

High concentration PEGylated quantum dot solution for color conversion applications

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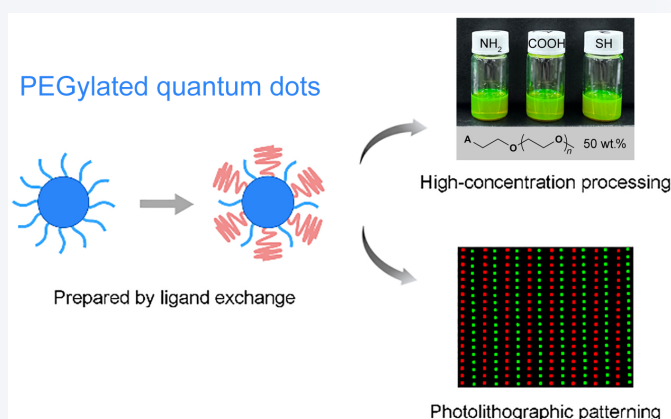
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ABSTRACT: Quantum dot color conversion is a key technology to fabricate full-color display panels. Because the optical performance of color conversion films is strongly correlated with the dispersion and concentration of quantum dots in the composite films, high loading quantum dots solution is of great importance. Herein, we fabricate a series of poly(ethylene glycol) (PEG)-ylated quantum dots in neutral solvents such as propylene glycol monomethyl ether acetate (PGMEA) and ethylene glycol dimethacrylate (EGDMA), achieving a maximum concentration of 50 wt.% with a maximum photoluminescence quantum yield of ~ 96%. Using PEGylated QDs in EGDMA, we developed quantum dot photoresist to fabricate color conversion patterns, achieving a high blue-light absorption over 90% at 450 nm with a photo conversion efficiency exceeding 55%. Furthermore, high-resolution color conversion patterns with a pixel density of up to 2450 pixels per inch (PPI) were successfully fabricated via direct photolithography. This work not only provides advanced materials for fabricating color conversion patterns for display application, but also opens up new opportunities for other technology.

KEYWORDS: quantum dot, color conversion, poly(ethylene glycol) (PEG)ylated, high concentration



1 Introduction

Quantum dot color conversion (QDCC) provides an important route to achieve wide color gamut display technology [1–4]. For liquid crystal display (LCD) application, red and green QDs are embedded into polymer matrix to form QD enhancement films (QDEF) or QD enhancement plates (QDEP) [5–7]. For organic light emitting diode (OLED) and micro light emitting diode (Micro-LED) applications, QDs are integrated with arrayed blue-light backplane to attain patterned full-color emission [8–10]. In these applications, QDs are firstly dissolved into specific solvents (isobornyl acrylate (IBOA), propylene glycol monomethyl ether acetate (PGMEA), etc.) and then processed into polymer

composites (films, plates, and patterns) [11–13]. In the QDCC applications of OLED and Micro-LED, it is very necessary to fabricate photoresist with high-loading QDs for achieving high blue light absorption [14–17]. Therefore, the solubility of QDs plays a crucial role in determining their processing ability and significantly influences their optical performance, such as blue-light absorption and photo conversion efficiency (PCE) [18, 19].

The dispersion of QDs mainly relates with the interactions between surface ligands and solvent, including steric repulsion, electrostatic interaction and their combination [20–22]. For the dispersion in nonpolar solvents such as n-hexane, toluene, and chlorobenzene, QDs are capped with long alky-chain ligands including oleic acid (OA), oleylamine (OLA), and others [23, 24]. For the polar solvents (N,N-dimethylformamide (DMF), dimethyl sulfoxide (DMSO), and H₂O), QDs are capped with small molecules (6-mercaptohexan-1-ol (MCH), 3-mercaptopropionic acid (MPA), etc.), polymer ligands (poly(ethylene glycol) (PEG), poly(maleic anhydride) (PMA)), and inorganic ligands [25–28]. For the neutral solvents (1-methoxy-2-propanol (PGME), PGMEA, etc.), the ligands of QDs are replaced with acrylate ligands such as

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mono-2-(methacryloyloxy)ethyl succinate (MMES), 2-carboxyethyl acrylates (CEA), and others [11, 29, 30]. To achieve high-concentration QD solution in nonpolar solvents, branched-chain ligands are introduced to increase the conformation entropy [31, 32]. To our knowledge, only a few works concern the concentration of QDs in polar and neutral solvents, and the maximum concentration in these solutions is less than 30 wt.%, especially in the case of PGMEA for photoresist (Table S1 in the ESM).

PEGylation has been a successful strategy to transfer colloidal nanocrystals into polar and neutral solvents [33–36]. However, the dispersion and concentration of PEGylated QDs in PGMEA have rarely been investigated. In this work, we investigated a series of PEGylated QDs in PGMEA and monomers, achieving a maximum concentration of 50 wt.% with a maximum photoluminescence quantum yield (PLQY) of ~96%. We further developed PEGylated QDs based photoresist for color conversion applications, and fabricate green and red QDCC films with high blue-light absorption and PCE.

2 Results and discussion

Figure 1(a) illustrates the preparation process of methoxy poly(ethylene glycol) (mPEG)-ylated QDs. The ligands of mPEG-A ($A = \text{SH}, \text{COOH}, \text{NH}_2$) contain coordinating groups and ether linkages. The coordinating groups bind to the surface of QDs, while the ether chains render the ligands of QDs compatible with neutral solvents, according to the rule of “like dissolves like” [37], as shown in Fig. 1(b). The long-chain PEG ligands offer enhanced steric repulsion, thereby increasing both the dispersion concentration and stability of QDs in solvents such as PGMEA and monomers like ethylene glycol dimethacrylate (EGDMA). In particular, the good dispersion of PEGylated QDs in EGDMA enables the ultraviolet (UV) cross-linked fabrication of high-loading composite with uniform dispersed QDs, as shown in Fig. 1(c).

