Highly Luminescent and Stable Si-Based CsPbBr$_3$ Quantum Dot Thin Films Prepared by Glow Discharge Plasma with Real-Time and In Situ Diagnosis

Zhenxu Lin, Rui Huang,* Wenxing Zhang, Yi Zhang, Jie Song, Hongliang Li, Dejian Hou, Yanqing Guo, Chao Song, Neng Wan, and Paul K. Chu*

Although all-inorganic perovskite quantum dots (QDs) have outstanding optoelectronic properties, they tend to have poor stability in air and water, at high temperatures, and under light irradiation. Herein, a glow discharge plasma process incorporating real-time and in situ diagnosis is designed for efficient encapsulation to improve the stability of CsPbBr$_3$ QD films. An ammonia/silane plasma which has less destructive effects on CsPbBr$_3$ QDs is used in plasma-enhanced chemical vapor deposition to produce a-SiN$_x$:H on the CsPbBr$_3$ QDs. The a-SiN$_x$:H encapsulating layers endow CsPbBr$_3$ QDs with long-term stability during exposure to air, at a high temperature (205 °C), and in water. In contrast to severe degradation of pure CsPbBr$_3$ QDs under UV illumination, the CsPbBr$_3$ QDs/a-SiN$_x$:H films show more than 5-folds increase in photoluminescence intensity after UV illumination for 80 d and long-term stability is observed after UV illumination for 140 d. The plasma treatment not only stabilizes CsPbBr$_3$ QDs, but enhances photoluminescence efficiency by combining with illumination as well. The nanocomposite films assembled into commercial InGaN chips feature strong cold white emission. Our results reveal a practical way to design and fabricate highly luminescent as well as stable Si-based CsPbBr$_3$ QD films for future development of optoelectronic devices.

1. Introduction

All-inorganic cesium lead halide perovskite (CsPbX$_3$, X = Cl, Br, and I) quantum dots (QDs) which possess superior optical properties such as high photoluminescence quantum yields (PLQYs) and narrow emission line widths have promising applications in photovoltaic devices, photodetectors, light-emitting diodes (LEDs), high-definition displays, and low-threshold lasers. However, these applications are currently limited mainly by the poor stability of CsPbX$_3$ QDs stemming from the inherent ionic nature. In particular, degradation of CsPbX$_3$ QDs is accelerated by UV light irradiation, at a high temperature, and in polar solvents such as water. Different strategies have been proposed to stabilize CsPbX$_3$ QDs and formation of a surface coating on CsPbX$_3$ QDs is an effective approach to improve photostability. Recent experiments indicate that surface coatings composed of ligands, polymers, silica, or Al$_2$O$_3$ not only protect the CsPbX$_3$ QDs from oxygen and moisture attack, but also prevent ion migration, consequently improving the stability of the QDs in unfavorable environments. For instance, CsPbBr$_3$/SiO$_3$ Janus nanocrystal films show only a slight drop (2%) in the PL intensity after UV illumination for 9 h. Nonetheless, despite recent advances, the long-term stability of CsPbX$_3$ QDs, especially photostability, is still not sufficient.

Glow discharge plasma treatment is a common cleaning and surface processing method in the microelectronics industry. A glow discharge plasma produced by collisions between electrons and gas molecules containing reactive radicals, ions, and excited species has high surface activation efficiency. The plasma treatment can modify materials surfaces in multiple ways by simply adjusting the experimental parameters such as the gas source, power, pressure, and treatment time. However, because CsPbX$_3$ QDs are sensitive to the surroundings, the reactive species in the glow discharge plasma can interact easily with atoms on the CsPbX$_3$ QD surface to produce surface defects during the plasma process and cause surface damage or ligand loss from the...
CsPbX\textsubscript{3} QDs leading to decomposition\cite{30}. Therefore, many factors must be considered before plasma-based deposition can be applied to environmentally sensitive compounds.

