Enhanced Photostability and Photoluminescence of PbI$_2$ via Constructing Type-I Heterostructure with ZnO

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Improving the stability of lead iodide (PbI$_2$), especially photostability, is in crucial demand for the realization of application-level optoelectronic devices. In this regard, deposition of organic polymers on PbI$_2$ as a protective layer is a common strategy to improve its stability, but polymers with low thermal conductivity generally cannot produce the desired effect. Herein, a novel strategy is proposed for improving the photostability of PbI$_2$ at different excitation wavelengths, including 320, 405, and 532 nm, via constructing type-I heterostructure with ZnO with high thermal conductivity. In addition, due to the type-I band alignment between PbI$_2$ and ZnO, the photogenerated carriers in ZnO can be transferred to PbI$_2$, resulting in a nearly eightfold photoluminescence enhancement of PbI$_2$ under 320 nm laser excitation. The ZnO as a protective layer forming type-I heterostructure is evidenced as a feasible strategy for enhancing the photostability and photoluminescence of PbI$_2$, facilitating the development of practical applications.

1. Introduction

Since the discovery of graphene, 2D materials have attracted significant attention in basic sciences and promising applications in electronics, valleytronics, optoelectronics, and sensors, due to their unique physical and chemical properties. Apart from graphene, there are many other semiconducting or insulating materials in the family of 2D materials, such as hexagonal boron nitride (h-BN), black phosphorus (BP), transition metal oxides (TMOs), transition metal dichalcogenides (TMDs), and so forth. Among them, TMDs materials with a rich variety of electronic and optical characters had been widely studied over the past decade in optoelectronic devices. However, the bandgap transition of TMDs is quite sensitive to its thickness, where the bandgap could crossover from indirect to direct only when the thickness of TMDs thins down to monolayer. Unfortunately, the relatively low absorbance in the monolayer TMDs system limits the further improvement of their optoelectronic device performances.

Compared with TMDs materials, lead iodide (PbI$_2$) is also a layered semiconductor but exhibits an opposite bandgap dependence with TMDs, where the band structure of PbI$_2$ shifts from direct to indirect bandgap as the thickness decreases from multilayer to monolayer. Therefore, PbI$_2$ could become a good supplement for the existing TMDs and other 2D optoelectronic materials. In addition, PbI$_2$ has a wider bandgap, higher light absorption coefficient, and better perseverance of direct bandgap than TMDs materials and has potential applications in nuclear radiation detectors, low-threshold lasers and high-efficiency photodetectors. However, there is a fly in the ointment, that is, the stability, especially photostability, of PbI$_2$ is inferior to that of TMDs materials. The poor photostability of PbI$_2$ would result in its structural damage and property degradation upon laser irradiation and obstruct its progress of practical applications. Regrettably, so far, the improvement of photostability of PbI$_2$ has not been effectively solved yet. One common strategy of protecting PbI$_2$ is to deposit organic polymers as encapsulation layers, such as polydimethylsiloxane (PDMS), but the relatively low thermal conductivity of these polymers cannot produce a desired improvement in the photostability of PbI$_2$. Therefore, it is urgent to seek a more effective strategy to prevent the PbI$_2$ from suffering structural damage and property degradation upon laser irradiation, and meanwhile maintain its photon absorption and radiation.

In this work, we have proposed a novel and feasible strategy for improving the photostability of PbI$_2$ via the construction of type-I heterostructure with ZnO with high thermal conductivity. In the PbI$_2$/ZnO heterostructure, the photostability of PbI$_2$ can be improved at different excitation wavelengths, including 320, 405, and 532 nm. The essential reason for the improvement of
photostability is that the ZnO offers the desired path of heat dissipation for PbI₂, which benefits from the high thermal conductivity of ZnO that is approximately two orders of magnitude higher than organic polymers. More impressively, the photoluminescence (PL) of PbI₂ in the heterostructure demonstrates nearly eightfold PL enhancement compared with the pristine PbI₂ because the photogenerated electrons and holes can be transferred from the ZnO to the PbI₂ due to the type-I band alignment. This work not only opens up a novel and feasible strategy to improve the photostability and PL of PbI₂, but also minimizes the negative influences from the protective layer and obtains significant PL enhancement of PbI₂.

