Enhanced fluorescence of CsPbBr$_3$/ZnO heterojunction enabled by titanium nitride nanoparticles

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Abstract

We prepared CsPbBr$_3$/ZnO heterojunctions by self-assembling colloidal CsPbBr$_3$ quantum dots (QDs) on the surface of the ZnO film. The fluorescence of CsPbBr$_3$/ZnO heterojunctions was modulated by titanium nitride nanoparticles (TiN NPs) to obtain highly photoluminescent CsPbBr$_3$/TiN/ZnO heterojunctions. The results showed that when the TiN thickness was 51 nm, the fluorescence of the CsPbBr$_3$/TiN/ZnO heterojunction was enhanced by 3.2 times compared to that of the CsPbBr$_3$/ZnO heterojunction. TiN NPs combined most of the photo-generated electrons with the holes on the surface of the TiN/CsPbBr$_3$ heterojunction, which increased the electron transfer rate and reduced non-radiative recombination. This method of enhancing heterojunction fluorescence could provide a new pathway for photovoltaic, light-emitting diode (LED), photodetector, light sensor, and image sensor applications.

1. Introduction

Halide lead perovskite CsPbX$_3$ (X = Br, Cl, I) quantum dots (QDs) have emerged as a promising class of semiconductor materials. Owing to their excellent long-term stability, high electron mobility [1, 2], narrow emission linewidth [3], and high quantum yields [4], CsPbX$_3$ QDs have become promising candidates for application in light-emitting diodes (LEDs) [5, 6], photoluminescence materials [7–9], and optoelectronic devices [10, 11]. Recently, it has been widely reported that CsPbBr$_3$ QDs (photoactive materials) can be combined with other metal oxide semiconductor materials to form heterojunction [12–14].

However, there are many defects and impurities on the surface of metal oxide semiconductors, which can carry traps on the heterogeneous interface, increase non-radiative recombination, and reduce light radiation [14–16], resulting in the suppression of heterojunction fluorescence. Much effort has been devoted to improving the luminous performance of the heterojunctions. Placing either nanoparticles or a thin film on the surface of a metal oxide semiconductor material may help overcome the limitations derived from the intrinsic bandgap of the material [17, 18]. Bai et al. [19] synthesized a CsPbBr$_3$/Au/Al$_2$O$_3$ heterojunction using a self-assembly method. Compared with the CsPbBr$_3$/Al$_2$O$_3$ heterojunction, the fluorescence was enhanced by 2.8 times. The surface plasmon resonance of Au NPs can stimulate the production of hot carriers, which promotes the utilization of photo-generated carriers in the heterojunction of perovskite quantum dots (PQDs) thus enhancing the heterojunction fluorescence [19]. Au NPs are preferred for thermo-electronic applications because of their high carrier concentration. However, its high cost does not lend itself to its mass production. In contrast, another class of highly conductive materials, such as titanium nitride (TiN), zirconium nitride (ZrN), and tantalum nitride (TaN), have an energy band structure similar to that of noble metals [20]. These materials are inexpensive and require a simple preparation method. Therefore, they are promising candidates for effective excitation of hot electrons in the visible region of the spectrum [21–23].
TiN NPs are among the most widely used nanomaterials in optoelectronic devices [24–26]. Because the electronic structure of TiN is composed of ionic bonds, covalent bonds, and metal bands, the p-orbital energy level of nitrogen is lower than the Fermi energy level, resulting in movement similar to that of the free electrons of precious metals such as Au and Ag [27, 28]. Ishii et al [29] prepared planar TiN/ZnO/TiN trailers. Compared with the Au/ZnO/Au structure, the photocurrent prepared with TiN was much larger than that prepared with the Au structure. In addition, TiN is also a quasi-metallic material, and its high conductivity enables it to replace noble metal materials such as Au [30–32] and facilitates carrier transport and collection. The TiN film can also act as a remover that selectively contacts the electro-conductive and hole-blocking effects, promoting carrier separation and extraction [33].

In this work, we prepared TiN/ZnO heterojunctions by depositing TiN NPs on the surface of ZnO thin films using the centrifugal casting method. A CsPbBr3/TiN/ZnO heterojunction was fabricated on a TiN/ZnO surface by colloidal self-assembly of CsPbBr3 QDs. Compared to the CsPbBr3/ZnO heterojunction, the fluorescence of the CsPbBr3/TiN/ZnO heterojunction was enhanced. The role of TiN NPs was to control the direction of electron transfer in the heterojunction to enhance fluorescence. Furthermore, this method does not require complex experimental conditions or chemical processing. This easily scalable and highly reproducible strategy may provide new avenues for the application of large-scale photosensors and photodetectors.