Radiative relaxation of excited species in the plasma emits light as shown in Figure 1b and the light can be utilized to analyze the plasma and diagnose the process\cite{35,36}. In this work, light is used to stimulate emission from CsPbBr\textsubscript{3} QDs due to the high PL QYs as shown in Figure 1c. By monitoring the emission from CsPbBr\textsubscript{3} QDs with optical emission spectroscopy (OES), degradation of CsPbBr\textsubscript{3} QDs during the plasma treatment is monitored in real time and in situ for the first time to study the interactions between the different chemical species and QD surface. Since the ammonia/silane plasma has a smaller effect on CsPbBr\textsubscript{3} QD degradation, it is adopted to synthesize hydrogenated amorphous silicon nitride (a-SiN\textsubscript{x}:H) encapsulating layers on the CsPbBr\textsubscript{3} QDs. The a-SiN\textsubscript{x}:H encapsulating layers provide long-term stability to the CsPbBr\textsubscript{3} QDs during air exposure, thermal treatment, and immersion in water. In contrast to severe degradation observed from pure CsPbBr\textsubscript{3} QDs under UV illumination, the CsPbBr\textsubscript{3} QDs/a-SiN\textsubscript{x}:H inorganic nanocomposite shows more than fivefolds increase in the PL intensity after UV irradiation for 80 d and long-term stability is observed after continuous UV illumination for at least 140 d.

2. Results and Discussion

Figure 1a illustrates the glow discharge plasma as well as real-time and in situ diagnostics system in the high-frequency plasma-enhanced chemical vapor deposition (HF-PECVD) reactor equipped with an optical emission spectrometer. Different gases including NH\textsubscript{3}, O\textsubscript{2}, NH\textsubscript{3} + SiH\textsubscript{4}, and O\textsubscript{2} + SiH\textsubscript{4} are used to form the plasmas to produce light to excite the CsPbBr\textsubscript{3} QDs to emit green light as shown in Figure 1c. The bright green emission from CsPbBr\textsubscript{3} QDs can be clearly observed from the different plasmas with the naked eye. Prolonged exposure of the CsPbBr\textsubscript{3} QDs to the plasmas causes a decline in green emission and the evolution of the green emission during plasma exposure is studied by acquiring the optical emission spectra (Figure 2). The intensity of the green emission from the CsPbBr\textsubscript{3} QDs decreases rapidly by 80% (10 min)\cite{20} and it is thus apparent that the oxygen plasma causes extensive degradation of the CsPbBr\textsubscript{3} QDs. In fact, degradation in the oxygen plasma is significantly faster than that in air (Figure 5a). It has been shown that oxygen etches some of the unstable CsPbBr\textsubscript{3} QDs and the dissociated ions from the eroded CsPbBr\textsubscript{3} QDs migrate to the stable CsPbBr\textsubscript{3} QDs to foster QD growth\cite{10}. In contrast, the emission intensity from the CsPbBr\textsubscript{3} QD films exposed to an ammonia plasma decreases slightly in the initial stage (Figure 2f,g) and by only 13% after 20 min (Figure 2h and Figure S3, Supporting Information), implying that the ammonia plasma causes less damage than an oxygen plasma. A plasma composed of ammonia in lieu of
oxygen and another gas may be more suitable for depositing the coating on the CsPbBr$_3$ QDs. In fact, ammonia is often combined with silane to form amorphous silicon nitride films at a low temperature as passivation layers in integrated circuits because of the high thermal stability, chemical inertness, and good dielectric properties.$^{[37]}$ Therefore, the effects of combined ammonia and silane plasma exposure on the CsPbBr$_3$ QDs are investigated by OES (Figure 2–l). Similar to the ammonia plasma, the green emission intensity from CsPbBr$_3$ QDs decreases slightly during ammonia and silane plasma exposure initially (Figure 2j,k and Figure S3, Supporting Information). The ammonia/silane plasma has smaller degradation effects on the CsPbBr$_3$ QDs and is more suitable for preparing amorphous silicon nitride (a-SiN$_x$;H) encapsulating layers on the CsPbBr$_3$ QDs. In our comparative experiments involving a silane/oxygen plasma, rapid decrease in the green emission from CsPbBr$_3$ QDs is observed in the initial stage (Figure 2n,o, Figure S3, Supporting Information) and the oxygen-containing plasma destroys the CsPbBr$_3$ QD surface because of oxygen etching.