In this study, we employed CdSe/ZnS core-shell QDs with

ligands of trioctylphosphine (TOP) and stearic acid (SA). The original ligands can be replaced by mPEG ligands with different terminal groups under 100 °C and 30 min, yielding clear and transparent QD dispersions in different solvents. As shown in Fig. 2(a) and Fig. S1 in the Electronic Supplementary Material (ESM), the PEGylated QDs can be well dispersed in neutral solvents and monomers, such as in PGMEA, EGDMA, 2-methoxyethyl acrylate (MEA), and methyl methacrylate (MMA), and the maximum QD concentration can be up to 50 wt.%. The surface ligands of pristine QDs and PEGylated QDs were characterized by Fourier-transform infrared spectroscopy (FTIR). Figure 2(b) shows the FTIR spectra of pristine QDs, mPEG-SH 1000 QDs, and mPEG-SH 1000. In the pristine QDs, two prominent peaks corresponding to the stretching vibrations of carboxylate (COO^-) are observed at 1540 and 1460 cm^{-1} , confirming the termination of carboxylate surface termination. Although these peaks are weaker in mPEG-SH 1000 QDs, the appearance of the C–O (~1200 cm^{-1}) peak characteristic of PEG confirms that mPEG-SH 1000 ligands have replaced the alkyl ligands on the QDs. Further evidence of PEG ligand exchange was provided by ^1H nuclear magnetic resonance (^1H NMR) spectroscopy. Figure 2(c) shows the ^1H NMR spectra of pristine QDs, mPEG-SH 1000 QDs, and mPEG-SH 1000. In the pristine QDs, the peak at 1.35 and 1.55 ppm can be attributed to TOP and SA, respectively, as shown in Fig. 2(d) and Fig. S2 in the ESM. These two signals were reduced after ligand exchange, and new signals appear at 3.40 and 3.65 ppm, corresponding to the O–CH₂ and O–CH₃ groups of mPEG-SH 1000, respectively.

We further investigated the influence of PEG molecular weight on the dispersibility of PEGylated QDs in PGMEA. As shown in Fig. S3 in the ESM, the mPEG with molecular weights less than 1000 can form clear and transparent solutions in PGMEA. When the molecular weight approaches to 2000, the solution appeared turbid due to reduced solubility. As shown in Fig. S4(a) in the ESM, PEGylated QDs with molecular weights of 350, 750, and 1000 in

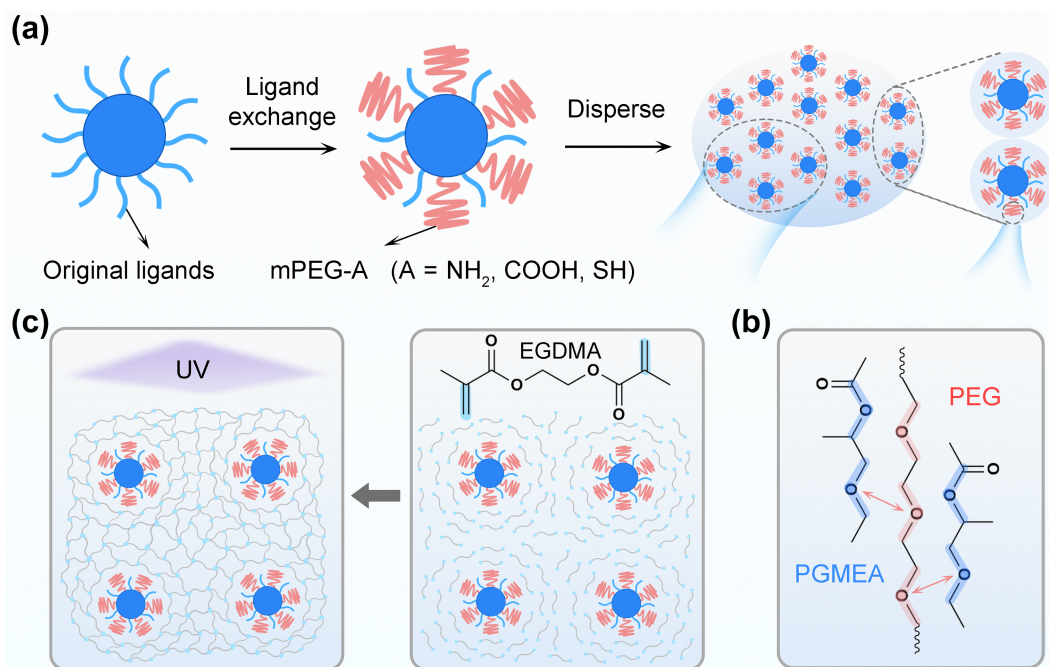


Figure 1 (a) Schematic illustration of the preparation of PEGylated QDs via ligand exchange. (b) Schematic illustration of the “like dissolves like” rule between PEG and PGMEA. (c) UV crosslinking process of QDs dispersed in EGDMA.