2. Materials and methods

2.1. Preparation of ZnO Sol-gel and ZnO thin film
To prepare the precursor solution, zinc acetate dihydrate (0.5 g, 99.9%, Sigma-Aldrich) and ethanolamine (137.5 μL, 99.5%, Sigma-Aldrich) were dissolved in 2-methoxy ethanol (5 mL, 99.0%, Sigma-Aldrich). The rubber-sealing paste was stirred for 24 h at room temperature. Using a 1.5 cm × 1.5 cm × 0.5 mm polished silicon wafer as a substrate, the Si substrate was treated before cleaning. The substrate was cleaned with a 2:1 volume ratio of HF:H2O (1:5 g, 99.0%, Sigma-Aldrich) prepared planar TiN/ZnO/TiN trailers. Compared with the Au/ZnO/Au structure, the photocurrent prepared with TiN was much larger than that prepared with the Au structure. In addition, TiN is also a quasi-metallic material, and its high conductivity enables it to replace noble metal materials such as Au [30–32] and facilitates carrier transport and collection. The TiN film can also act as a remover that selectively contacts the electro-conductive and hole-blocking effects, promoting carrier separation and extraction [33].

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2.2. Fabrication of CsPbBr3/ZnO heterojunction
Raw colloidal CsPbBr3 QDs were prepared using the heat injection method (in the supplementary information (available online at stacks.iop.org/MRX/9/026406/mmedia)). S1 shows a flow chart of the synthesis of colloidal CsPbBr3 QDs. The average size of the single CsPbBr3 QDs was 9.55 nm in S2 (in the supplementary Information). The CsPbBr3 QDs stock solution was diluted with n-hexane at a ratio of 1:10 to the CsPbBr3 QDs solution and pasted the ZnO film on the inner side of the cuvette with double-sided tape. The CsPbBr3 QDs solution was slowly added and the concave surface of the liquid was sufficient to cover the entire film. As the solvent continued to evaporate, CsPbBr3 QDs self-assembled on the surface of the ZnO film. Took it out gently, put it into the vacuum drying oven at 80 °C to dry and ready for use.

2.3. Fabrication of CsPbBr3/TiN/ZnO heterojunction
The process for preparing the CsPbBr3/TiN/ZnO heterojunction was shown in figure 1. The ZnO film substrate was placed in a 50 ml centrifuge tube and tilted slightly, followed by the addition of TiN (particle size of approximately 20 nm, 99.0%, Aladdin) solution (TiN NPs were dispersed in deionized water by sonication at concentrations of 1, 3, and 10 μg mL⁻¹). This tube was then centrifuged at 8,000 rpm for 20 min, the clear supernatant was discarded, the substrate was gently removed from the tube, and uniform deposition of TiN NPs on the surface of the ZnO film was observed. The films were further dried in a vacuum drying oven at 80 °C to allow complete evaporation of the deionized water from the films. The CsPbBr3 QD stock solution and n-hexane were diluted at a ratio of 1:10, and the TiN/ZnO film was pasted on the inner side of the cuvette with double-sided tape. The diluted CsPbBr3 QD solution was slowly added and the concave surface of the liquid was sufficient to cover the entire film. As the solvent continued to evaporate, CsPbBr3 QDs self-assembled on the surface of the TiN/ZnO film; Took it out gently, put it into a vacuum drying oven at 80 °C for drying and ready for use.

2.4. Characterizations
The optical quality of the film was characterized by a custom PL system, which included a continuous 365 nm wavelength laser (LLS365, Ocean Optics) as the excitation source and a fiber optic spectrometer (QE6500, Ocean Optics). The crystal structure of the CsPbBr3 QDs and ZnO films were characterized using an x-ray diffractometer (XRD, Smart Lab XG, Rigaku). The morphology of CsPbBr3 was observed using transmission
3. Results and discussion

3.1. Surface morphology and optical properties of ZnO film at different annealing temperatures

Figures 2(a)–(d) showed the AMF morphology for different annealing temperatures (150 °C, 200 °C, 250 °C, 300 °C) (see inset). The root mean square values of the surface roughness of the ZnO films annealed at different temperatures were 11, 2.59, 2.57 and 3.39 nm, respectively. The surface roughness indicated that better flatness of ZnO film could be obtained when the annealing temperature was 250 °C.