The environmental and structural stability of the CsPbBr$_3$ QDs with the a-SiN$_x$;H encapsulating layer is assessed. The a-SiN$_x$;H/CsPbBr$_3$ QDs/a-SiN$_x$;H sandwiched structure is first designed to construct the CsPbBr$_3$ QD/a-SiN$_x$;H encapsulating layer films, as shown in Figure 3a. To improve the quality of a-SiN$_x$;H and minimize thermal decomposition of CsPbBr$_3$ QDs, the a-SiN$_x$;H coating process is carried out at 80 °C. Figure 3b shows the cross-sectional scanning electron microscopy (SEM) image of the CsPbBr$_3$ QD/a-SiN$_x$;H nanocomposite and a CsPbBr$_3$ QD film with a thickness of ≈130 nm is covered uniformly by a a-SiN$_x$;H film with a thickness of 15 nm. To coat the CsPbBr$_3$ QDs with as much a-SiN$_x$;H as possible, the thickness of the CsPbBr$_3$ QD films is reduced to ≈11 nm (Figure 3c).

The high-resolution transmission electron microscopy (HRTEM) image in Figure 3d shows that the CsPbBr$_3$ QDs retain the orthorhombic lattice parameter of 0.29 nm along the crystalline direction of (202) before and after deposition of the a-SiN$_x$;H coating. The EDS spectrum and elemental maps of Cs, Pb, Br, Si, and N shown in Figure 4b,c further confirm that the uniform nanocomposite film consists of a CsPbBr$_3$ QDs

Figure 2. Optical emission spectra for different gas plasmas and CsPbBr$_3$ QD films excited by different gas plasmas: a–d) O$_2$ plasma, e–h) NH$_3$ plasma, i–l) NH$_3$ + SiH$_4$ plasma, and m–p) O$_2$ + SiH$_4$ plasma.
a-SiNₓ:H encapsulating layer. The local bonding configurations of the a-SiNₓ:H encapsulating layers are determined by the Fourier-transform infrared (FTIR) spectra in which the intense band at \( \approx 850 \) cm\(^{-1}\) and weak bands at \( \approx 2140 \) and \( 3350 \) cm\(^{-1}\) are assigned to Si–N stretching, Si–H stretching, and N–H stretching, respectively (Figure S4, Supporting Information).[38] a-SiNₓ:H has an optical bandgap of 3.65 eV (Figure S5, Supporting Information) and the emission and absorption spectra of the CsPbBr₃ QDs do not change much after deposition of a-SiNₓ:H (Figure S6, Supporting Information).

The stability of the CsPbBr₃ QDs/a-SiNₓ:H nanocomposites is evaluated in different environments that would normally cause serious degradation in the CsPbBr₃ QDs. Figure 5a shows the PL intensity of the CsPbBr₃ QDs/a-SiNₓ:H nanocomposites as a function of storage time in air. After storing for more than 225 d in air (temperature and humidity from 15 to 30 °C and 40% to 70%, respectively), no apparent PL intensity deterioration is observed from the CsPbBr₃ QDs/a-SiNₓ:H nanocomposites. In fact, the PL intensity increases gradually due to light excitation and this issue will be discussed later in the photostability test. In contrast to the CsPbBr₃ QDs/a-SiNₓ:H nanocomposites, the pure CsPbBr₃ QDs exhibit rapid PL quenching after storage in air for only a few days (Figure 5a).

To evaluate the thermal stability of the CsPbBr₃ QDs/a-SiNₓ:H nanocomposites, we compare the temperature-dependent integrated PL intensity of the pure CsPbBr₃ QDs and CsPbBr₃ QDs/a-SiNₓ:H nanocomposites during heating and cooling cycles. As shown in Figure 5b, thermal quenching...
of PL is clearly observed from both samples as the temperature is increased from 25 to 205 °C. With regard to the pure CsPbBr₃ QDs, approximately 60% decrease in the PL intensity is observed (inset in Figure 5b) and it is generally attributed to growth of QDs during the annealing process.[11] However, for the CsPbBr₃ QDs/a-SiNₓ:H nanocomposites, PL thermal quenching can be recovered after the cooling process and even a small enhancement in the PL intensity is observed after heating and cooling. The PL peak of the CsPbBr₃ QDs/a-SiNₓ:H nanocomposites also exhibits reversible modulation during the heating and cooling cycles (Figure S7, Supporting Information) and the peak returns to the initial position after the heating and cooling cycles. The results demonstrate the remarkably improved thermal stability after deposition of a-SiNₓ:H, similar to that observed from Mn²⁺-doped CsPbBr₃ QDs.[19] Zou et al. reported that incorporation of Mn²⁺ into CsPbBr₃ lattices increased the formation energy of CsPbBr₃ QDs consequently improving thermal stability. However, the improvement here has a different mechanism. It can be attributed to the constraint exerted by the CsPbBr₃ QDs/a-SiNₓ:H interface which not only inhibits the growth of CsPbBr₃ QDs, but also maintains the well-defined crystalline structure with an orthorhombic lattice parameter of 0.29 nm of the pristine CsPbBr₃ QDs in the coated CsPbBr₃ QDs despite repetitive heating and cooling (Figure S8, Supporting Information).