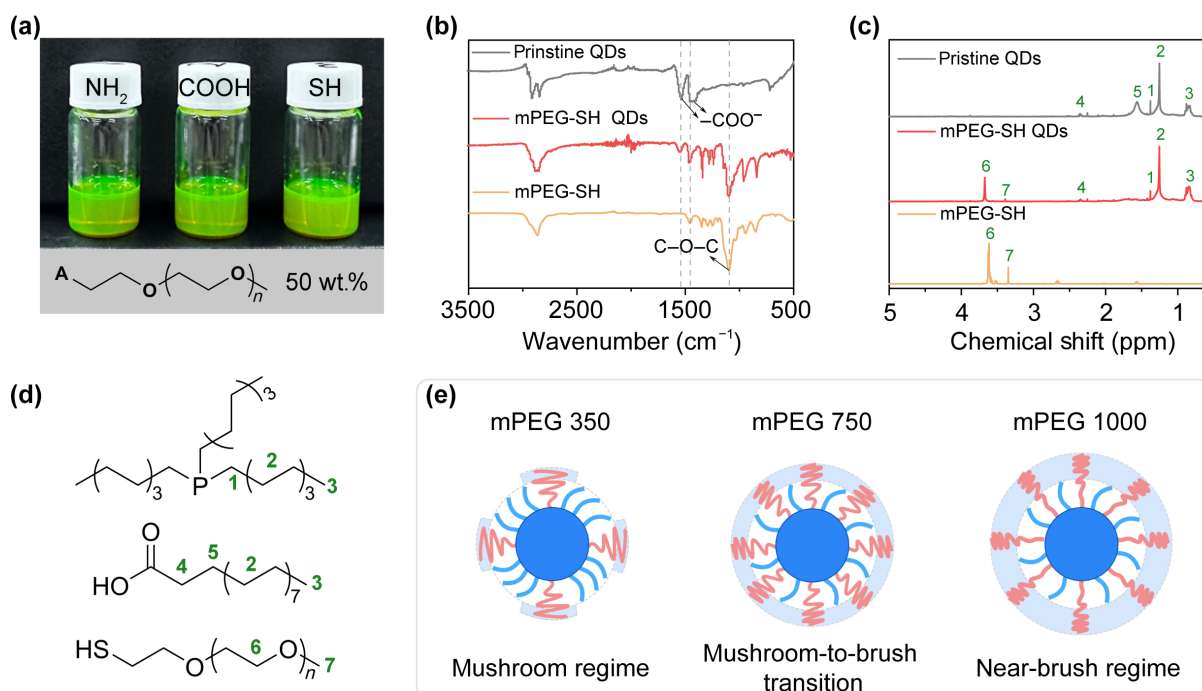


Figure 2 Structural characterization of PEGylated QDs. (a) Photograph of PEGylated CdSe/ZnS QDs dispersed in PGMEA at a concentration of 50 wt.%. (b) FTIR, and (c) ¹H NMR spectra of pristine QDs, mPEG-SH 1000 QDs, and mPEG-SH 1000. (d) Chemical structure of TOP, SA, and mPEG-SH. (e) Schematic illustration of PEG chain conformation on the QD surface. The light blue region represents the solvated PEG corona in PGMEA, which stabilizes the dispersion of QDs.

PGMEA were mixed with the antisolvent (n-hexane) and centrifuged. The precipitation of the PEGylated QDs increased with increasing molecular weights of PEG, indicating that increasing the PEG molecular weight improved the solubility of the QDs. Figure S4(b) in the ESM shows the transmittance spectra of pristine QDs (in toluene) and PEGylated QDs (in PGMEA). The lowest transmittance at 700 nm was observed at a molecular weight of 350, which is attributed to scattering due to QD aggregation in solution. Figure S4(c) in the ESM shows the dynamic light scattering (DLS) results for pristine QDs (in toluene) and PEGylated QDs (in PGMEA). With molecular weight of PEG increasing, the particle size became smaller and narrow distributed. Notably, PEGylated QDs with a molecular weight of 1000 exhibited consistent size distributions regardless of the terminal group, as shown in Fig. S4(d) in the ESM. After the storage of 50 days at room temperature ($\sim 25^\circ\text{C}$), the hydrodynamic radius of the PEGylated QDs remained consistent with the initial state, and both particle size and polydispersity index (P.I.) remained stable throughout (Figs. S4(e) and S4(f) in the ESM).

The colloidal stability of PEGylated QDs in PGMEA strongly depends on the molecular weight of PEG and the conformation of the grafted chains. The conformational state of grafted polymer chains can be evaluated using the dimensionless interaction parameter $\chi = \sigma \pi R_g^2$. According to classical polymer brush theory, $\chi < 1$ corresponds to a non-overlapping mushroom regime, whereas $1 < \chi < 5$ represents the mushroom-to-brush transition regime, where significant chain overlap induces partial chain stretching and the formation of a solvated polymer corona [38, 39]. Here, we calculated the dimensionless interaction parameter χ to be 0.67 for mPEG 350-modified QDs, 3.49 for mPEG 750-modified QDs, and 4.75 for mPEG 1000-modified QDs, based on their respective grafting densities ($\sigma = 0.63, 1.37$, and 1.32 chains nm^{-2} , calculated based on TGA and ¹H NMR data, as shown in Fig. S5 in the ESM)

and radii of gyration ($R_g = 0.58, 0.90$, and 1.07 nm). As schematically illustrated in Fig. 2(e), mPEG 350-modified QDs form a sparse, mushroom-like surface conformation, in which the isolated PEG chains provide limited solvation and insufficient steric stabilization, leading to pronounced interparticle aggregation. In contrast, mPEG 750- and mPEG 1000-modified QDs lie in the mushroom-to-brush transition regime. In this regime, the overlapping PEG chains induce a substantially thicker solvated corona and stronger steric repulsion, suppressing QD aggregation and improving colloidal dispersibility in PGMEA. Notably, mPEG 1000-modified QDs exhibit superior colloidal stability compared to their mPEG 750-modified counterparts. This can be explained by their larger radius of gyration and higher χ value ($\chi = 4.75$), which places the grafted PEG chains closer to the true brush regime. Consequently, mPEG 1000 forms a thicker and more highly overlapped solvated corona, thereby providing stronger steric and solvation stabilization against interparticle aggregation.