2. Results and Discussion

Compared with TMDs materials, 2D layered PbI₂ has a similar hexagonal lattice structure, where a lead atom layer is sandwiched between two layers of iodine atoms. Here, strong covalent bonds provide in-plane stability in the layer, while the weak van der Waals forces keep every layer stack together, as shown in Figure 1a. Similar to other 2D materials, PbI₂ can be used to build van der Waals heterostructures with other semiconductor materials, regardless of lattice mismatch and other stringent conditions. In addition, large-area, uniform, and high-quality PbI₂ flakes can be synthesized via facile solution processing method at atmosphere, which undoubtedly broaden the possibility of the PbI₂-based electronic devices with low manufacture cost and high integration in future. Therefore, we have successfully fabricated 2D PbI₂ flakes on Si/SiO₂ substrate via drop-cast technology (more details in Experimental Section) instead of physical vapor deposition method that generally requires rigorous conditions such as high temperature, vacuum environment, and so forth. Figure 1b shows the optical image of PbI₂ flakes with different thicknesses in which these PbI₂ flakes demonstrate regular hexagonal or triangle shape with sharp edge. To characterize their thicknesses, we first have performed atomic force microscopy (AFM) scanning for three different samples that are marked by white dashed lines in Figure 1b. Corresponding AFM images are shown in Figure 1c. As can be seen, the PbI₂ flakes in the three regions demonstrate smooth and flat surfaces as well as different thicknesses, which are around 12, 207, and 553 nm, respectively. Subsequently, we have conducted PL and Raman spectroscopy measurements to further characterize these PbI₂ flakes with different thicknesses at room temperature. In terms of previous works, the PL emission of PbI₂ at room temperature mainly originates from the recombination of bound and free excitons as well as the recombination of donor–acceptor pairs (DAPs), and the corresponding PL peak locates at about 510 nm (i.e., 2.43–2.44 eV), which fits well with our experimental data. In Figure 1d, the PL intensity of PbI₂ at around 510 nm gradually decays with the thickness decreasing from 553 to 12 nm. The thinning PbI₂ flakes accompanied with the dropped light absorption would reduce the PL quantum efficiency, and meanwhile induce the band structure to change from direct to indirect as the thickness thins to the monolayer. Different from PL spectra, the Raman spectra of PbI₂ are too weak to recognize at room temperature, and therefore, we have to increase the excitation power to irradiate the PbI₂ flakes so as to obtain observable Raman signals. Therefore, it is inevitable that the crystal quality of PbI₂ flakes is damaged by high excitation power owing to its poor photostability. In this way, the signal-to-noise of Raman spectra of the degenerated PbI₂ flakes would be dramatically reduced. To balance the intensity and signal-to-noise in the Raman spectra, we continuously optimize the laser power shining on the samples and choose a moderate excitation power of 500 μW. Figure 1e shows the characteristic Raman peaks of PbI₂ at around 75, 97, 113, and 216 cm⁻¹, which are identified as E₂g.
$A_{1g}$, 2LA(M), and 2LO(M) modes, respectively. Similar to PL spectra, the dropped light absorption with the decreasing thickness of PbI$_2$ leads to these Raman modes tending to be weaker, even barely visible.