The CsPbBr₃ QDs/a-SiNₓ:H nanocomposite also shows good water resistance. The PL from pure CsPbBr₃ QDs is quenched immediately upon immersion in water, but the coated nanocomposite exhibits stability for at least 9 h (Figure 5c and Figure S9 and Video S1, Supporting information), clearly showing that a-SiNₓ:H is an effective encapsulating layer to protect the CsPbBr₃ QDs from water attack.

In general, fabrication of CsPbBr₃ QDs with long-term photo-stability is challenging because UV light causes the CsPbBr₃ QDs to grow and increases the surface defect states.[10,39] Consequently, the PL intensity from the pure CsPbBr₃ QDs diminishes significantly under continuous UV light (365 nm, 8 W) illumination (Figure S10, Supporting Information). However, after the CsPbBr₃ QDs are coated with a-SiNₓ:H, the PL intensity increases under continuous UV light illumination, a process referred to as photoactivation (Figure 5d).[40] The PL intensity increases by more than five times after UV irradiation for 80 d. Thus, although the PL intensity from pristine CsPbBr₃ QDs drops by ≈60% after coating with the a-SiNₓ:H encapsulating layer at 80 °C, the PL intensity of the nanocomposite is still significantly (1.3 times) larger than that of the pristine CsPbBr₃ QDs after continuous UV illumination for 80 d (Figure S11, Supporting Information). The enhanced PL is stable during subsequent continuous UV illumination for at least 140 d (Figure 5d). The QY of the CsPbBr₃ QDs/a-SiNₓ:H
nanocomposites thin film is about 68%. However, considering the large difference in the refractive indexes between CsPbBr$_3$ (=3.1) and a-SiN$_x$ (=1.9), the fraction of external light is small because most of the emitted light is either absorbed by the various layers or confined in the a-SiN$_x$ layers as guided modes.$^{[41]}$ Therefore, the PL internal quantum efficiency should be much greater than 68%. In spite of the enhanced PL under UV illumination, there is no appreciable shift in the PL peak position (inset in Figure 5d), indicating that the size of the CsPbBr$_3$ QDs coated with a-SiN$_x$:H does not change. Photoactivation has been observed from different types of QDs.$^{[42–46]}$ and is considered to result from photoannealing, light-assisted adsorption of water or photo-oxidation, charged defect passivation, and reorganization of the crystal framework.$^{[42–46]}$ Since the CsPbBr$_3$ QDs are encapsulated with a-SiN$_x$:H layers, light-assisted adsorption of water or photo-oxidation can be neglected. Furthermore, only a small enhancement in the PL intensity can be observed after the nanocomposites are annealed at up to 200 °C (Figure 5b). Therefore, the thermal annealing effect caused by UV light illumination cannot account for photoactivation in this case. In fact, for all-inorganic perovskite QDs, it is believed that photoactivation results from photoinduced structural reorganization and filling of some mid-bandgap trap states by photogenerated charge carriers.$^{[45]}$ According to this mechanism, illumination can transform the dark QDs into bright QDs. Photoinduced conversion from dark QDs to bright QDs will be accelerated during more intense illumination.$^{[45]}$ This is consistent with the observed results that when the nanocomposites are illuminated with stronger light (15.9 W cm$^{-2}$), the time needed to increase the PL intensity by fivefolds is just 120 min as shown in Figure S11 in the Supporting Information and it is significantly shorter than the 80 d required by the nanocomposites during illumination with UV light (0.16 W cm$^{-2}$) as shown in Figure 5d. (Figure 6b). The photoactivity of the nanocomposites is further evaluated by blue LED illumination. Evolution of the PL intensity under strong blue light illumination (15.9 W cm$^{-2}$) shown in Figure S14 in the Supporting Information is similar to that under UV light illumination. However, intense blue light irradiation (15.9 W cm$^{-2}$) for 120 min enhances the PL intensity by five times and the time is much less than that (80 d) under UV light illumination (0.16 W cm$^{-2}$). It is because photinduced conversion from dark QDs to bright QDs is accelerated during intense illumination as discussed above.$^{[45]}$ When the illumination power density is increased to 33.1 W cm$^{-2}$, the PL intensity deteriorates after strong blue illumination for 60 min, but the PL intensity is restored after blue illumination ceases for 160 min.

