Past, present, and future of WCG technology in display

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Abstract
We will introduce the development trend of colorant and color technology along the grown of display industry. Wide color gamut (WCG) technology with high contrast ratio and transmittance has been developed from colorant design to color filter process, product reliability, and performance enhancement. In this paper, WCG technology for liquid crystal display (LCD) and organic light emitting diode (OLED) and trend of colorant, which is including color conversion material (CCM), were discussed. We hope that it will help you to understand the development flow of colorant in the display industry.

KEYWORDS
BT.2020, colorant, color conversion material, fluorescence dye, Nano Color, photo resist, wide color gamut

1 | INTRODUCTION

Color materials are one of the most important fields in display technology and have been developed along the grown of display industry. Color filter (CF), back light unit, and polarizer affect to color characteristic of display. Among them, colorant for CF is one of the important materials for display performance such as luminance and color reproduction. Therefore, colorants that are required to have high transmittance, performance, and high reliability and material design technology are also continuously improving. Color materials, which are applied in display panel, are closely related to colorant synthesis, dispersion, CF process, and reliability of product. Therefore, design colorants for wide color gamut (WCG) technology are important from basic research of color material to improving property of product (Figure 1). J. Namgoong et al. studied effective structure for improving dispersion through the synthesis of dyes with various functional groups such as bulk, polarity, and ionic properties. As a result, increasing contrast ratio (CR) and transmittance were succeeded by applying highly dispersive dye suitable for hybrid color photo resist (PR). In the field of color conversion material (CCM) such as fluorescence dye (FD) and quantum dot (QD) for WCG, the basis and application of characteristics according to the aggregate between molecules have been studied. X. Zhang studied dyes with a plate structure differ in their characteristics depending on how they are aggregated. It has been reported that different aggregation occurs spontaneously depending on the solvent in PR and fluorescence properties different from those of monomer are expressed.

Display industry has been developed to a lot of applications, such as cathode ray tube, liquid crystal display (LCD), and organic light emitting diode (OLED). Main key words of display are cost of product, WCG, high dynamic range, and new form factor, which are Curved, Bended, Roll-able, Flexible, and VR/AR display. Especially for representing vivid color image, WCG technique is very important. Color gamut has been required to

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enlarging from BT.709 and DCI-P3 to BT.2020. Recently, BT.2020 has been interested in various fields such as broadcasting media and medical field, because BT.2020 can cover 99.9% of natural color.

In this paper, we would like to introduce about development trend of colorant in rapidly changing display industry and how to use colorant in WCG technology.

2 CHARACTERISTICS OF COLORANT

Figure 2 shows history of colorant development for display. Color development trends are changed from high CR to high transmittance and WCG. High CR was achieved through colorant size atomization and dispersion optimization. Thereafter, for improving transmittance of colorant, high transmittance of pigment and dye are being developed for high transmission of colorant. In addition, combination of colorants has been changed from all pigment type to hybrid (mixing pigment and dye) type or all dye type. And functional dyes are becoming important for WCG. Detail of properties of colorant is as follows.

2.1 Contrast ratio

As shown in Figure 3A, minimizing scattering can be achieved by atomization of colorant particle and optimizing dispersion between each colorant. Improving CR of colorant is possible by minimizing scattering. LCD is optical element by operating with optical anisotropic LC; degree of polarization is very important in LCD system. Therefore, scattering by colorants, which affect to degree

![Diagram of colorant properties](image)
of polarization and display performance, has to be mini-
mized. For colorant atomization, colorant refinement
through organic nanocrystallization technology by precip-
itation method has been reported.14 As this relation,
crystal grain size and crystalline control technology are
linked to the display industry. It is possible to increase
transmittance through atomization and uniform disper-
sion of the pigment. For the low power consumption, CF
characteristics with high transmittance are required.
For this reason, the combination of colorants is changing from
pigment type to hybrid type or all dye type. Therefore, dis-
persion technologies of dye are being studied steadily.4

2.2 Transmittance

Figure 3B shows the change of transmittance along the
development of colorant.15,16 By improving the colorant
structure through the modification of the center metal,
the transmittance of G58 was improved as compared with
G36, as shown in A.15

Increasing the transmittance of colorant is very impor-
tant to decreasing power consumption and improving
luminance of display. In the case of OLED, the transmitt-
ance of the colorant is directly related to the lifetime of
the electric luminescent element. It can lead to increasing
time of optical component and decreasing cost of dis-
play by reducing the number of LED chips. To meet the
ENERGY STAR standard of monitors and notebooks,
development of all dye type is main direction for improv-
ing transmittance.17 Most of the colorants currently used
in displays are combined with pigments. On the other
hand, only some Blue and Violet dyes are used. Because
CF process of display requires high thermal resistance at
230° and chemical resistance of colorant, available dyes
are still limited.