Based on the synthesized PbI$_2$ flakes, we next focus on how to improve their photostability without sacrificing the efficiency of photon absorption and radiation. Currently, the mainstream principle of improving the photostability of PbI$_2$ is to cover protective layers directly onto its surface, not only to conduct the heat caused by the photothermal effect away from PbI$_2$, but also to prevent the PbI$_2$ from suffering hydration and oxidation in the atmosphere. Following the principle, we try to select a wide bandgap semiconductor material with a high thermal conductivity as protective layers to form type-I heterostructure with PbI$_2$. ZnO, a typical representative of the third-generation semiconductors, has a wide direct bandgap of 3.37 eV and high thermal conductivity of $\approx 37$ W m$^{-1}$ K$^{-1}$, which is generally two orders of magnitude higher than organic polymers. Therefore, ZnO could serve as the desired material of the protective layer for PbI$_2$ and meanwhile, maybe, form type-I band alignment with PbI$_2$. To intuitively verify the feasibility of this combination, the ZnO capping layer should not have large coverage because it is not beneficial to build a contrast region for naked PbI$_2$ and ZnO/PbI$_2$ heterostructure, considering the PbI$_2$ flakes with a scale of only tens of microns. For this purpose, we choose ZnO nanowire in place of other structures such as quantum dot and thin film, as a demonstration to combine with PbI$_2$ flakes. The ZnO nanowires can be facilely synthesized via the hydrothermal method (see Experimental Section for more details) and transferred anywhere on the surface of PbI$_2$ flakes, forming van der Waals heterostructure with controllable regions (see Figure 2a).

For the protective layer of PbI$_2$, an important prerequisite is high light transmissivity so that the photon absorption of the protective layer is reduced to the minimum. As shown in Figure 2c, the absorption edge of ZnO nanowire locates at about 380 nm, while the absorption edge of PbI$_2$ flake locates at about 520 nm.

Figure 2. a) Optical image of ZnO nanowire and PbI$_2$ flake. Scale bar is 10 $\mu$m. b) The height profile of ZnO nanowire (upper plane) and PbI$_2$ flake (lower plane) in part (a). c) UV–vis absorption spectra of the as-grown ZnO nanowire and PbI$_2$ flake at room temperature. Power-dependent PL spectra of d) pristine PbI$_2$ and e) ZnO/PbI$_2$ heterostructure under 405 nm laser excitation, where the power density ranges from 200 to 700 W cm$^{-2}$. f) The PL intensity of pristine PbI$_2$ and ZnO/PbI$_2$ heterostructure as a function of power density, which are extracted from parts (d) and (e), respectively.

With the increasing power density, the PL peak of pristine PbI$_2$ flake demonstrates a significant attenuation trend, while the PL signal from the ZnO/PbI$_2$ heterostructure is almost unchanged. To compare the difference intuitively, the PL intensity from the pristine PbI$_2$ and the ZnO/PbI$_2$ heterostructure is extracted and shown in Figure 2f. It can be seen that the PL intensity of PbI$_2$ from the heterostructure always maintains at around $2.8 \times 10^3$ even though the power density increases from 200 to 700 W cm$^{-2}$. By contrast, the PL intensity of pristine PbI$_2$ decreases from $1.6 \times 10^4$ to $0.3 \times 10^3$ in the same range of power density. The phenomenon can be attributed to the degradation of PbI$_2$ upon laser irradiation due to its poor photostability, which leads
to the reduction of PL quantum efficiency. Rather, the photo-

stability of PbI$_2$ in the heterostructure has represented a
dramatic improvement, indicating the ZnO nanowire could
supply effective protection for PbI$_2$ flake. In addition, we have
also compared the protective effect of PDMS with ZnO nano-
wire, and the corresponding results are shown in Figure S1,
Supporting Information. As expected, the photostability of
PbI$_2$ flake covered by ZnO nanowire is demonstrably superior
to that of PDMS.