The surface morphology of the ZnO film annealed at 150 °C showed a striped structure (as shown in figure 2(a)), due to the greater activity of the ZnO NPs in the film, there was a greater chance of collisions between the particles, causing them to agglomerate [34]. When the annealing temperature was increased, the striped structures of the clusters disappeared. The gradual decrease in ZnO surface activity was attributed to the decrease in organic matter in the ZnO film. However, when the annealing temperature exceeded 250 °C, the organic matter on the surface of ZnO was completely evaporated, and the roughness of the ZnO film was increased with the boosting temperature [35]. The XRD patterns of ZnO film annealed at different temperatures were shown figure 3(a). Obviously, the characteristic peaks at 31.76°, 34.42°, and 36.25° correspond to the (100), (002), and (101) diffractions of the ZnO film, respectively, and match well with PDF # 36–1451 [36]. When the annealing temperature was set at 250 °C, the primary peaks became stronger and sharper, indicating that they had the better crystal quality. The Raman spectra of ZnO film annealed at different temperatures were shown in figure 3(b). The scattering peaks located at 330 cm\(^{-1}\), 378 cm\(^{-1}\), and 435 cm\(^{-1}\) originate from the second-order phonon modes and E\(_{21}\) phonon modes, respectively [37].

3.2. Surface characteristics of TiN/ZnO heterojunction

As shown in figure 4(a), TiN NPs were deposited on the surface of ZnO under the action of centrifugal force, and the positive charges caused by the oxygen vacancies on the surface of the ZnO film could adsorb the negatively charged TiN NPs. The surface topography of the TiN NPs sample was obtained by SEM, and it can be clearly seen from figure 4(b) that a large number of almost spherical TiN NPs were deposited uniformly on the substrate.[38] From the particle size distribution, the average particle size was calculated and found to be approximately 21.06 nm, which was basically consistent with the original particles in figure 4(c). The same method was used to deposit different concentrations of TiN NPs on the surface of ZnO, which were 1, 3, and 10 \(\mu g\) ml\(^{-1}\), respectively. The SEM images of different concentrations of TiN NPs were shown in S3 (supplementary information). In the inset, it was observed that the particle size of TiN NPs hardly changed. The thickness of TiN NPs deposited at different concentrations. It can be seen that the thickness of the TiN NPs increased with the increase of concentration. We measured the thicknesses of the TiN NPs deposited under the same conditions, as shown in figure 4(d), with corresponding film thicknesses of 51, 96, and 151 nm, for TiN NPs concentrations of 1, 3, and 10 \(\mu g\) ml\(^{-1}\), respectively.
3.3. Surface characteristics of CsPbBr$_3$/ZnO heterojunction and CsPbBr$_3$/TiN/ZnO heterojunction

The SEM image of the surface morphology of the CsPbBr$_3$/ZnO heterojunction was shown in figure 5(a). The CsPbBr$_3$ QDs and their clusters were clearly observed in figure 5(b). The size of a single CsPbBr$_3$ QD was vertically 11.5 nm [39], which was in agreement with the raw material of CsPbBr$_3$ QDs in S2 (Supplementary Information). Compared with CsPbBr$_3$/ZnO heterojunctions, the surface of the CsPbBr$_3$/TiN/ZnO heterojunction was flatter than that of the CsPbBr$_3$/ZnO heterojunction, as shown in figures 5(c)–(d). The lateral size of the CsPbBr$_3$ QD clusters was reduced from 106 nm to 81 nm. The uniform distribution of CsPbBr$_3$ QDs on the TiN/ZnO surface was due to the fact that the TiN NPs change the surface affinity of the ZnO film, making it unable to agglomerate on the TiN/ZnO surface. The white spheres observed in figure 5(c) may have

![Figure 2](image1.png)

Figure 2. AFM images of ZnO film annealed at different temperatures (a) 150 °C, (b) 200 °C, (c) 250 °C, (d) 300 °C.

![Figure 3](image2.png)

Figure 3. (a) XRD 2θ scan pattern of ZnO film at different annealing temperatures; (b). Raman spectra of ZnO film at different annealing temperatures.
been caused by the incomplete coverage of TiN NPs by CsPbBr3 QDs. Compared to figure 4(b), it can be clearly observed that the CsPbBr3 QDs were covered around the TiN NPs.

3.4. PL spectrum analysis of CsPbBr3/ZnO heterojunction and CsPbBr3/TiN/ZnO heterojunction

We measured the PL spectra of CsPbBr3, ZnO film, CsPbBr3/ZnO and CsPbBr3/TiN/ZnO heterojunctions using a customized PL system at room temperature, as shown in figure 6(a). The PL peak of the CsPbBr3 film exhibited a single-peak distribution, with a peak at 510 nm. The PL spectrum of the ZnO film consists of two emission peaks, one being the excitonic emission peak at 372 nm and the other a broad peak caused by the deep-level emission of surface oxygen vacancies in the visible range of 426–700 nm [40]. Similarly, the CsPbBr3/ZnO heterojunction also exhibited two PL spectra: one was the excitonic emission peak at 372 nm, and the other was continuously distributed in the visible region from 463 nm to 675 nm, which was due to the self-assembly of CsPbBr3 QDs on the surface of the ZnO film to form a CsPbBr3/ZnO heterojunction. Most of the energy from the colloidal CsPbBr3 QDs was transferred to the ZnO film, and some of the photo-carriers were quenched on the ZnO surface [41]. Another part of the photo-generated carriers underwent electron-hole reconstruction at the ZnO defects, which enhanced the defect fluorescence of ZnO [42]. However, the enhancement of the interface fluorescence was relatively small. The photo-generated carriers were significantly lost during the transportation process, which reduced the carrier utilization.

