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High-quality Imaging Micro-LED Display based on Quantum Dot CSP Technology

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Abstract

We have proposed a new method of quantum dots (QD) chip scaled package technology and developed the world-first bin-free QD micro-LED display. Experimental result shows that the wavelength derivations of red and green color of QD CSPs are under 0.6nm, which enables us to use over 95% of a blue wafer. Furthermore, the quantum yield of red ones only drops under 5% after 1000 hours to apply commercial products. From the research work, we expect that the QD μ-CSP will become the core technology to dominate future TV, home theatre, and signage markets.

1. INTRODUCTION

1.1. Micro-LED Technology

The gallium nitride-based light-emitting diodes (LEDs) [1] have been widely used as a solid-state lighting source or the backlight unit of a liquid crystal display (LCD) owing to their high luminous efficiency and long lifetime. Nowadays, the usage of LEDs is regarded as a conventional solution for digital signage video displays. As the technology to make LED structures thinner and smaller in a wafer level has advanced significantly, it is widely accepted that the micro-LED (μ-LED) [2] will be the essential part of the next-generation displays, such as infinite contrast TVs, foldable mobile displays, and pure color virtual reality (VR) screens. In general, the μ-LED is defined by the extremely-small LED of which size is under 100um. Its primary features can be described by wide color gamut, fast response, high brightness, infinite contrast, and low power.

Thanks to the merits of μ-LEDs, the activities related to μ-LED technology has increased continuously. In 2017, Sony Corporation has been in the limelight by the launch of a μ-LED display referred by Crystal LED Display System (CLEDIS) [3] at The International Consumer Electronics Show, as shown in Fig. 1(a). The 4K μ-LED display is composed of 144 modules and every pixel in the module consists of red, green, and blue μ-LEDs. The size of each μ-LED is under 30×30um. They report that the brightness and contrast of CLEDIS are maximally 1000 cd/m^2 and more than 1,000,000: 1, respectively.

Other chip makers have been also involved to develop μ-LED technology. PlayNitride Inc. demonstrated a 34×58um μ-LED display and their transfer technique. LuxVue Tech. also introduced an electrostatic adsorption transfer technique to attach μ-LEDs on modules successfully. Recently, VueReal Tech., a venture company in Canada, has developed high efficiency a μ-LED display [4] as shown in Fig. 1(b). Their brightness efficacy of red, green, and blue μ-LEDs goes up to 40 cd/A, 100 cd/A, and 20 cd/A, respectively. As such, μ-LED technology has been progressing very fast all over the world.

(a) Sony's CLEDIS (b) VueReal's μ-LED display

Figure 1 Advance of Micro-LED technology

1.2. Problem Statements

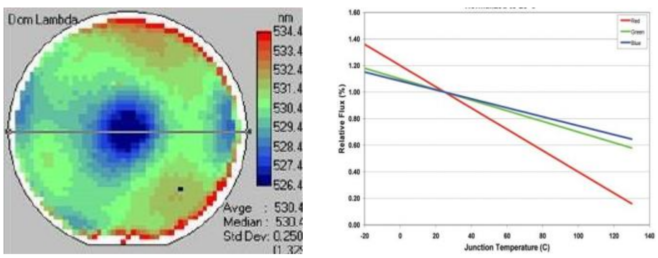
However, μ-LEDs still suffer from the inherent problems of conventional LEDs, such as wide bin distribution and red color discoloration. In order to make an LED display, we usually employ LEDs sorted by chip makers according to their wavelength and brightness. The sorting procedure is called binning [5].

Since the wavelength distribution of red μ-LEDs is under 5nm, the binning issue will not become a critical problem. In the case of blue μ-LEDs which have about 10nm, it is not so sensitive to human eyes that we may tolerate color differential or solve the binning problem by software-based color calibration. However, the wavelength distribution of green μ-LEDs becomes about 15 nm within a wafer, as shown in Fig. 2(a). Unfortunately, green color is included in the most sensitive wavelength (530~550nm) to human eyes. If we sort green μ-LEDs for 1 bin level, 3nm allowance, we may only use about 35% of their wafer, which makes chip cost increase significantly.

The luminous efficacy of μ-LEDs decreases with increased junction temperature. Higher junction temperature, resulting from increased power dissipation or changes in ambient temperature, can have a significant effect on light output. Red μ-LEDs manufactured from aluminum indium gallium phosphorus (AlGaInP) materials are more sensitive to temperature effects than blue and green μ-LEDs based on indium gallium nitride (InGaN) materials [6] as shown in Fig. 2(b). It describes the relative flux of red, green and blue chips in accordance with junction temperature. As the worst case, the efficacy of red μ-LEDs decreases by 80% when junction temperature increases from 25°C to 120°C. Degrading the performance of red chips according to junction temperature leads to red color discoloration.