2.3 Electrical property

Material of color PR is closely related to the line process
and product reliability. Along the electrical property of
material, problems such as pattern defect and stain dur-
ding the CF process and color characteristic degradation
in product are appeared. For overcoming these problems,
many researches about process technique and electrical
property have been reported with the development of
high coloring new colorants.6 A. Kim et al8 reported it
found out that color characteristic of green colorant in
liquid crystal cell was decreased under high temperature,
high humidity, and strong light stresses. The degradation
of color characteristic was verified by placing liquid crys-
tal cell made of color chip coated with color PR under the
environment for 24 hours. It was confirmed that struc-
tural deformation of colorant affects the color characteris-
tic. As shown in Figure 4, to confirm the color
characteristic change of degraded color chip according
to external thermal energy, degraded color chips were
placed in a room temperature and 100°C, respectively.
As a result, color characteristic recovery was occurred
by heating to the degraded color chip. Through this
result, color characteristic degradation was analyzed to
be caused by a weak bond between colorant and water,
as shown in Figure 4B’. It was also confirmed that the
degree of structural deformation of colorant was different
along the dispersant even if the same colorants were
used. These mechanisms were experimentally proved.

In the electrical field of operating LCD, it has been stud-
ied in terms of panel design and material of LC cell. In gen-
eral, various methods such as resistivity, voltage hold
ratio, ion density, and residual DC have been proposed
as evaluation methods of LC electric characteristic, and
materials causing degradation of electric characteristics
have been reported.18–20 Color PR is composed of various
3 | WCG APPLICATION

3.1 | WCG for LCD

Figure 5 shows the structure of LCD. WCG technologies of LCD have been developed into separately light emitting diode (LED) package, optical sheet, color PR, and polarizer.

a. KSF and B-rG are usually used to LED material for WCG; research for increasing the color purity of the light source has been continuously carried out. E. Niikura et al.21 realized 98% of BT.2020 with applying R/G/B laser diode, which have almost single wavelength of light. J. Choi et al.22 developed a new phosphor-based Nano IPS LED to improve the color reproduction. DCI coverage ratio and sRGB area ratio of conventional IPS LED were 84% and 109%, respectively, but Nano IPS LED could be increased to 99% and 135%, respectively.

b. QD sheet and CCM are used for the optical sheet, and SUHD and QLED TV are the representative products. To use QD material as QD PR with in cell coating type, materials after the QD PR process should be capable of low temperature processing (or QD PR should have a heat resistance of 230°C). In particular, when linearly polarized light passes through QD, linearly polarized state changes to nonpolarized state because of
scattering characteristics. In order to use QD on LCD, in cell polarizer technology must be accompanied.
c. In the case of CF, it is necessary to develop high color strength of colorants for WCG. Since the colorant content of color PR is usually limited to 30% to 45%, for increasing color purity without decreasing transmittance, high transmittance and coloring pigment of dye are required in order to increase color reproduction without adding more colorant. Blue dye is commonly used in display industry and new dyes with high color strength continuously being developed.
d. As a multivalued polarizer technology of WCG solution, Nano Color technology that is using light absorption polarizer (LAP) is representative, as shown from A to A’. Recently, LG Display Co Ltd succeeded in commercializing IPS Nano Cell display. Nano Color is a technology that utilized fine molecules of 1-nm size, and ultrafine molecules precisely adjust the wavelength of the color, thereby widening the color gamut and increasing the accuracy. Tetraazoporphyrin is mainly used to implement the technology of this concept. Z. Chen et al. studied the variation of Q-band and B-band characteristics with metal ion application in a tetraazoporphyrin structure without a center metal. The effect of short-wavelength direction shift was found out depending on the size and electronegativity of the central metal ion. On the basis of this research, color reproduction rate could be increased. LG Display Co Ltd is commercializing and selling Nano Cell display with next generation WCG technology to worldwide.

Figure 6 shows characteristic difference of panels between conventional technology and Nano Color technology. Nano Color technology is realized by using colorant that can selectively absorb color. As shown in spectrum of Figure 6B, by applying LAP with Nano Color technology, the red and green regions of the light source are divided; thereby, the color reproduction is increased. The red image quality of the real panel is also improved like Figure 6B’. In addition, because of Nano Color technology, the reflectance of the real panel is reduced by 73% compared with the conventional technology and can be confirmed with the human eye, as shown in Figure 6B”.

Figure 7 shows the spectrum of the colorant used in LAP with Nano Color technology and the direction of development. As shown in Figure 7A, the colorant used for LAP has an absorption shoulder in green region, which degrades green brightness of panel. For improving green brightness, the technique of removing the left shoulder is important. By reducing full width at half maximum (FWHM) of the transmission spectrum between green and red regions, spectrum of light source can be sharper and the color can also be deeper, as shown in Figure 7B. Other method of increasing color gamut is move the wavelength peak like Figure 7C and to use new absorption spectrum that had additional absorption peak between blue and green regions like Figure 7D. As a result, approach using functional dyes is continuously required. We are continuing to study new colorants and functional dyes to obtain target spectrum as in Figure 7.