To suppress the defect fluorescence of the CsPbBr3/ZnO heterojunction, TiN NPs were added between the CsPbBr3 QD film and ZnO film as a storage medium for photo-generated carriers [43]. The PL spectra of the CsPbBr3/TiN/ZnO heterojunction were significantly stronger than those of the CsPbBr3/ZnO heterojunction. This further confirms that TiN NPs promoted the utilization of photo-generated carriers.

To clearly observe the enhanced fluorescence of differential heterojunctions, we drew a bar diagram at the peak fluorescence of ZnO, CsPbBr3/ZnO, and CsPbBr3/TiN/ZnO heterojunctions sand the bar diagram, as shown in figure 6(b). Compared to the ZnO and CsPbBr3/ZnO heterojunctions, the fluorescence of the CsPbBr3/TiN/ZnO heterojunctions was enhanced. Owing to the induction of TiN NPs. The photo-generated carriers of CsPbBr3 QDs were transferred to the ZnO film to increase the peak fluorescence and interfacial fluorescence of the two heterojunctions. TiN NPs played a more important role in promoting the transfer of photo-generated carriers.

As shown in figure 6(c), the PL spectra of the CsPbBr3/TiN/ZnO heterojunction were the most intense when the thickness of the TiN NPs was 51 nm, and the PL spectral intensity of the CsPbBr3/TiN/ZnO
heterojunction varied with the thickness of the deposited TiN NPs. The PL spectra first increased and then decreased with an increase in the deposited thickness of TiN NPs. To compare the PL enhancement effect on the surface of the CsPbBr$_3$/TiN/ZnO heterojunction, the enhancement coefficient plot shown in figure 6(d) shows that the maximum enhanced fluorescence was 3.2 times higher than that of the CsPbBr$_3$/ZnO heterojunction.

Compared with the fluorescence of the CsPbBr$_3$ film in figure 6(a), the fluorescence peak of the TiN/CsPbBr$_3$ interface radiation was obviously red-shifted, because the Fermi level of TiN was lower than that of the CsPbBr$_3$ film, and the electrons in the conduction band of CsPbBr$_3$ moved toward TiN/CsPbBr$_3$ interface transfer, and the interface electron-hole recombination occurred below the conduction band of the CsPbBr$_3$ film to radiate fluorescence. Comparing the fluorescence peak intensities of CsPbBr$_3$/TiN/ZnO heterojunctions with different deposition thicknesses, the fluorescence peaks gradually weakened with the increasing of deposition thickness. The analysis shows that with an increase in the TiN NPs concentration, more TiN NPs were deposited on the surface of ZnO, and the TiN film became thicker, which blocked the transport of photo-generated carriers between the CsPbBr$_3$ QDs film and the ZnO film. The carriers were more easily consumed during the transport process, resulting in a decrease in the number of electron-hole recombination at the heterojunction interface.

3.5. The physical mechanism analysis of enhanced fluorescence of CsPbBr$_3$/ZnO and CsPbBr$_3$/TiN/ZnO heterojunctions

The energy level diagram of the material-dependent band positions of the CsPbBr$_3$/ZnO heterojunction is shown in figure 7(a). Energy level diagrams help understand the charge carrier dynamics and transport mechanisms in heterojunctions. The ZnO band gap and work function were 3.3–3.4 eV [44, 45] and 4.3–4.9 eV [46], respectively. The band gap and work function of CsPbBr$_3$ were 2.4–2.5 eV [47, 48] and 3.7 eV [49], respectively. The energy transfer process of the CsPbBr$_3$/ZnO heterojunction can be understood as: (1) The electrons of the CsPbBr$_3$ QDs and ZnO film were simultaneously pumped to their conduction band level ($E_C$) by a 365 nm laser, leaving holes in the valence band level ($E_V$). Because the CBs of CsPbBr$_3$ QDs were larger than