In order to solve wide bin distribution and red color discoloration of μ-LEDs, we pay attention to color conversion functionality of quantum dots (QD) [7]. By applying red and green QDs on blue μ-LEDs, we can maintain the wavelength derivation of green and red color under 1nm. Furthermore, since blue μ-LEDs retain their optical quality more consistently than red ones, the color conversion method can sustain pure red color regardless of junction temperature.

However, it is not easy to directly apply QDs on blue μ-LEDs due to their low-reliability [8]. The reliability issues can be three-folds: 1) Photoluminescence (PL) quantum yield (QY) of QDs will be decreased permanently by heat, humidity, or oxygen flowed in from the outside environment. 2) QDs may be collapsed by strong blue light. 3) Finally, the dispersion of QDs drops dramatically in chemically-combined with binding resins, such as epoxy and silicon.



(a) Wide bin distribution (b) Red color degradation

Figure 2 Inherent problems of μ-LEDs

In this paper, we present a new method to solve those problems using chip scaled package (CSP) technology [9, 10] and color conversion functionality of QDs, named as QD CSP. The main contribution of this work is two-folded: 1) we implement a *bin-free QD CSP display in the world first* and evaluate its optical characteristic, and 2) we develop *high reliable QD CSPs using siloxane-based encapsulation*.

This paper is organized as follows. Section II introduces the basic concept for the proposed QD μ-CSP and overall manufacturing process in detail. Then, Section III measures and evaluates optical characteristics of QD CSPs. Finally, in Section IV, we conclude this paper.

2. QD CSP TECHNOLOGY

2.1. Proposed QD μ-CSP Structure

We introduce Quantum Dot micro-CSP (μ-CSP) technology that is a simple chip process in single wafer level using color conversion functionality of QD and blue μ-LEDs. Figure 3 represents the proposed structure conceptually. Blue chips are located on the lower part of QD μ-CSP. In the case of red and green ones, QDs are on the blue chips and the blue one has no QDs because it does not need to do any color conversion.

The side part of QD μ-CSP is coated by reflective materials, such as Al or Ag. The mirror wall enables us to reflect blue light inward and to increase forward brightness. Finally, a blue cut filter layer is on the upper part to make pure red and green color. In the case of blue μ-CSP, it has no blue cut filer layer.

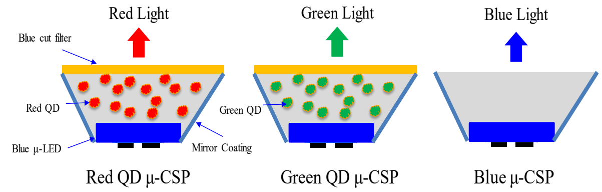


Figure 3 The proposed QD μ-CSP(Red/Green/Blue) structure

2.2. Manufacturing Process of QD μ-CSP

Overall QD μ-CSP manufacturing processes are shown in Fig.4. First, InGaN epitaxy layer grows on a sapphire substrate to create blue μ-LEDs. The important thing is that the side part of InGaN should be coated by reflecting materials such as Al or Ag. Figure 4(a) shows the reflecting material blocks blue light and helps it go upward. Then, a temporary substrate such as a glass is attached on blue μ-LEDs. The temporary substrate has a role to hold on blue μ-LEDs in the step of QD coating process.

Next, a laser lift-off (LLO) process [11] is followed. As shown in Fig. 4(b), LLO is a procedure to take out the sapphire substrate from the blue μ-LEDs. Due to high hardness of the sapphire substrate, it is very difficult to cut InGaN uniformly to form blue μ-LEDs. Therefore, it is necessary for us to take out the sapphire substrate before dicing. Then, we move to the isolation process so as to separate each blue μ-LED from a connected epitaxy layer.

