However, the epitaxially grown wide band-gap semiconductor layer and the SiAlO coating play crucial roles in extending the service life of QDs by protecting them from the detrimental effects of high temperatures and intense light exposure.

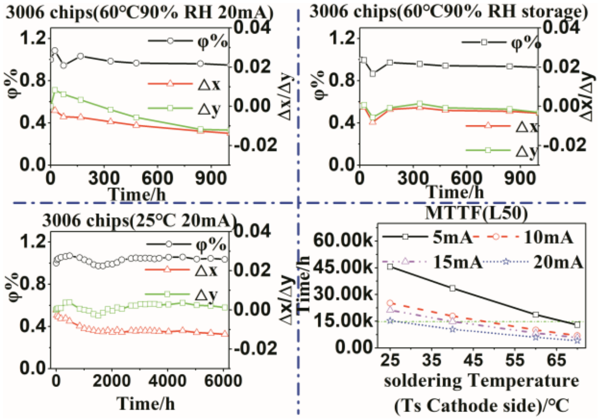

Figure 4. Color shift and luminous brightness and MTTF of G-QD@KSF 3006 chips during accelerated aging tests and extended normal operation.

We conducted accelerated aging tests on G-QD@KSF 3006 chips under operational and storage conditions of 60 ℃ and 90% relative humidity. Figure 4 summarizes the CIE 1931 color shift and fluctuations in luminous brightness and MTTF observed during these tests. The QD-based 3006 chips showed a color shift within ±0.015 and a 5.2% decrease in luminous brightness after 1000 hours of continuous operation. During storage, the chips exhibited a minuscule color shift within ±0.004 and a 7.5% decrease in luminous brightness. As depicted in Figure 4, G-QD-based 3006 chips operated for over 6000 hours at a standard working current of 20mA and a room temperature of 25 ℃, with only a trivial decrease in luminous brightness and minimal color shift in the green light. This aging performance indicates that QD-based LEDs can satisfy the stability requirements for small and medium-sized screen displays. As of publication, no other QD LED products on the market can simultaneously meet the demands for mass production and extended service life. The life parameters of the 3006 chip LED with G-QD@KSF were determined through accelerated aging experiments. With a 5mA current drive and an operating temperature (Ts) of 25℃, the mean time to half brightness decay (MTTF) for the LED is approximately 45,000 hours. As the LED's operating temperature (Ts) increases, its MTTF gradually decreases. When the Ts temperature is about 65°C, the MTTF is about 15,000 hours. In addition, the life of the LED is inversely proportional to its driving current. When the LED's drive current is increased to 20mA, it can maintain a life of 15,000 hours at 25℃. This life performance is sufficient to meet the actual needs of notebook (NB), tablet personal computer (TPC), mobile, and other IT display products.

3. LCD application

We have designed a G-QD@KSF LED with a 3006 package structure for use in the backlight unit (BLU) of NB computers, which were then assembled and tested. We tested the optical performance, environmental reliability, and display effects of the G-QD@KSF LED display module and compared the results with those of the β-sialon@KSF LED, which is mass-produced using the 3006 package structure. We evaluated the practical application characteristics of QD LEDs, including their performance, reliability, and display quality.

3.1. Optical properties of display modules

Table 2 and Figure 5 present the optical parameters of the G-

QD@KSF and β-sialon@KSF LCD modules, revealing significant differences in their performance. The analysis shows that the green QD in the G-QD@KSF LCD module exhibits a narrower full width at half maximum (FWHM) and higher color purity for its green color points. Furthermore, the green QD enhancement leads to a more vibrant red color in the display. This difference is mainly attributed to the green light leakage from β-sialon in the 580-610 nm range, which diminishes red color purity. In contrast, the narrow FWHM of the green-emitting QD completely prevents such light leakage. Thanks to its narrow FWHM at the green wavelength, the G-QD@KSF module achieves a complete coverage of the sRGB and Adobe color spaces (100% each) and 99.28% of the DCI-P3 color space. In comparison, the β-sialon@KSF module covers 100% of the sRGB color space but only 75.48% of Adobe and 76.87% of DCI-P3. Moreover, the G-QD@KSF LCD module is designed to be compatible with blue light eye protection requirements. Both BLR and BLTF meet the stringent TUV standards, with BLR being less than 50% and BLTF less than 0.085. These standards ensure that the display module exhibits excellent low blue light characteristics.