### 3. Conclusion

Highly luminescent and stable Si-based CsPbBr$_3$ QD thin films are prepared on a glow discharge plasma system with real-time and in situ diagnostics. An ammonia/silane plasma has less destructive effects and is employed to fabricate a-SiN$_x$:H encapsulating layers on the CsPbBr$_3$ QDs. The CsPbBr$_3$ QDs/a-SiN$_x$:H nanocomposite films possess excellent environmental and structural stability as exemplified by the long-term stability during exposure to air for 225 d, at a high temperature of 205 °C in air, and during immersion in water. Moreover, the PL intensity increases by more than five times after UV irradiation for 80 d and it remains stable during continuous UV illumination for 140 d. The nanocomposite films assembled into commercial InGaN chips exhibit strong cold white emission thus demonstrating the commercial potential. Our results reveal an effective and practical way to improve the stability and
PL properties of CsPbBr₃ QD thin films and the technique and materials bode well for development of optoelectronic devices based on inorganic cesium lead halide perovskite QDs.

4. Experimental Section

CsPbBr₃ QD Thin Film Preparation and Plasma Treatment: The solution (10 mg mL⁻¹) of pristine CsPbBr₃ QDs in hexane was purchased from Nanjing MKNANO Tech. Co., Ltd. and the CsPbBr₃ QDs were synthesized according to the procedures described by Protesescu et al. The 10 mg mL⁻¹ CsPbBr₃ QD solution was spin-coated onto a quartz substrate at a rate of 4000 rpm for 30 s. Afterward, the CsPbBr₃ QD films were exposed to different radio frequency (RF)-generated plasmas in a very high frequency plasma-enhanced chemical vapor deposition (VHF-PECVD) system. During the plasma treatment, the pressure was maintained at 30 Pa and the detailed experimental parameters are shown in Table S1 in the Supporting Information.

Glow Discharge Plasma and Real-Time and In Situ Diagnostics System: The system was composed of a VHF-PECVD reactor and Photo Research PR-655 SpectraScan spectroradiometer, as shown in Figure 1a. In the real-time, in situ diagnostics process, the plasma was used to stimulate emission from CsPbBr₃ QDs and the emission was recorded by a Photo Research PR-655 SpectraScan spectroradiometer at room temperature.

Preparation of CsPbBr₃ QD/a-SiNₓ:H Nanocomposites: The a-SiNₓ:H/ CsPbBr₃ QDs/a-SiNₓ:H sandwiched structure was designed to construct CsPbBr₃ QDs/a-SiNₓ:H encapsulating layer films by the VHF-PECVD technique. The a-SiNₓ:H thin films with a thickness of 15 nm were first prepared on silicon wafers and quartz substrates using a gas mixture of SiH₄ and NH₃ as the precursor. The flow rate of SiH₄ was maintained at 3 sccm, while the flow rates of NH₃ were varied 7.5, 10, or 15 sccm so as to tune the optical band gap of a-SiNₓ:H to be between 3.65 and 4.15 ev. The RF power, deposition pressure, and substrate temperature were 30 W, 60 Pa, and 80 °C, respectively. After deposition of the a-SiNₓ:H films, the 0.25 mg mL⁻¹ CsPbBr₃ QD solution was spin-coated onto the substrates at 4000 rpm for 30 s. Finally, the CsPbBr₃ QD films were covered by 15 nm thick a-SiNₓ:H films.

Characterization of CsPbBr₃ QD/a-SiNₓ:H Nanocomposites: The bonding configurations of the nanocomposite were studied by FTIR and the structure was characterized using a Philips X'Pert30 scanning electron microscope and high-resolution transmission electron microscope (Titan 80-300). The film composition was determined by QUANTAX EDS. The absorption measurements were performed in the transmission mode on the Shimadzu UV-3600 spectrophotometer. The continuous PL spectra were acquired on the Jasco UV FluoroLog-3 spectrophotometer equipped with a 450 W continuous Xe lamp and the PL decay curves were recorded on an Edinburgh FLS980 spectrometer. The PLQY was determined by a calibrated integrating sphere (Edinburgh FLS980). The emission spectra and intensity of the corresponding LED were measured using the Photo Research PR-655 SpectraScan spectroradiometer in air and at room temperature.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

amorphous silicon nitride, CsPbBr₃ quantum dots, glow plasma, high stability, plasma enhanced chemical vapor deposition

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Supporting Information


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Supporting Information

**Highly Luminescent and Stable Si-Based CsPbBr$_3$ Quantum Dot Thin Films Prepared by Glow Discharge Plasma with Real-Time and In Situ Diagnosis**

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Table S1. Experimental parameters for the plasma treatment of CsPbBr\textsubscript{3} QD films.