Allowing for the aforementioned power-dependent irradiation
experiments are only performed under a single excitation source
of 405 nm; therefore, more options for the excitation sources
should be considered to roundly prove the reliability of the
ZnO nanowire improving the photostability of PbI$_2$. In this
regard, we have chosen two other excitation sources except for
405 nm to irradiate the PbI$_2$ and ZnO/PbI$_2$ heterostructure,
which are UV light at 320 nm and visible light at 532 nm, respect-
ively. During the power-dependent irradiation experiments, the
two excitation sources are used to irradiate the naked PbI$_2$
and ZnO/PbI$_2$ heterostructure at various power densities, respec-
tively. The irradiation time is fixed at nearly 2 s. Subsequently,
under 405 nm laser excitation the PL spectra of the irradiated
PbI$_2$ flakes are collected to monitor the degradation of PbI$_2$. To
avoid negative effects caused by the 405 nm laser, the output
power is set at a relatively low level, only 1 μW (power density \( \approx \) 100 W cm$^{-2}$) in all PL measurements. Figure 3a,b separately
demonstrates the PL spectra of pristine PbI$_2$ flake and ZnO/
PbI$_2$ heterostructure in which they are irradiated by 320 nm laser
with power density from 200 to 700 W cm$^{-2}$. As expected, the PL
intensity of pristine PbI$_2$ gradually decreases as the power
density increases, indicating the PbI$_2$ flake without the protective
layer appears as a visible degradation upon 320 nm laser irradia-
tion (Figure 3c). For the heterostructure, the PL intensity of PbI$_2$
tends to stay stable below the power density of 400 W cm$^{-2}$, and
then begins to slightly decay as the power density further
increases. The reason might be that the photon of 320 nm laser
with higher energy could generate more phonons via relaxation
process to enhance the photothermal effect and erode the protec-
tive effect of ZnO. Even so, the PL signal-to-noise and intensity
of PbI$_2$ in the heterostructure are still higher than that of the
naked PbI$_2$. In contrast, the PL spectra from both pristine
PbI$_2$ flake and ZnO/PbI$_2$ heterostructure that are irradiated by
532 nm laser are almost unchanged with the increasing irradiation
power density (see Figure 3d–f). The result is due to the
photon energy of 2.33 eV (532 nm) is lower than the bandgap
of PbI$_2$, which suppresses its photon absorption at the wave-
length of 532 nm and reduces the degradation of PbI$_2$ induced
by the photothermal effect. We also have performed illumination
time-dependent PL spectra of PbI$_2$ flake and ZnO/PbI$_2$ hetero-
structure irradiated by 320, 405, and 532 nm laser which are
shown in Figure S2, S3, and S4, Supporting Information, respect-
ively. Under the three excitation wavelengths, the PL intensity
of PbI$_2$ flake and ZnO/PbI$_2$ heterostructure with increasing the illu-
mination time exhibits a similar variation trend, respectively. The
PL intensity of pristine PbI$_2$ gradually decreases as the illumina-
tion time increases, while the PL intensity of the ZnO/PbI$_2$ het-
erostructure demonstrates relative stability with illumination
time, further indicating the ZnO could supply effective protec-
tion for PbI$_2$ flake. In addition, it is intriguing that the PL inten-
sities of PbI$_2$ in the heterostructure irradiated by 320 and 532 nm

![Figure 3. PL spectra of a) pristine PbI$_2$ and b) ZnO/PbI$_2$ heterostructure treated by 320 nm laser with power density ranging from 200 to 700 W cm$^{-2}$. c) The PL intensity of pristine PbI$_2$ and ZnO/PbI$_2$ heterostructure as a function of power density, which are extracted from parts (a) and (b), respectively. PL spectra of d) pristine PbI$_2$ and e) ZnO/PbI$_2$ heterostructure treated by 532 nm laser in the same range of power density. f) The PL intensity of pristine PbI$_2$ and ZnO/PbI$_2$ heterostructure as a function of power density, which are extracted from parts (d) and (e), respectively. These PL spectra are all excited by a 405 nm laser with a low power density of 100 W cm$^{-2}$.](image-url)
laser are higher than that of the naked PbI$_2$ at each irradiation power density, as shown in Figure 3c.f.