Table 2. The Optical parameters of the display module

Item	β-sialon@KSF LCD module	G-QD@KSF LCD module
Rx	0.6382	0.6906
Ry	0.3235	0.3088
Gx	0.3014	0.2120
Gy	0.6172	0.7360
Bx	0.1503	0.1408
By	0.0525	0.0375
BLR	59.61%	30.77%
BLTF	0.082	0.073
Green FHWM	52nm	28nm
Color gamut (Match rate @CEI1931)	100% @sRGB 75.48% @Adobe 76.87% @DCI-P3	100% @sRGB 100% @Adobe 99.28% @DCI-P3

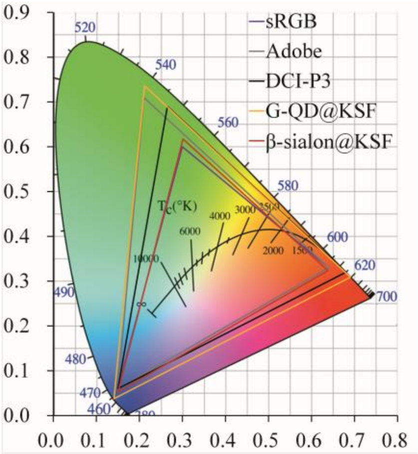

Figure 5. Color gamut contrast diagram

To achieve a high color gamut display, we have optimized the color filter film (CF) in our LCD panel. The CF material design has been upgraded from the standard R1/G1/B1 configuration to the high-color-gamut R2/G2/B2 configuration. As shown in Figure 6, the new CF has a narrower light transmission capacity in the 480-600nm range, which matches the G-QD@KSF LED spectrum. This optimization improves the color purity of the display module and achieves the best color display effect. Furthermore, the transmission spectrum indicates that the new CF's narrower transmission range in the green light spectrum (480-610nm) reduces the overlap with both blue and red light ranges. Consequently, the likelihood of green light from the BLU leaking into the blue spectrum (460-540nm) during CF filtering is diminished. Similarly, the leakage of green light into the red spectrum (570-610nm) is also significantly reduced. In essence, the new CF reduces the interference of green light with blue and red light, thereby enhancing the color purity of both. Thus, the new CF enhances the display effects for blue and red while also refining the green display performance of the module.

To directly compare the color differences, we tested the visible spectra of both the G-QD@KSF and β-sialon@KSF LCD modules, as depicted in Figure 7. Within the 490-600nm green light wavelength range, the G-QD@KSF LCD module exhibits a narrower spectral range, more accurately reflecting the spectral properties of the G-QD@KSF LED. This results in the G-QD@KSF LED exhibiting green light characteristics with high color purity, which in turn enables the display module to achieve high color gamut performance. Concurrently, the new CF's filtering effect reduces interference light within the 480-530nm and 580-610nm ranges. This significantly enhances the color purity of the R/G/B primary colors in the G-QD@KSF display module, providing a foundation for achieving a greater number of color gray levels in liquid crystal deployment.