The PEGylated QDs were further characterized using absorption and PL emission spectra, as shown in Figs. 3(a) and 3(b). The absorption curves of the QDs before and after ligand exchange completely overlap, and no obvious shift is observed in the PL emission peak and full width at half maximum (FWHM). These results suggest that the ligand transfer from TOP/SA to mPEG is non-damaging to the QD surface. Furthermore, transmission electron microscopy (TEM) images reveal that the QD size remains essentially unchanged after the reaction (Figs. S6 and S7 in the ESM), consistently measured at 11.36 ± 0.29 nm. Similarly, as shown in Fig. S8 in the ESM, the X-ray diffraction (XRD) patterns of the QDs before and after ligand exchange exhibit highly consistent diffraction peak positions and relative intensities. Furthermore, the pristine QDs have a PLQY of 95%, while the QDs after ligands exchange have a PLQYs of $\sim 96\%$, $\sim 88\%$, and $\sim 88\%$ for mPEG-SH 1000, mPEG-COOH 1000, and mPEG-NH₂ 1000,

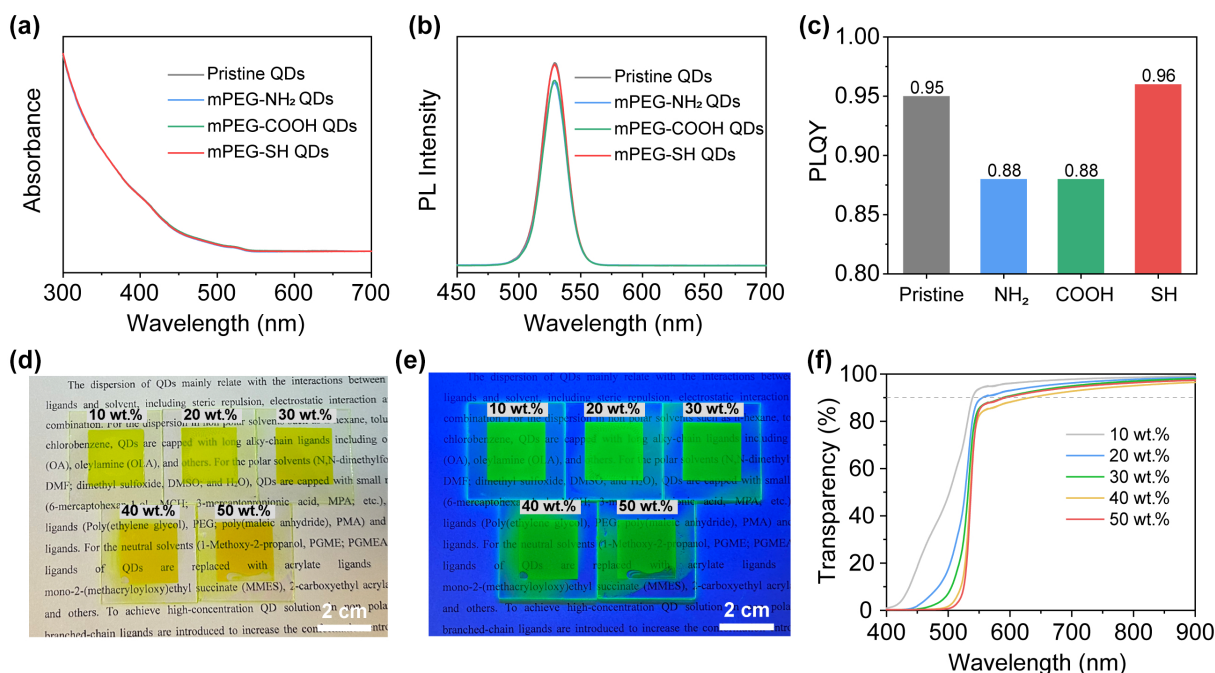


Figure 3 Optical properties of PEGylated QDs. (a) Absorption, (b) PL spectra, and (c) PLQY of CdSe/ZnS QDs before (in toluene) and after (in PGMEA) ligand exchange. (d) Photographs of QD films with varying concentrations under daylight. (e) Photographs of QD films with varying concentrations under 365 nm excitation. (f) Transmittance spectra of QD films with varying concentrations.

respectively, as summarized in Fig. 3(c). These observations demonstrate that the mPEG modification only regulates the surface chemical environment of QDs. After 50 days of storage at room temperature, the PEGylated QDs maintained optical properties consistent with their initial state, as shown in Fig. S9 in the ESM.

Using PEGylated QDs, we prepared 60- μ m QD composite films with the concentrations of 10 wt.%, 20 wt.%, 30 wt.%, 40 wt.%, and 50 wt.%, shown in Fig. 3(d). These composite films were prepared by UV curing of the EGDMA solutions containing PEGylated QDs and photoinitiator 819. As the QD concentration increases from 10 wt.% to 50 wt.%, the QD films gradually changed from green to yellow-green in color, while still maintaining excellent transparency. Meanwhile, all films exhibited intense fluorescence emission under 365 nm excitation, shown in Fig. 3(e). Figure 3(f) shows the transmittance spectra of the above-mentioned QD films. The high transmittance of composite films at longer wavelength suggests the good dispersion of QDs.

Furthermore, the mPEG ligand exchange exhibits a notable degree of versatility. Figure S10 in the ESM demonstrates the successful ligand exchange of mPEG on CdSe/ZnS QDs with different emission wavelengths and FWHM. Figure S11 in the ESM further illustrates the applicability of mPEG ligand exchange to other types of QDs. Figure S12 in the ESM shows that PEGylated QDs maintain good dispersibility in other “green solvents” such as PGME, EGMEA, and diethylene glycol monoethyl ether acetate (DGMEA) at a concentration of 5 wt.%.