To find out the underlying reason for the PL enhancement, we have performed PL measurements in nonirradiated PbI$_2$ and ZnO/PbI$_2$ heterostructure to rule out the influence that, maybe, is caused by laser irradiation treatment, as shown in Figure 4a. Similarly, the PL intensity mapping of PbI$_2$ is conducted in a rectangular area that contains naked PbI$_2$, ZnO nanowire, and ZnO/PbI$_2$ heterostructure (see Figure 4b). Corresponding optical image of the rectangular area is demonstrated in the inset of Figure 4a. It can be seen that the overall PL intensity in the heterostructure (marked by the dashed red line) is stronger than that of the naked PbI$_2$ region, even though the distribution of PL intensity is not uniform. Further analysis of the unequal distribution of PL intensity will be discussed later. It should be noted that there is no appreciable PL signal on the suspended area of ZnO nanowire, that is, the position outside of PbI$_2$ flake, which further indicates the PL enhancement is irrelevant to the separate ZnO nanowire. Therefore, we focus on the ZnO/PbI$_2$ heterostructure and monitor the variation in structure and symmetry of PbI$_2$ flake via the Raman spectroscopy. For clarity, we have compared the Raman spectra of the location with the strongest PL intensity in the heterostructure with that of naked PbI$_2$. Coincidentally, the Raman signal intensity collected in the heterostructure is also stronger than that of naked PbI$_2$, just like the case of PL intensity, but there is no significant difference in the two spectra except for intensity. Consequently, the structure and symmetry of PbI$_2$ can be considered to maintain undamaged during the process of PL enhancement. According to previous works,$^{[38,39]}$ ZnO nanowire with hexagonal cross section is a natural whispering-gallery-mode (WGM) microcavity and could strengthen the light–matter interactions through the total internal reflection mechanism. Figure 4d shows the schematic illustration of the WGM light path generated inside the ZnO nanowire. Therefore, a reasonable explanation is that the enhanced light–matter interactions in the ZnO nanowire can serve as a WGM resonator to increase the intensity of excitation source, that is, incident into PbI$_2$, resulting in the enhancements in both PL and Raman spectra of PbI$_2$. For the nonuniform intensity distribution of them, it may be attributed to the inhomogenous topography of microcavity along the ZnO nanowire, which may be caused by the transferring process of nanowire. The inhomogenous microcavity gives rise to the varying degrees of enhancement for the intensity of incident light into PbI$_2$.

In terms of our aforementioned assumption, if the ZnO/PbI$_2$ heterostructure could exhibit a type-I band alignment of their band positions, the photocarriers in ZnO would be propelled toward PbI$_2$ as long as the photon energy of the excitation source

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**Figure 4.** a) PL spectra from the pristine PbI$_2$ and the ZnO/PbI$_2$ heterostructure under 405 nm laser excitation. The inset is optical image of ZnO nanowire and PbI$_2$ flake, and its corresponding PL intensity image is shown in part (b). The red dashed line in part (b) is the coverage area of ZnO nanowire. c) Raman spectra of pristine PbI$_2$ and the ZnO/PbI$_2$ heterostructure. d) Schematic illustration of the WGM light path generated inside the ZnO nanowire.
is more than the bandgap of ZnO. The corresponding schematic diagram is shown in Figure 5a. Through the literature research,\(^{40,41}\) the conduction band minimum (CBM) and valence band maximum (VBM) of ZnO are separately located at \(-4.35\) and \(-7.72\) eV, while the CBM and VBM of PbI\(_2\) are located at \(-4.44\) and \(6.82\) eV, respectively. In principle, the combination of ZnO and PbI\(_2\) could form type-I band alignment (see Figure 5b). It means that in the heterostructure, the PL intensity of ZnO would be dramatically reduced, while the increased photocarriers in the PbI\(_2\) would enhance its PL intensity. To verify it, we have conducted PL measurements for pristine PbI\(_2\), ZnO nanowire, and ZnO/PbI\(_2\) heterostructure, respectively, where the excited areas of pristine PbI\(_2\), ZnO nanowire, and ZnO/PbI\(_2\) heterostructure are separately marked as the black, red, and blue dots, as shown in the inset of Figure 5c. Here, the PL spectra of them were collected under the same experimental condition in which the excitation source was 320 nm laser with the power of \(\approx 400\) nW and the laser spot was about 1 \(\mu\)m. In Figure 5c, the PL spectra of ZnO nanowire consist of a narrow near-band-edge exciton emission at \(\approx 380\) nm and a broad deep-level defect emission ranging from 430 to 660 nm, which is well in accord with previous reports.\(^{40}\) The deep-level defect emission of ZnO mainly originates from the capturing of band-edge excitons at defects. That is to say, the number of band-edge excitons is proportional to the intensity of deep-level defect emission. Due to the ZnO/PbI\(_2\) heterostructure with type-I band alignment, the band-edge excitons could transfer from ZnO toward PbI\(_2\), leading to a decrease in the number of band-edge excitons in ZnO. Therefore, the intensity of both band-edge exciton and deep-level defect emission of ZnO in heterostructure would be dramatically reduced compared with pristine ZnO nanowire, as previously predicted.