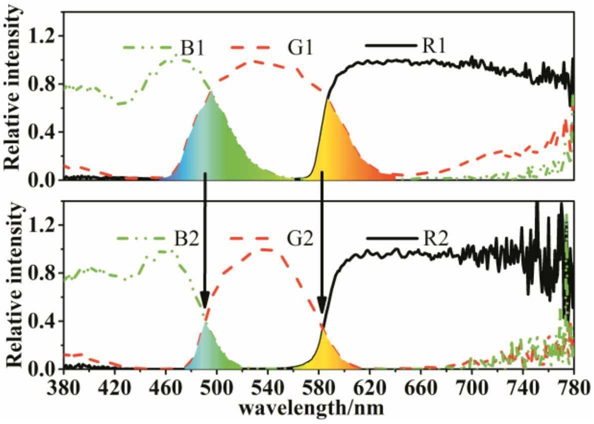

Figure 6. Comparison of light transmission spectrum of color filter

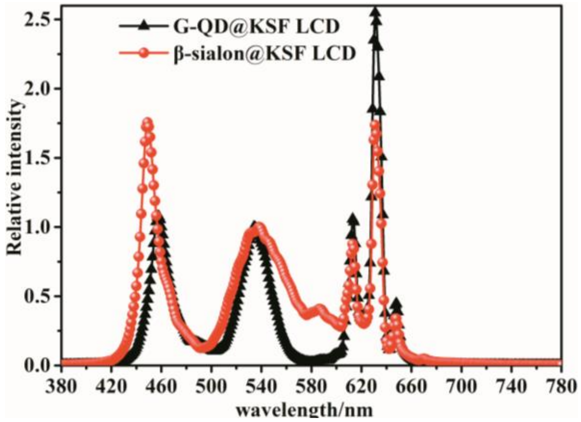

Figure 7. Visible light spectrum comparison of LCD modules

Table 3. LCD environmental reliability test results

Item 240h	β-sialon@KSF LCD			G-QD@KSF LCD		
	ΔΦ	Δx	Δy	ΔΦ	Δx	Δy
THO	-3%	-0.006	-0.012	1%	-0.010	-0.009
HTO	-3%	-0.002	-0.005	-3%	-0.009	-0.007
THS	-6%	0.002	-0.002	-3%	-0.003	0.003
HTS	-1%	0.005	0.003	-7%	0.004	-0.003
TST	-4%	0.002	-0.003	-3%	-0.001	-0.002

Table 4. Common NB display module temperature test results

LCD with bent structure design		LED TS/℃	AA/℃
At 25℃ ambient temperature	60Hz	31.6	28.6
	120Hz	43.1	30.3
	240Hz	46.5	30.4

Figure 8. Comparison of digital images displayed by β-sialon@KSF LCD notebook and G-QD@KSF LCD notebook.

3.2. Environmental reliability analysis

To determine if G-QD@KSF is suitable for mass production of IT display products, we integrated G-QD@KSF LCD into the NB display module and conducted a series of environmental reliability tests to assess their lifespan requirements. The results were then compared with those of the commonly used β-sialon@KSF LED display module, as detailed in Table 3. Under test conditions including 50 ℃ and 80% relative humidity operation (THO), 60 ℃ high temperature operation (HTO), 60 ℃ and 90% relative humidity storage (THS), 60 ℃ high temperature storage (HTS), and -20 ℃ to 60 ℃ cold and thermal shock (TST) with 100 cycle, the G-QD@KSF module exhibited brightness changes and color shifts that were comparable to the β-sialon@KSF product. These findings suggest that the G-QD@KSF LED is suitable for use in IT display products.

Different design schemes in NB products result in varying heating conditions, creating different environmental conditions for the LED and affecting its lifespan. To determine if G-QD@KSF is suitable for a broader range of product applications, we tested temperatures in LCD modules with various bent structures, as detailed in Table 4. In bent structure LCD modules, the PCBA circuit board is designed near the LED, affecting the LED temperature through PCBA heat dissipation. The tests revealed that the temperature at the LED is higher than in the surrounding display area. Furthermore, as the refresh rate of the display product increases, the PCBA's heat output rises, leading to a corresponding increase in LED temperature. When the ambient temperature is 25 ℃, the maximum operating temperature (Ts) of the LED is about 46.5 ℃. Based on the life test results for the G-QD@KSF LED shown in Figure 4, its MTTF at Ts of 48℃ with a current drive of less than 10mA can reach 15,000 hours. If the operating temperature (Ts) of the display product exceeds 50 ℃, the determined current for this LED will not exceed 10mA. For example, at 5mA, the temperature of Ts can reach 65℃. This can basically meet the life needs of IT display products, such as NB, TPC, mobile and other products.

3.3. Display effect comparison

As shown in Figure 8, a NB based on G-QD@KSF LCD has a larger color gamut space to render a more vivid image than a NB based on β-sialon@KSF LCD. Especially for the display of green and red content, G-QD@KSF LCD can show more color details. As a result, NB users can perceive richer color content. It is worth noting that the visual brightness of G-QD@KSF-based display is significantly higher than that of β-sialon@KSF under the same operating current. This phenomenon can be attributed to the Helmholtz-Krausch effect, in which higher color purity enhances perceived brightness.

4. Impact of this research

In this letter, we demonstrate for the first time mass-producible QD LED chips integrated with QD as photoluminescent color converters using a traditional dispensing process. Compared to conventional β-sialon phosphors, the QD LED devices have a narrower FHWM, and can achieve higher color gamut display with CF. Additionally, through band-gap engineering and the application of silica-aluminum oxide coatings on the QD, our devices exhibit a decent lifespan under both operational and storage conditions. We designed the G-QD@KSF LED device into the notebook product to achieve a wider gamut display, 100% sRGB and 100% Adobe and 99.28% DCI-P3 gamut coverage. Combined with the actual Ts temperature of LED in notebook products and the MTTF test results of LED, it can be shown that the existing G-QD@KSF LED can meet the actual needs of notebook and other IT display products. The research content of this paper is to upgrade the high color gamut display technology from the original QD film technology to G-QD@KSF LED technology.

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6. References

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