To explore the use of PEGylated QDs for color conversion applications, QDCC films were fabricated via direct photolithography employing their monomer dispersions. As shown in Fig. S13 in the ESM, the preparation process of QDCC films involves casting, development, exposure, and post-baking. Figure 4(a) summarizes the PCE of QDCC films at different processing stages. These composite films of mPEG-SH 1000 QDs exhibit an increase in the PCE compared to those from pristine

QDs. The decrease in PL intensity after development is likely associated with the absorption of ambient moisture by the QD film during the rapid evaporation of the developer solvent (PGMEA). The photolithographic process has minimal impact on the PCE of the QD films.

Blue-light absorption and conversion efficiency are critical parameters for evaluating QDCC performance. Figure S14 in the ESM shows the effect of QD concentration on absorbance and PCE, with a uniform film thickness of 60 μ m. When the QD content approached 25%, the QDCC film exhibited an absorbance above 90%, while the PCE reached approximately 45%. Further increasing the QD concentration enhances blue-light absorption but leads to a further reduction in PCE, which is attributed to the self-absorption effect of the QDs. Meanwhile, the practical applications of QDCC layers typically require a thickness of less than 10 μ m [40, 41]. To address this issue, TiO₂ based scattering particles were introduced to enhance blue-light scattering, thereby improving blue-light absorption while maintaining a high PCE. Figure 4(b) shows the spectra of QDCC films after blue light absorption. At a QD content of 20 wt.% and a scattering particle (TiO₂) content of 10 wt.%, the green QDCC films (QDCC-G) achieves a blue-light absorption of 91.5% and a PCE of 57% at a thickness of 4.9 μ m, while the red QDCC films (QDCC-R) reaches 92.0% absorption and 55% PCE at a thickness of 2 μ m, as shown in Fig. 4(c). The influence of QDCC thickness on optical performance is further detailed in Fig. S15 in the ESM. After the introduction of scattering particles, the PCE remained above 50% while maintaining a blue-light absorption of over 90%. These results demonstrate that integrating the QDCC films with a blue backlight enables efficient blue-light absorption and conversion.

Furthermore, we fabricated a series of QD patterns with different sizes. Figure 4(d) shows a fluorescence microscopy image of a 20 μ m red square pattern, exhibiting high contrast between bright red emission and dark background, along with sharply defined