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**Figure 5.** AFM surface morphologies of CsPbBr$_3$/ZnO and CsPbBr$_3$/TiN/ZnO heterojunctions. (a). AFM morphology of CsPbBr$_3$/ZnO heterojunction; (b). The size distribution of CsPbBr$_3$ QDs on the surface of CsPbBr$_3$/ZnO heterojunction; (c). AFM morphology of CsPbBr$_3$/TiN/ZnO heterojunction; (d). The size distribution on the surface of CsPbBr$_3$/TiN/ZnO heterojunction.
those of ZnO defects, the excited hot electrons and $E_C$ electrons were easily transported to the $E_C$ of ZnO defects through diffusion effects and built-in electric fields, while holes also accumulate at their interfaces. (2) $E_C$ electrons and holes recombined to emit fluorescence. The higher the photo-carrier density, the more fluorescent
photons were radiated at the ZnO interface. Owing to the electron transfer of CsPbBr₃ QDs, the fluorescence intensity of the ZnO film was enhanced, whereas that of the CsPbBr₃ QDs was reduced. (3) Some of the electrons that were not transferred to the interface fall back into their $E_V$, recombine with holes, and emit intrinsic fluorescence. Therefore, exciton fluorescence of CsPbBr₃ QDs can also be observed.

The Fermi level of TiN on oxides was 4.2 – 4.3 eV, [50] and the work function was 4.2–4.6 eV [33, 51]. It was clear from the schematic in figure7 (b) that a small Schottky barrier was formed between TiN and ZnO. Under appropriate UV irradiation, both TiN and ZnO generate charge carriers through their respective inter-band transition processes. Then, the charge carriers from TiN can be easily injected into the $E_C$ of ZnO, thereby enhancing the hole recombination of carriers in the ZnO $E_V$. [50] The energy transfer process of the CsPbBr₃/TiN/ZnO heterojunction can be understood as: (1) A 365 nm laser simultaneously excites the ZnO surface and CsPbBr₃ QDs to facilitate the separation of their electron-hole pairs. Electrons were then pumped to their corresponding $E_C$, leaving holes in their $E_V$. Hot electrons above its $E_C$ may be transferred to its interface and fall directly from its $E_C$ to emit fluorescence. A reduced recombination rate was considered an effective way to enhance interfacial radiation. (2) The organic molecules on the surface of TiN NPs and colloidal CsPbBr₃ QDs can store electrons and holes,[52] reduce the direct recombination of electron-hole pairs on the corresponding $E_C$ and $E_V$, and increase the number of different interface carriers. The electron trap effect of TiN NPs can capture more hot electrons, $E_C$ electrons, and defect electrons on the heterojunction to migrate to the CsPbBr₃ QDs interface and the interface of the ZnO film, and achieve potential equilibrium through electrons. (3) The up-and-down transfer of electrons in the s-p band to the Fermi energy was beneficial to the energy utilization of fluorescence and increased the number of interface electrons. The d-band electrons from TiN NPs can absorb the fluorescence energy of CsPbBr₃ QDs, and ZnO film were pumped to their s-p bands to enhance the interfacial radiation. (4) With an increase in the number of surface electrons in TiN NPs, the interfacial recombination of electrons and holes leads to enhanced interfacial radiation. [53, 54] We observed fluorescence enhancement at 376 nm for the ZnO film and at 519 nm for the CsPbBr₃ QDs. The enhanced fluorescence was due to the transfer of photo-generated carriers through carrier diffusion, as well as the trap and electron conductor effects of TiN. Owing to the existence of surface plasmons in the surface state of the TiN NPs, [29, 55] the hot electrons of the higher $E_C$ of the CsPbBr₃ QDs with higher $E_C$ were directly swept and transferred to the $E_C$ in the defect state of the ZnO film. Only a small fraction of the electrons fell and recombined with holes. Therefore, the defect fluorescence was weakened due to the inhibitory effect of TiN NPs.

4. Conclusion

In summary, CsPbBr₃/ZnO and CsPbBr₃/TiN/ZnO heterojunctions were prepared using colloidal self-assembly and centrifugal casting methods, and the PL effect of TiN NPs on the CsPbBr₃/ZnO heterojunction was fully studied. Compared with the CsPbBr₃/ZnO heterojunction, the fluorescence of the CsPbBr₃/TiN/ZnO heterojunction was enhanced by 3.2 times with a thickness of TiN film of 51 nm. This was attributed to the surface plasmon state of TiN NPs serving as an intermediate energy level between CsPbBr₃ QDs and ZnO, which improved the electron transfer rate at the heterojunction interface and reduced non-radiative reconstruction. However, as the deposition thickness of the TiN NPs was increased, the photo-generated carriers of CsPbBr₃ QDs were more easily lost during the transfer process, resulting in the wreaking of the radiation fluorescence of the heterojunction CsPbBr₃/TiN/ZnO being wreaked. This method of fluorescence enhancement and energy transfer can be widely used in photovoltaics, photodetectors, LEDs, light sensing, and photocatalysis.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