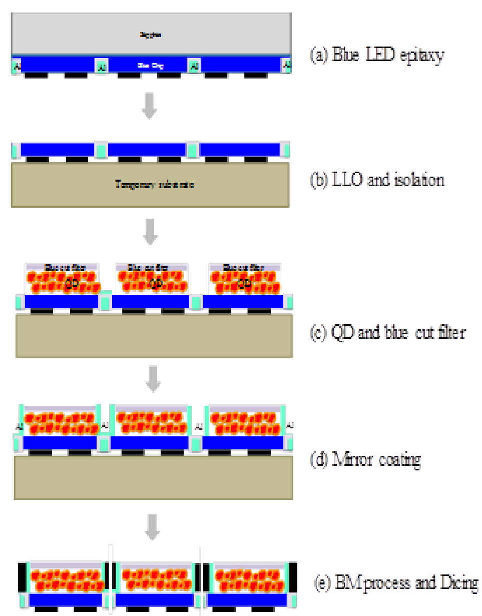


Figure 4 Manufacturing process of QD μ-CSP

Figure 4(c) represents the QD coating and blue cut filter process. Red or green QDs are coated on the blue μ-LEDs in the process. In general, QD is combined with resins such as silicon or epoxy to form liquid state. After coating the liquid QD on the blue chip, we harden it using ultraviolet (UV) light. Next, a blue cut filter layer is generated on top of QDs. For example, In the case of red QD μ-CSP, some blue light is converted to red color by red QDs. Some blue light directly emits without red color conversion. Therefore, the output light can be red or blue light. The blue cut filter blocks the output blue light to increase the purity of red color. So does the case of green QD μ-CSPs.

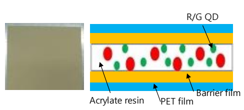
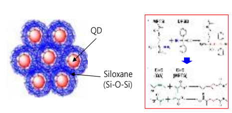
Then, a mirror coating process [12] is followed. Figure 4(d) depicts side mirror wall coating using Al. This process intercepts the blue light not to pass to side direction. Next, black matrix (BM) and dicing processes should be done. As shown in Fig. 4(e), in order to increase the contrast ratio in the QD μ-CSP display, black resin molding on BM area is applied. Finally, we can manufacture QD μ-CSPs after dicing process.

2.3. Encapsulated QD with Siloxane Resin

Conventional QDs suffer from low reliability against heat, humidity, and oxygen. For example, in the step of mirror coating in Fig 4(d), the operating temperature will be over 100°C. Furthermore, when we bond QD μ-CSP on a module, the temperature of soldering reflow is even over 250°C. The high temperature definitely makes them collapsed. Therefore, the existing core-shell structure is not suitable to implement the proposed QD μ-CSP.

Recently, Kim et al. [8] has developed a novel method to improve QD reliability. They reported that the fabrication of a siloxane-encapsulated QD film exhibited stable emission intensity for long time even at high temperature and humidity. In this paper, we implement the encapsulated QDs and apply them into our QD μ-CSP structure.

Table.1. COMPARISON OF ACRYLATE QD FILM AND SILOXANE QD FILM

Division	Acrylate QD Film	Siloxane Encapsulated QD
Structure		
Method	· Hydrocarbon (C-H) barrier based encapsulation ① Acrylate resin + QD ② Barrier film Addition to protect QD from oxygen ③ PET file addition to protect QD from external shock	·Siloxane (Si-O-Si) encapsulation ① Silane resin + QD ② sol-gel condensation reaction ③ free radical addition reaction
Dispersion stability	 Flocculation happens	 No flocculation happens

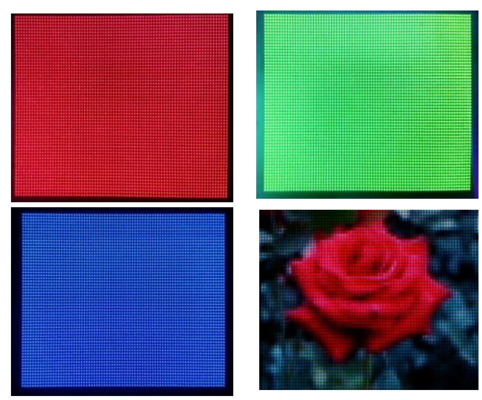
Basically, the siloxane-encapsulated QD is based on sol-gel condensation reaction and free radical addition reaction. The ligands on QD's surfaces have oleic acid characteristic. When silane precursors, which are also oleic acid, are mixed with the ligands of QDs together, a hydrophobic interaction between silane and QD ligands is operated. The hydrophobic interaction helps Si-O-Si combination between QD ligands and silane. The chemical operation is called as sol-gel condensation reaction.