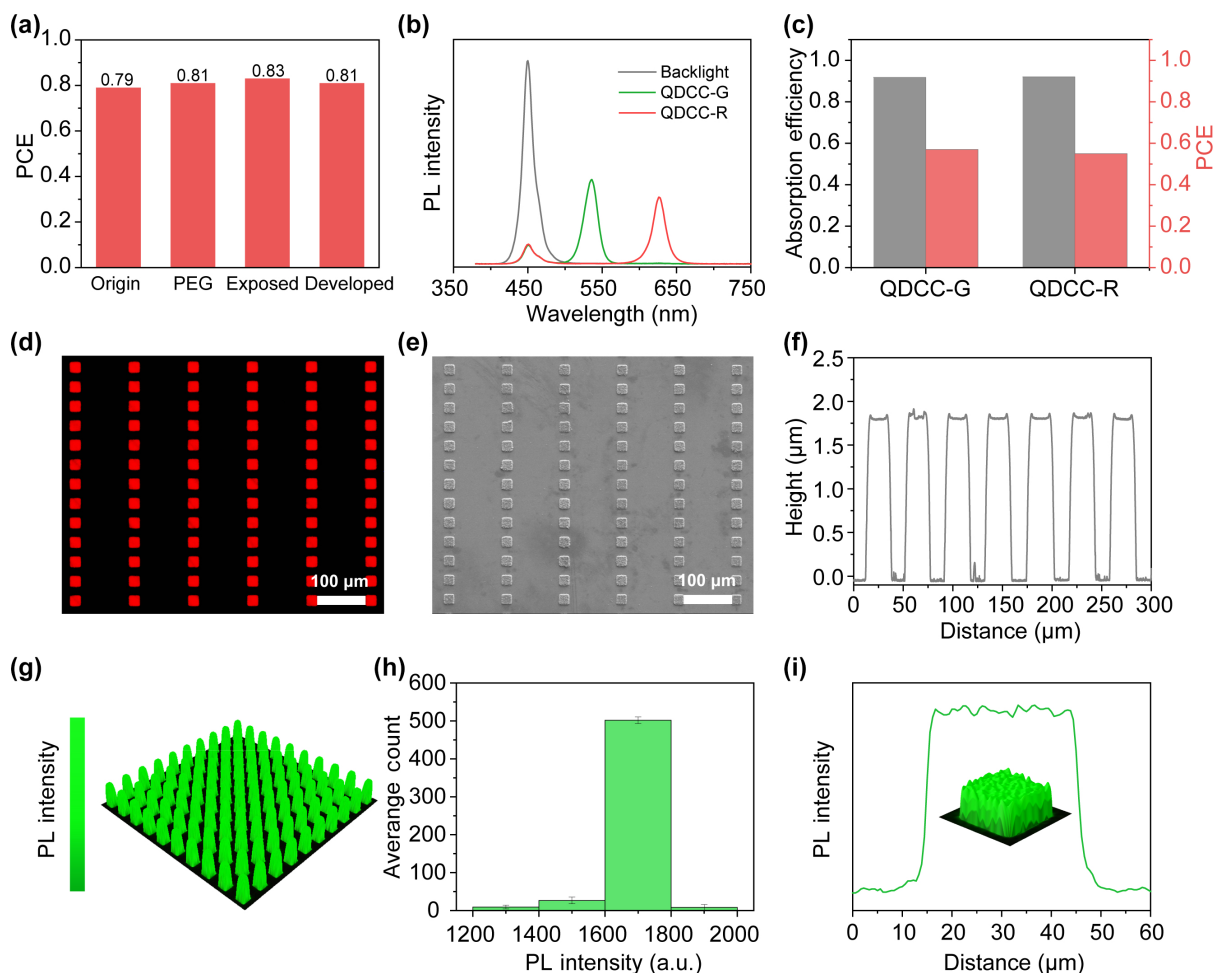


Figure 4 Characterization of QDCC films prepared via direct photolithography. (a) The PCE of QD films after ligand exchange, exposure, and development. (b) PL spectra of green and red QDCC films excited by backlight (450 nm). (c) Absorption efficiency and PCE of green and red QDCC films. (d) Fluorescence image, (e) SEM image, and (f) height profile of the red square patterns. (g) Emission intensity distribution image 100 square pixels with a side length of 30 μm . (h) Average emission intensity statistical distribution of 546 square pixels with a side length of 30 μm . Error bars represent standard deviation (the statistical data and errors were presented in Table S3 in the ESM). (i) Radial emission intensity distribution of a single 30 μm square pixel, inset image is the surface-emission intensity of the pixel.

edges. Scanning electron microscopy (SEM) images further reveal a smooth surface and high contrast between exposed and unexposed regions within these patterned arrays. As shown in Fig. 4(e) and Fig. S16 in the ESM, clean edges indicate that all exposed patterns are fully cured, while the unexposed areas have been completely removed. Cross-sectional analysis confirms that the thickness of the photolithographic patterns is approximately 1.7 μm (Fig. 4(f)).

We further evaluated the luminescence uniformity of the QDCC patterns using fluorescence microscopy. Figure 4(g) depicts the emission intensity map of a QDCC array composed of 100 square pixels with a side length of 30 μm , showing desirable fluorescence uniformity across all pixels. Expanding the statistical analysis to 546 square pixels (Fig. S17 in the ESM), the histogram of fluorescence intensity reveals that approximately 92% of the pixels fall within the intensity range of 1600–1800, shown in Fig. 4(h), demonstrating excellent luminescence uniformity across the QDCC pixel array. Moreover, Fig. 4(i) presents the radial and surface fluorescence intensity profiles of a single 30 μm square pixel, illustrating the homogeneous emission within each individual pixel of the QDCC pattern.

To demonstrate the scalability of photolithographic fabrication using PEGylated QD monomer dispersions, we fabricated a series

of patterns using QDs of different colors on both rigid and flexible substrates. The substrates were first treated with 3-(methacryloyloxy)propyltrimethoxysilane (TMSPMA) to expose acrylate groups on the surface, enabling the quantum dot photoresist (QDPR) to react with these active groups under UV irradiation, forming covalent bonds. Owing to structural similarity, substrates treated with TMSPMA exhibited significantly stronger adhesion compared to those treated with previously reported vinyltrimethoxysilane (VTMS) [42, 43], shown in Fig. S18 in the ESM. Figures 5(a)–5(d) display macroscopic green “dragon” and red “maple leaf” patterns, as well as green and red stripe arrays with a linewidth and pitch of 20 μm . Figure 5(e) shows circular patterns with a diameter of 5 μm , corresponding to a resolution of up to 2540 PPI, which is sufficient to meet the resolution requirements for augmented reality (AR) and virtual reality (VR) displays [43, 44]. Figure 5(f) presents red-green dual-color square patterns with a diameter of 20 μm . Additional pixelated patterns of various sizes and shapes are provided in Fig. S19 in the ESM. Furthermore, using the same substrate functionalization process, we successfully patterned PQDs on flexible polyethylene terephthalate (PET) substrates, glass, and silicon wafers, as shown in Figs. 5(g)–5(i) and Fig. S20 in the ESM, highlighting the broad integration