<table>
<thead>
<tr>
<th>Precursors</th>
<th>Flow rate (sccm)</th>
<th>r.f. power (W)</th>
<th>Pressure (Pa)</th>
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<td>30</td>
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<tr>
<td>O\textsubscript{2}</td>
<td>10</td>
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<td>30</td>
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<tr>
<td>SiH\textsubscript{4} + NH\textsubscript{3}</td>
<td>3 + 15</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>SiH\textsubscript{4} + O\textsubscript{2}</td>
<td>3 + 10</td>
<td>30</td>
<td>30</td>
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</table>
Figure S1. PL intensity versus plasma treatment time for different radio frequency (r.f.) power in O₂ plasma treatment of CsPbBr₃ QD films.
Figure S2. PL intensity versus plasma treatment time for different r.f. power in NH₃ plasma treatment of CsPbBr₃ QD films.
Figure S3. Green emission intensity from the CsPbBr$_3$ QD films excited by different plasma gases as a function of plasma treatment time.
**Figure S4.** FTIR spectrum of the a-SiN$_x$:H/CsPbBr$_3$ QDs/a-SiN$_x$:H film with the inset showing the FTIR spectrum of the pristine CsPbBr$_3$ QDs film.
Figure S5. Tauc plots of the a-SiN$_x$:H shell prepared with SiH$_4$ (3 sccm) and NH$_3$ (7.5 sccm) and calculated from the absorption spectra. $E_{\text{opt}}$ is deduced from the Tauc equation $(ahv)^{1/2} = B^{1/2} (hv - E_{\text{opt}})$, where $hv$ is the photon energy and $\alpha$ is the absorption coefficient.$^{[1]}$
Figure S6. Emission and absorption spectra of the CsPbBr$_3$ QDs before and after deposition of a-Si$_x$N$_y$:H.
Figure S7. Temperature-dependent PL spectra of the a-SiNx:H /CsPbBr3 QDs/ a-SiNx:H films for different annealing temperature in the heating-cooling process.
Figure S8. High-resolution TEM image of the CsPbBr$_3$ QD with the a-SiN$_x$:H shell after the heating and cooling process.
Figure S9. PL spectra as a function of time acquired from the CsPbBr$_3$ QDs/a-SiN$_x$:H nanocomposite films immersed in water.
Figure S10. PL intensity of the pristine CsPbBr$_3$ QDs film versus continuous UV (365 nm, 8W) illumination duration.
Figure S11. PL spectra of the CsPbBr$_3$ QDs film before and after deposition of a-SiN$_x$:H films and a-SiN$_x$:H/CsPbBr$_3$ QDs/a-SiN$_x$:H nanocomposite film stored under continuous UV (365 nm, 8 W) illumination for 221 days.
Figure S12. PL decay traces of the CsPbBr$_3$ QDs/ a-SiN$_x$-H nanocomposite film stored while being irradiated continuously with UV (365 nm, 8 W) for 0 day, 5 days, and 165 days, respectively. The decay traces are fitted with the double exponential decay function: $I(t)=I_0+I_1 \cdot \exp(-t/\tau_1)+I_2 \cdot \exp(-t/\tau_2)$, where $I_0$ is the background level and $I_i$ and $\tau_i$ ($i=1,2$) are the amplitude and lifetime of each exponential decay component, respectively.$^{[2]}$
Figure S13. Variation of PL intensity of the CsPbBr$_3$ QDs/a-SiN$_x$:H nanocomposite film during continuous UV (365 nm, 8W) illumination for different time. S1, S2, and S3 represent the a-SiN$_x$:H films with optical bandgaps of 3.65, 3.90, and 4.15 eV, respectively.
Figure 14. Evolution of the PL intensity from the CsPbBr$_3$ QDs/a-SiN$_x$:H nanocomposite film during continuous blue light illumination for different light power density.
References