Additionally, if we cure the siloxane encapsulated QD with UV light, it harden by bonding C-C combination via free radical addition reaction. Since siloxane has high reliability against head and humidity, the inside QDs are protected by robust siloxane. Consequently, the siloxane encapsulated QD tolerates high temperature and humidity. Table 1 summarizes the comparison between conventional acrylate QD film [13] and siloxane encapsulated QD

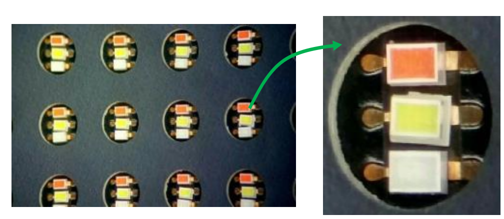
3. QD CSP EVALUATION

3.1. Bin-free QD CSP

In order to evaluate bin-free possibility and the proposed structure, we implemented a QD CSP module using micro-size blue LEDs (300×150um) and commercial QDs with die-bonding. The resolution and pixel pitch of the module were 60×80 and 2.5mm, respectively. The size of each QD CSP was 400×250um and the thickness of its QD layer was 150um for enough color converting. A blue cut filter layer was also applied.



(a) QD CSP module implementation



(b) Enlarging QD CSP module

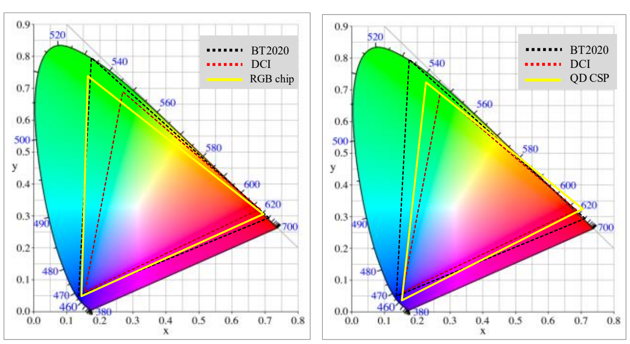
Figure 5 Implementation of QD CSP structure

Figure 5 shows the QD CSP module and a part of the module captured by a microscope, respectively. As shown in Fig. 5(a), red, green, and blue colors were successfully represented by the implemented QD CSPs. The dominant wavelengths of red, green, and blue color were 618nm, 540nm, and 465nm, respectively. In the QD CSP module, the full width at half maximum of red, green, and blue QD CSPs were 32nm, 23nm, and 17nm, which is to the point of satisfying DCI coverage. Luminous intensities of red, green, and blue QD CSPs were 45.5mcd, 167.8 mcd and 104 mcd, respectively, at 3.0V and 5mA. The brightness of full white was about 500 cd/m2.

Optical characteristics, such as wavelength derivation and color gamut, were also measured via an integrating sphere by inserting the implemented QD CSP onto it. As shown in Table 2, because of QD's significant features such as narrow emission bandwidth and broad absorption spectrum, the wavelength derivation of red and green color of QD CSP was about 0.6nm and 0.3 nm, respectively. On the other hand, the wavelength deviation of red and green color of conventional RGB chips was 1.6 and 6.9nm, respectively. It means that the proposed QD μ-CSP can be bin-free. In the bin spectrum, if the wavelength distribution of red and green color is under 1nm, it enables us to use over 95% of a blue wafer for RGB micro-LED manufacturing.

TABLE II
Wavelength Derivation and Color Gamut Comparison

Chip Type		RGB chip		QD CSP	
		Red	Green	Red	Green
Dominant Wavelength (nm)	*Sample 1*	620.1	520.5	616.3	538.6
	Sample 2	621.3	527.4	616.9	538.8
	Sample 3	620.9	525.6	616.7	538.3
	Sample 4	621.7	523.6	616.5	538.4
	Sample 5	620.4	524.8	616.4	538.6
W. Derivation (nm)		**Δ1.6**	**Δ6.9**	**Δ0.6**	**Δ0.3**
DCI Coverage (%)		**93.6**		**99.8**	



(a) Conventional RGB chips (b) QD CSP

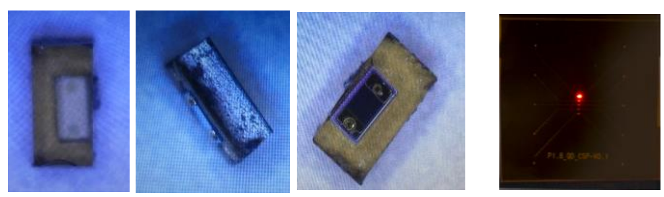
Figure 6 The comparison of DCI coverage

Thanks to the tunable wavelength feature of QDs, the proposed method could move the dominant wavelength of green light onto around 540nm. The color gamut covered by QD CSP was about 99.8% on DCI color space, while the conventional RGB chip covered 93.6% on the same color space. Because DCI coverage [14] is an important factor in TV and home theatre applications, the implemented QD CSP could be a practical solution for commercial products. Figure 6 shows DCI coverage of conventional RGB chip and QD CSP.