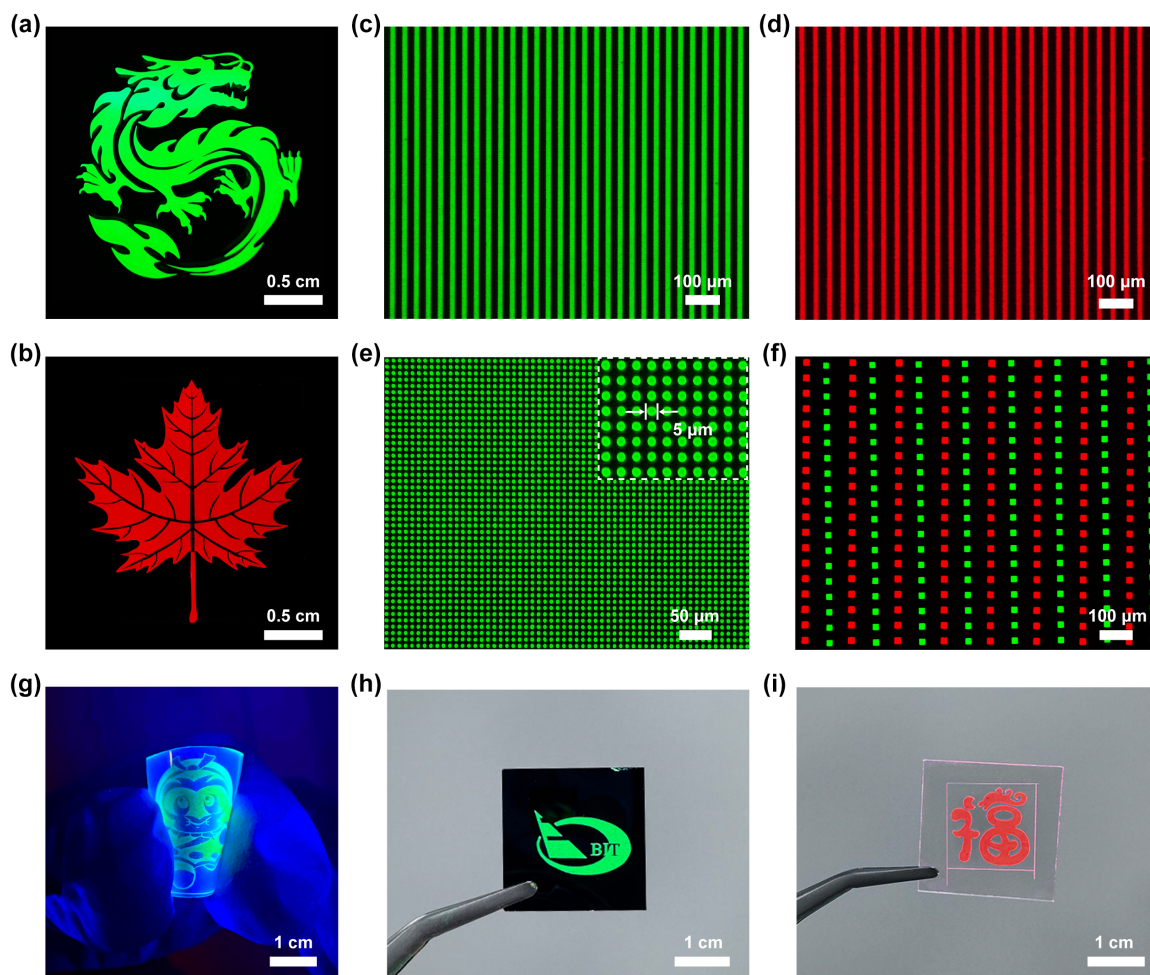


Figure 5 Multicolored QD patterns prepared by direct photolithography. (a) Green “dragon” and (b) red “maple leaf” patterns. (c) Green, (d) red stripe pattern with a width of 20 μm . (e) Green circle patterns with a diameter of 5 μm . (f) Green and red square patterns with a diameter of 20 μm . (g) Photograph of green cartoon on the flexible PET under UV light. (h) Photograph of green cartoon on the silicon wafer under UV light. (i) Photograph of green cartoon on the glass under UV light.

compatibility of the photolithography approach and its potential for flexible display applications. These results demonstrate that direct photolithography using PEGylated QDs in polymerizable monomers enables the fabrication of multicolor, multi-substrate, high-resolution, and highly uniform QDCC patterns.

3 Conclusion

In summary, we developed PEGylated QDs with high concentration in neutral solvents such as PGMEA, EDGMA, and subsequently fabricated pixelated QDCC patterns via direct photolithography process. The mPEG-A ($A = \text{SH}, \text{COOH}, \text{NH}_2$) functionalized CdSe/ZnS QDs can be well dispersed in neutral solvents with a maximum concentration of 50 wt.% and a maximum PLQY of $\sim 96\%$. In particular, the PEGylated QDs in EDGMA can be photolithographically processed into films and patterns. The resulted green QDCC films have an absorbance of 91.7% and a PCE of $\sim 57\%$ at 450 nm excitation, while the red QDCC films reached 92.0% and $\sim 55\%$, respectively. Finally, we successfully fabricated red and green QDCC pixelated patterns with a minimum feature size of 5 μm , corresponding to a resolution as high as 2450 PPI. In the future, the PEGylated QDs based QDPR can be further improved by designing the structure of QDs. In all, the PEGylated QDs not only provide advanced materials for QDCC

based display technology but also open up new opportunities for other photonics applications.

4 Experimental

4.1 Chemicals

PGMEA ($\geq 99\%$), PGME ($\geq 99\%$), EGMEA ($\geq 98\%$), DGMEA ($\geq 99\%$), MMA ($\geq 99\%$), MEA ($\geq 98\%$), EGDMA ($\geq 98\%$), phenylbis(2,4,6-trimethylbenzoyl)phosphine oxide (819, $\geq 97\%$), titanium dioxide (TiO_2 , 100 nm, $\geq 99\%$), VTMS ($\geq 98\%$), and 3-(methacryloyloxy)propyltrimethoxysilane (MPTMS, $\geq 97\%$), and n-hexane ($\geq 99\%$) were purchased from Shanghai Aladdin Biochemical Technology Co., Ltd. mPEG-SH, mPEG-COOH, and mPEG-NH₂ were purchased from Shandong Baositai Medical Materials Co., Ltd. Quantum dot materials, including green- and red-emitting CdSe/ZnS core-shell quantum dots, were purchased from Beijing Beida Jubang Science & Technology Co., Ltd. All chemical reagents were used as received without further purification.

4.2 Ligand exchange

In a typical process, 1 g of QDs, 0.5 g of mPEG-A 1000 ($A = \text{SH}, \text{COOH}, \text{or } \text{NH}_2$), and 3.5 mL of PGMEA were mixed and heated to

100 °C for 30 min. After cooling, the QDs were precipitated by adding 10 mL of n-hexane. Following centrifugation for 5 min, the supernatant was removed, and the precipitated QDs were redispersed in PGMEA or EGDMA at the desired concentration.

4.3 Preparation of quantum dot photoresist

In a typical procedure, a mixture of 0.25 g EGDMA and 0.25 g TiO₂ was first ball-milled for 10 min to afford solution A. 0.5 g of QDs, 0.05 g of photoinitiator 819, and 1.45 g of EGDMA were then mixed and ball-milled for 10 min to obtain solution B. Finally, solution A and solution B were mixed and then ball-milled for 10 min to obtain the QDPR.

4.4 Substrate pretreatment

Various substrates were sequentially cleaned in deionized water, ethanol, acetone, and isopropanol under ultrasonication for 15 min each, then dried with a nitrogen stream. A small amount of MPTMS was deposited onto the substrates under vacuum at 100 °C for 4 h.