3.2 | WCG for OLED

In general, there are two types of OLEDs. One is the RGB independent OLED light source structure using shadow mask. The other is a white OLED structure that represents color by using color PR with depositing white OLED light source. Mobile products are usually applied RGB OLED structure. On the other hand, TV products are used white OLED structure because of mask deflection problem caused by large size of TV product.

Figure 8 shows representative bottom emission structure of white OLED. In this structure, there are organic
electro luminescence device, color PR, and polarizer that affect the color representation. Unlike LCDs, OLED structure cannot be used optical sheet. Therefore, additional layers for WCG should be a coating type PR. In the color PR part, WCG can be realized by applying CCM.

Figure 9A shows structure with FD, one of CCM, layer applied. Figure 9B shows general absorption and emission spectrum shape of each red and green FD. The octaethylporphyrin, perylene, anthracene, fluorescein, and coumarin are commonly known emissive molecule, and their properties can be varied with this design. To increase purity of the color in the red color, the absorption band of 530 to 560 nm and the emission band of 620 to 640 nm are considered. Scanning electron microscope (SEM) image of suggested structure applying FD layer on color layer is shown Figure 9C. For applying CCM to displays, quantum efficiency of single CCM system has been studied. However, photo luminescence property and quantum efficiency of binary CCM system are rarely reported. As a CCM, the FD that has better heat resistance than QD had been studied in our group. S. Kim et al researched the efficiency of binary FD PR along the combination and its content. When the binary system of FD was applied, luminance and coverage to BT.2020 of panel were increased. It was experimentally verified that energy was transferred by energy transfer mechanism when two types of FD were adjacent. The viewing angle property and color difference along the compositions of FD PR were also studied in our group. S. Lee et al confirmed the characteristic of fluorescence efficiency along combination and process condition. As a result, dependence of fluorescence property was found out along the condition of ultraviolet exposure among the photolithography process. Improvement of color characteristic was confirmed by experiment with real OLED panel. As a result of the spectrum trend of experiment, it is confirmed that the optimal combination with the light source was possible (Figure 10). This means that applying binary system of FD compared with single FD system would help reduce power consumption and

**FIGURE 7** Development direction of colorant for Nano Color technology. A, Removing the shoulder peak in green region, B, reduction of full width at half maximum peak (FWHM, 30 nm or less), C, move the wavelength peak, D, adding green and blue absorption peak

**FIGURE 8** Structure of white organic light emitting diode (OLED) panel. Three technologies are available for wide color gamut (WCG) implementation: combination of organic emitting layer, color filter, and polarizer.
improve lifetime of light source. Further studies are needed to prevent quenching and aggregation by the structure of each matrix.

To obtain high color strength, red and blue colorants have to be improved absorbance, and green has to be developed new materials with altered transmission spectra to optimally match with the light source. In addition, the colorant itself is required narrow spectrum, high transmittance, and low cost.

FIGURE 9  A, Structure with color conversion material layer: fluorescence dye layer stacked on color layer. B, General absorption and emission spectrum shape of red and green fluorescence dyes. C, Scanning electron microscope (SEM) image of side view: fluorescence dye layer stacked on color photoresist layer

FIGURE 10  Performance of fluorescence dye layer in real organic light emitting diode (OLED) panel. Spectrum of OLED light source with or without fluorescence dye layer. “A” shows wide color gamut (WCG) by application of red fluorescence dye layer in red pixel

4 | SUMMARY

As mentioned earlier, color materials have different designs depending on various problems like defect and stain in CF process and electric characteristic changes according to the model change. Therefore, a lot of research activities such as identification of defect mechanism and new concept proposal are needed. In WCG technology, the importance of not only high color reproduction but also the final visual impression of the display device such as coloring feeling and reflection reduction is increasing. Our team is also studying various functional materials for the reducing reflectance and visual impression as well as high color reproduction using optical simulation tool. Colorants have been steadily developed from high CR, improving transmittance, and to WCG for representing natural color in display industry. To improve color gamut for WCG, increasing content of colorant is also being applied. However, excessive content increased has an adverse effect to CF process and products. For overcoming these problems, colorants that have good color strength are necessary.

Display industry is changing very fast. In order to produce high value panel required for the market, such as AR/VR, auto product, and u-LED, not only improving panel performance but also new application technology is very important. To achieve this, there are many challenges and difficult problems for everyone. However, various tasks and questions are bound to have an answer.

The development of all materials including colorants is actually slow, and there is no present of display industry without materials. The challenges that we face today can be solved when technologies in each field are closed linked and working together. We have been researching the color field for a long time and I would like to express my sincere thanks and appreciation to everyone who has given us a lot of help, cooperation, and advice.
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