[1] Ghosh J, Mawlong L P, Manasa G, Pattison A J, Theis W, Chakraborty S and Giri P 2020 Solid-state synthesis of stable and color tunable cesium lead halide perovskite nanocrystals and the mechanism of high-performance photodetection in a monolayer MoS2/CaPbBr3 vertical heterojunction J. Mater. Chem. C 8 3917–3934
[2] Yu J, Liu G, Chen G, Li Y, Xu M, Wang T, Zhao G and Zhang L 2020 Perovskite CaPbBr3 crystals: growth and applications J. Mater. Chem. C 8 6326–6341
[3] Shen Z, Song P, Qiao B, Cao J, Bai Q, Song D, Xu Z, Zhao S, Zhang G and Wu Y 2019 Impeding anion exchange to improve composition stability of CaPbX3 (X = Cl, Br) nanocrystals through facilely fabricated CaPbBr6 shell Chin. Phys. B 28 086102
[4] Li et al 2018 Identification and modulation of electronic band structures of single-phase β-AlxGa1–xO3 alloys grown by laser molecular beam epitaxy Appl. Phys. Lett. 113 041901
[5] Zhang C, Wang S, Li X, Yuan M, Turyanska L and Yang X 2020 Core/shell perovskite nanocrystals: synthesis of highly efficient and environmentally stable FAPbBr3/CaPbBr3 for LED applications Adv. Funct. Mater. 30 1901582
[6] Su H, Zhu K, Qin J, Li M, Zuo Y, Wang Y, Yu C, Cao J and Li G 2021 Large-area fabrication: the next target of perovskite light-emitting diodes Chin. Phys. B 30 085650
[7] Shinde A, Gohlaut R and Mahamuni S 2017 Low-temperature photoluminescence studies of CaPbBr3 quantum dots The Journal of Physical Chemistry C 121 14872–8
[8] Chen X, Zhang F, Ge Y, Shi L, Huang S, Tang J, Lv Z, Zhang L, Zou B and Zhong H 2018 Centimeter-sized CaPbBr6 crystals with embedded CaPbBr3 nanocrystals showing superior photoluminescence: nonstoichiometry induced transformation and light-emitting applications Adv. Funct. Mater. 28 1706567
[9] Yao Z, Liang X, Hu X and Fan J 2021 Green and efficient photodegradation of norflaxacin with CaPbBr3-rGO/Bi2WO6 S-scheme heterojunction photocatalyst Colloids Surf., A 628 120798
[10] Wang R, Zhou H, Wu B, Diao T, Wu L, Wang H, Peng X, Zhang J and Wang H 2021 Self-powered CaPbBr3 perovskite nanonet photodetector with a hollow vertical structure The Journal of Physical Chemistry Letters 12 7519–23
[11] Guo L, Gu Y, Yang Z, Tian S, San X, Liu J, Gao L, Qiao S and Wang S 2021 CaPbBr3 QDs modified vertically layered MoS2/Si heterojunction for fast UV–vis–NIR spectrum flexible photodetectors Adv. Mater. Interfaces 8 2002231
[12] Guo Z.-a., Zhang B, Li H, Ming H, Bala H, Yao S, Zhang J, Fu W, Cao J and Sun G 2020 Visible light responsive CaPbBr3/TiO2 photocatalyst with long-term stability in aqueous solution Mater. Lett. 274 128041
[13] Liu J, Liu F, Liu H, Yue J, Jin J, Impundu J, Liu H, Yang Z, Peng Z and Wei H 2021 Mixed-dimensional CaPbBr3@ZnO heterostructures for high-performance pn diodes and photodetectors Nano Today 36 101055
[14] Liu Z, Chen J, Huang C, Kiprono T G, Zhao W, Qiu W, Peng Z and Chen J 2020 Dependence of precursors on solution-processed SnO2 as electron transport layers for CaPbBr3 perovskite solar cells Nano lett. 20 2050161
[15] Zhu E, Zhao Y, Dai Y, Wang Q, Dong Y, Chen Q and Li D 2020 Heterojunction-type photocatalytic system based on inorganic halide perovskite CaPbBr3 Cl, J. Chem. 38 1718–22
[16] Li C, Han C, Zhang Y, Zang Z, Wang M, Tang X and Du J 2021 Enhanced photoresponsivity of self-powered photodetector based on ZnO nanoparticles decorated CaPbBr3 films Sol. Energy Mater. Sol. Cells 172 341–346
[17] Linic S, Aslam U, Boerigter C and Morabito M 2015 Photochemical transformations on plasmonic metal nanoparticles Nat. Mater. 14 567–576