4.5 Photolithography process

The QDCC arrays were fabricated using the quantum dot photoresist via the following steps:

- (i) Casting of QDPR: 800 rpm, 30 s.
- (ii) UV exposure: through a photomask, i-line (365 nm) exposure at 100 mJ/cm², 2 s.
- (iii) Development: immersion in PGMEA for 20 s to remove unexposed regions.
- (iv) Post-baking: 90 °C, 3 min.

4.6 Fabrication of 60-μm QDCC layers

A 60-μm deep glass groove was used to prepare thick films of the same thickness. QD/EGDMA solutions with varying concentrations were prepared by adding 2% photoinitiator 819, followed by thorough mixing. The QD solution was cast into the groove, subsequently compressed with another glass slide, and finally photocured under 100 mJ/cm² for 10 s. It should be noted that another piece of glass was placed over the sample to minimize oxygen inhibition.

4.7 Calculation of blue light absorption and PCE

The blue-light absorption of the QDCC films was quantitatively assessed through PL spectroscopy. This calculation relies on the attenuation of the excitation peak in the blue spectral region ($\lambda = 390\text{--}490$ nm), corresponding to the portion of incident excitation light that is not absorbed by the film but is scattered or re-emitted.

The detailed procedure is as follows:

- (i) The PL spectrum of the QD films were measured, encompassing both the excitation peak (390–490 nm) and the QD emission peak—specifically, 490–590 nm for green QDs or 590–690 nm for red QDs.
- (ii) The integrated intensities were calculated for both the excitation peak (I_s) in the 390–490 nm range and the luminescence peak designated as I_G for green QDs and I_R for red QDs within their respective emission ranges (490–590 nm for green QDs and 590–690 nm for red QDs).
- (iii) A reference PL spectrum was acquired under the same instrumental conditions. This reference, typically obtained from a bare substrate or a non-absorbing standard, provides the integrated intensity of the incident excitation light (I_{Ref}).

- (iv) The blue-light absorption percentage (A) was subsequently calculated using the following equations

$$A = 1 - \frac{\sum_{\lambda=390}^{490} I \Delta \lambda}{\sum_{\lambda=390}^{490} I_{Ref} \Delta \lambda}$$

$$I = I_G \text{ or } I_R$$

where $\Delta \lambda$ denoted the step size;

- (v) The PCE was then calculated using the following equations

$$PCE = \frac{\sum_{\lambda=490}^{590} I_G \lambda \Delta \lambda}{\sum_{\lambda=390}^{490} I_{Ref} \lambda \Delta \lambda - \sum_{\lambda=390}^{490} I_G \lambda \Delta \lambda}$$

for green QDCC films;

$$PCE = \frac{\sum_{\lambda=590}^{690} I_R \lambda \Delta \lambda}{\sum_{\lambda=390}^{490} I_{Ref} \lambda \Delta \lambda - \sum_{\lambda=390}^{490} I_R \lambda \Delta \lambda}$$

for red QDCC films.

4.8 Material characterization

The PL spectra were measured using an F-380 fluorescence spectrometer (Tianjin Gangdong Sci. & Tech. Development Co., Ltd., China). The absorption and transparency spectra were recorded on a UV-6100 UV-vis spectrophotometer (Shanghai Mapada Instruments Co., Ltd., China). The absolute PLQY was determined by a fluorescence spectrometer (calibrated multichannel spectrometer, PMA12) with an integrated sphere (C9920-02, Hamamatsu Photonics, Japan) excited by a LED light source (F5 DIP LED, 3 V, 20 mA) at a wavelength of 377 nm. Fourier transform infrared spectra were measured using a Nicolet iS50 (Thermo Scientific, Ltd.). The ¹H spectrum of the solution was measured using an AMX-400M NMR spectrometer from Bruker, USA. The XRD measurements were measured on a Bruker/D8 FOCUS X-ray diffractometer, using a Cu K α radiation source (wavelength at 1.5405 Å). Thermogravimetric analysis (TGA) experiments were carried out on Mettler Toledo TGA/DSC 2. SEM measurements were performed with SU-4800 microscope (Hitachi, Ltd.) equipped with a cold emission gun. TEM observations were performed using a JEM 2100 plus (JEOL Ltd., Japan) field-emission transmission electron microscope operated at 120 kV. The average size and distribution of QDs were obtained through a convolutional neural network-based detection and segmentation model and its supporting software [45]. The DLS measurement was performed with nanoparticle size analyzer (PSS, Ltd.) with a frequency analysis light scattering analyzer and a phase analysis light scattering analyzer. The thicknesses of QDCC films were measured by a step meter (STEP, Alpha-Step D-300, KLA, Ltd.). Fluorescence images were obtained using Nikon N-SIM A1R microscope. PL intensity of the optical images was manipulated using Camera software or Image J.

Electronic Supplementary Material: Supplementary material (further details of photographs of QDs in different solvents, particle size distributions of QDs, ¹H NMR spectroscopy of QDs and ligands, PLQY, TEM and XRD of QDs, long-term stability of QDs, PL spectrum, blue-light absorption and PCE of QDCC films, and fluorescence images of patterns) is available in the online version of this article at <https://doi.org/10.26599/NR.2026.94908956>.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and the Electronic Supplementary Material. Additional data related to this paper may be requested from the corresponding author upon request.

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Declaration of competing interest

All the contributing authors report no conflict of interests in this work.

Author contribution statement

Q. C. W.: Experimental design, project administration, data curation, writing manuscript. J. M. S.: Experimental implementation, project administration. X.-g. W.: Data curation. Y. Y. J.: Experimental design. D. B. H.: Data curation. J. B. S. and H. Z. Z.: Project administration, funding acquisition, writing manuscript. All the authors have approved the final manuscript.

Use of AI statement

None.

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