3.2. High-Reliability QD CSP

We have also verified the possibility of siloxane encapsulated QDs as the solution to minimize red color discoloration. In this experiment, reliability performance of siloxane encapsulated QD was evaluated at each step of QD CSP manufacturing process. After encapsulating siloxane with QDs, we make them cover the blue chip array, of which size is 225×125um, using Meyer Rod coating [15].

In order to bond the QD CSP onto a test module, we diced coated QD and carried out soldering. As shown in light test of Fig. 7, the encapsulated QD survived and had no damage even though the procedure temperature of reflow was 270°C. Furthermore, the process temperature of Al mirror coating was about 100°C which is to make conventional QDs damaged. The surprising result indicates that the siloxane encapsulated QDs are suitable for QD CSP process that operates at a very high temperature.



Top view Side view Bottom view Lighting Test

Figure 7 Encapsulated QD CSP implementation

In order to evaluate QD stability over time, we left of encapsulated QDs and conventional acrylate-resin QDs in 85°C and 85% relative humidity conditions for 40 days. The encapsulated QDs maintained the initial QY 62% almost constantly while acrylate-resin QDs exhibited decrease of PL QY from 62% to 20 %. This means that the red color discoloration can be overcome even in a harsh environment if we make a display using the red encapsulated QD CSP. Figure 8 shows the stability result of encapsulated QDs and conventional acrylate-resin QDs.

We also measured the color conversion efficiency (CCE) of encapsulated QD CSP. The CCE of QD CSP was 25% at concentration 1.5wt%, which was not changed after 40 days. From experiment results, it can be indicated that PL QY of the encapsulated QD was not degraded by heat and humidity for about 1000 hours.

In the experiment, we could verify the core functionalities of QD μ-CSPs. It is mentioned that the QD μ-CSP, RGB color generation in single wafer, can solve the binning issue effectively. Furthermore, the application of encapsulated QDs can be a practical method to overcome red color discoloration of μ-LEDs due to their high reliability and durability.

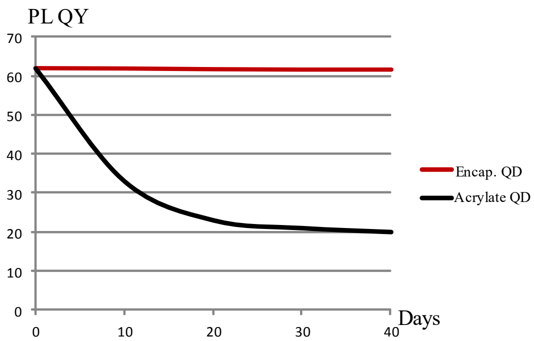


Figure 8 Performance of encapsulated QD CSP

3.3. Comparison with Commercial Products

The state-of-the-art commercial TVs are also based on QD technology. They utilize blue LEDs for light source and red/green QD sheets to make white light. The QD sheet is composed of QD layers and barrier film that has a role to protect QDs from heat and humidity. The proposed QD CSP is based on encapsulation methodology to improve QD reliability instead of a barrier film. We believe that our method is more suitable for the self-emission light source to be applicable on future various thin and flexible display.

The conventional LED displays such as signage and home theatre is made by red, green, and blue chips on a module. One of the reasons that LED displays are too expensive is due to binning process. The proposed QD CSP only uses blue chips and has no bin-management of red and green LEDs. Thanks to one bin generation (3nm allowance), the cost of QD CSPs is about 42 % lower than conventional RGB LEDs. In addition, the QD CSP process becomes much simpler than the conventional one.

3.4. Future Works

Current CCE of QD CSP is not enough compare with commercial QD sheet-based TVs which has up to 40% of red, green color conversion efficiency from blue excitation light, because it is not yet perfect structure for its optical inter-reflection and extraction.

Therefore, we are now on developing a blue light recycle mechanism using selective wavelength reflection such as distributed Bragg reflectors (DBR) [16]. In the near future, two times higher performance of CCE will be achieved by new structure of QD CSP.

4. CONCLUSION

We have presented a new structure of QD chip scaled package based on micro-LED technology. In order to verify the proposed method, a QD CSP module was implemented by using micro-size blue LEDs and commercial quantum dots. Then, we have evaluated its properties in terms of bin-free possibility and reliability. Experimental result shows that the wavelength derivation of red and green color of QD CSPs is under 0.6nm, while conventional LED chip one is 6.9nm. It means that the yield of a wafer is over 95%, and the quantum yield of QD CSPs only drops under 5% after 1000 hours so as to apply commercial products. As a future work, a blue light recycling method should be developed to significantly increase color conversion efficiency of QD μ-CSPs. We expect that the proposed method will become the core technology to dominate next-generation TV, home theatre, and signage markets.

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