[18] Wang Z, Shao L-P, Peng M, Bai Z-C, Zhang Z-P and Qin S-J 2019 Fluorescence spectra of colloidal self-assembled CdSe nano-wire on substrate of porous AuO3/Au nanoparticles Chin. Phys. B 28 068103
[19] Bai Z, Wang X, Zhang Z and Qin S 2020 Enhanced photoluminescence of a CaPbBr3/AZO film heterojunction enabled by coupling of gold nanoparticles Mater. Res. Express 7 106201
[20] Kumar M, Umekawa N, Ishii S and Nagaoka T 2016 Examining the performance of refractory conductive ceramics as plasmonic materials: a theoretical approach ACS Photonics 3 43–50
[21] Chen N, Lien W, Liu C, Huang Y, Lin Y, Chou C, Chang S and Ho C 2011 Excitation of surface plasma wave at TiN/air interface in the Kretschmann geometry Appl. Phys. Lett. 109 043104–043104
[22] Xu X, Dutta A, Khurjik J, Wei A, Shalaev V M and Boltasseva A 2020 TiN@TiO2 core–shell nanomaterials as plasmon-enhanced photosensitizers: the role of hot electron injection Laser Photonics Rev. 14 1900376
[23] Wan Y 2020 Modulation of localized surface plasmon resonance of the nanofluidic nanoparticle array based on graphene Optik 200 165420
[24] Khemiripour Z, Mahani F F and Mohkhtari A 2020 Performance improvement of thin-film silicon solar cells using transversal and longitudinal titanium nitride plasmon nanorobics Opt. Mater. 99 109532
[25] Xu C, Qiu G, Ng S P and Wu C-M L 2020 Nanostructured titanium nitride for highly sensitive localized surface plasmon resonance biosensing Ceram. Int. 46 20993–20998
[26] Messaid B E, I. Paven C, Talaighil R Z, Benzeraga R, Le Gendre L, Marlec F and Bensouici F 2020 Optimization of a rear system based on titanium nitride for a flexible CunS2 solar cell Optik 206 164355
[27] Gui L, Bagheri S, Strohfeldt N, Hentschel M, Zgrabik C M, Metzger B, Linnenbank H, Hu E L and Giessen H 2016 Nonlinear refractive plasmonics with titanium nitride nanoantennas Nano Lett. 16 5708–13
[28] Naldoni A, Guler U, Wang Z, Marelli M, Malara F, Meng X, Besteiro L V, Govorov A O, Kildishev A V and Boltasseva A 2017 Broadband hot-electron collection for solar water splitting with plasmonic titanium nitride Adv. Opt. Mater. 5 1601031
[29] Ishii S, Shinde S L, Jevasawun W, Fukuta N and Nagaoka T 2016 Hot electron excitation from titanium nitride using visible light ACS Photonics 3 1552–1560
[30] Venugopal N, Gerasimov E, Ershov A, Karpov S and Polyutov S 2017 Titanium nitride as light trapping plasmonic material in silicon solar cell Opt. Mat. 72 397–402
[31] Pan J, Pałchek R M, Judd FF and Baxter J B 2006 Effect of chromium–gold and titanium–titanium nitride–platinum–gold metallization on wire/ribbon bondability IEEE Trans. Adv. Packag. 29 707–13
[32] Guo W-P, Mishra R, Cheng C-W, Wu B-H, Chen L-J, Lin M-T and Gwo S 2019 Titanium nitride epitaxial films as a plasmonic material platform: alternative to gold as ACS Photonics 6 1848–54
[33] Liu Z, Liu X, Hou G, Chen J, Zhu T, Xu J and Chen K 2020 Doping-free titanium nitride carrier selective contacts for efficient organic–inorganic hybrid solar cells ACS Appl. Energy Mater. 3 9208–15
[34] da Silva B L, Abucafy M P, Manaia E B, Junior J A O, Chiari-Andréo B G, Pietro R C R and Chiavacci L A 2019 Relationship Between Structure And Antimicrobial Activity of Zinc Oxide Nanoparticles: An Overview 14 9393
[35] Toe M Z, Matsuda A, Han S S, Yaacob K A and Pung S Y 2020 Effect of annealing temperature on the performance of ZnO thin film deposited dye sensitized solar cell, AIP Conf. Proc., AIP Publishing LLC: 2020; p 020010 [https://doi.org/10.1063/5.0015699]

[36] Kathwate L, Umadevi G, Kulal P, Nagaraju P, Dubal D, Nanjundan A, Mote V J S and Physical A A 2020 Ammonia Gas Sensing Properties of Al doped ZnO Thin Films 313 112193

[37] George L and Shahi M 2021 In Electrochemical gating of CVD graphene–ZnO based transistor, AIP Conf. Proc., AIP Publishing LLC: 2021; p 020014 [https://doi.org/10.1063/5.0052570]

[38] Popov A A, Tselikov G, Dumas N, Berard C, Metwally K, Jones N, Al-Kattan A, Larrat B, Brugier D and Mensah S J S R 2019 Laser-Synthesized TiN Nanoparticles As Promising Plasmonic Alternative For Biomedical Applications 9 1–11

[39] Ge W, Shi J, Xu M, Wu Y and Fu J J J O M 2021 Dual Modulating Luminescence In All-Inorganic Perovskite CsPbBr3 Quantum Dots 113 110822

[40] Wang S, Zhu Z, Zou Y, Dong Y, Liu S, Xue J, Xu L, Dong Y and Song J 2020 A low-dimension structure strategy for flexible photodetectors based on perovskite nanosheets/ZnO nanowires with broadband photoresponse Science China Materials 63 100–9

[41] Liu H, Zhang X, Zhang L, Yin Z, Wang D, Meng J, Jiang Q, Wang Y and You J 2017 A high-performance photodetector based on an inorganic perovskite–ZnO heterostructure J. Mater. Chem. C 6 6115–22

[42] Narayanan N and Deepak N 2018 Realizing luminescent downshifting in ZnO thin films by Ce doping with enhancement of photocatalytic activity Solid State Sci. 78 144–55

[43] Mascaretti L, Dutta A, Kment S, Shahlev V M, Boltasseva A, Zbofil R and Naldoni A 2019 Plasmonic-enhanced photoelectrochemical water splitting for efficient renewable energy storage Adv. Mater. 31 1805513

[44] Cheng B, Ouyang Z, Chen C, Xiao Y and Lei S J S R 2013 Individual Zn 2 SnO 4–Sheath ZnO Heterostructure Nanowires For Efficient Resistive Switching Memory Controlled by Interface States 3 1–6

[45] Ismail M, Rahmani M K, Khan S A, Choi J and Kim S J 1 A S S 2019 Effects of Gibb’s Free Energy Difference and Oxygen Vacancies Distribution In A Bilayer ZnO/ZrO2 Structure For Applications To Bipolar Resistive Switching 498 145383

[46] Liu L, Diao Y and Xia S 1 J S R 2021 Feasibility Study on Si-doped ZnO with Cs Coating Surface For Solar Cell Anode 214 189–95

[47] Chen W, Xin X, Zang Z, Tang X, Li C, Hu W, Zhou M and Du J J O S S C 2017 Tunable Photoluminescence of CsPbBr3 Perovskite Quantum Dots For Light Emitting Diodes Application 255 115–20

[48] Yu Y, Zhou Y, Zhang Y, Zhang Y, Liu X, Liang X, Liu J, Chen S and Xiang W J J O L 2021 Novel CsPbX3@ Mica Composites With Excellent Optical Properties For High Efficiency And Wide Color Gamut White Light Emitting Diode 236 118129

[49] Guo M, Bo J, Chen X, Wan P, Chen M, Li Q, Luo C, Chen Y and Chen S J A E M 2021 Perovskite Solar Cells with Front Surface Gradient 11 2101080

[50] Poddar S, Bora J, Thakur S, Gogoi D, Basumary B, Borah S M, Adhikary N C and Pal A R J M 2022 Physics, Interband Transition in Plasmonic Titanium Nitride and its Contribution Towards ZnO-based Pyro-Phototronic Application 275 125290

[51] Podd E S and Pal A R J O M 2019 Hot Carrier Devices Using Visible and NIR Responsive Titanium Nitride Nanosheets With Stoichiometry Variation 97 109379

[52] Achiour A, Porto R L, Soussou M A, Islam M, Boujita M, Aissa K A, Le Brizoual L, Djouadi A and Brousse T J J O P S 2015 Titanium Nitride Films For Micro Supercapacitors: Effect of Surface Chemistry and Film Morphology On The Capacitance 300 525–32

[53] Gherman A M M, Vladescu A, Kiss A E and Farcau C 2020 Extraordinary optical transmission through titanium nitride-coated microsphere lattice Photonics and Nanostructures-Fundamentals and Applications 38 100762

[54] Lim B K, Park H S, See A K, Liu E Z and Wu S H 2002 Comparison of in situ and ex situ photo-deposition titanium nitride thin films J. Vac. Sci. Technol. B 20 2219–24

[55] Asencios J, Moro R, Luoy C and Talledo A 2020 High sensitive biosensors based on the coupling between surface plasmon polaritons on Titanium nitride and a planar waveguide mode Sensors 20 1784