As the broad deep-level defect emission of ZnO overlaps the PL emission of PbI\(_2\) (see Figure 5d), the actual contribution from deep-level defect emission is not observed intuitively in the PL spectra of the heterostructure. In contrast, the band-edge exciton emission of ZnO without overlapping the PL emission of PbI\(_2\) can be used as an ideal reference to indirectly acquire the PL contribution of ZnO in the heterostructure. First, the PL spectra of the ZnO nanowire and the heterostructure are normalized by respective band-edge emission of ZnO, as shown in Figure 5e. The band-edge exciton emission of the pristine ZnO is essentially coincident with that of the ZnO in the heterostructure. As positive correlation is in existence between the intensity of defect emission and the number of band-edge excitons, so we presume that the normalized PL emission of pristine ZnO is approximately equal to the PL contribution of ZnO in the normalized PL spectra of the heterostructure. Accordingly, the difference between the normalized PL spectra of the ZnO and the heterostructure can be considered as the PL contribution from PbI\(_2\) in the heterostructure. Subsequently, the normalized PL spectra of ZnO nanowire are subtracted by the normalized PL spectra of the heterostructure. In this way, the PL emission from the ZnO nanowire could be removed from the ZnO/PbI\(_2\) heterostructure, and the remaining part is only from the PL emission of PbI\(_2\). For convenient comparison with the heterostructure, the PL spectra of pristine PbI\(_2\), shown in Figure 5d, are also normalized by the near-band-edge emission of ZnO from the

![Figure 5](https://www.advancedsciencenews.com/)

**Figure 5.** a) Schematic diagram of the ZnO/PbI\(_2\) heterostructure for the illustration of the carrier interlayer transportation. The blue ball represents the carrier. The red straight arrow represents the interlayer transportation processes of the carrier. b) Band positions of ZnO and multilayer PbI\(_2\), implying type-I band alignment of the ZnO/PbI\(_2\) heterostructure. c) PL spectra of the pristine ZnO and the ZnO/PbI\(_2\) heterostructure. The inset is optical image of ZnO nanowire and PbI\(_2\) flake, where the black, red, and blue dots represent the excited areas of PbI\(_2\), ZnO, and ZnO/PbI\(_2\) heterostructure for PL spectra, respectively. Scar bar: 5 \(\mu\)m. d) PL spectra of the naked PbI\(_2\) and the ZnO/PbI\(_2\) heterostructure. e) PL spectra of pristine ZnO and ZnO/PbI\(_2\) heterostructure, normalized at respective near-band-edge emission of ZnO. f) The PL spectra of the PbI\(_2\) from the heterostructure (red curve) and the pristine PbI\(_2\) normalized by the near-band-edge emission of ZnO from the heterostructure (olive curve). These PL spectra are all excited by a 320 nm laser with output power of 400 nW.
heterostructure. Figure 5f shows the normalized PL spectra of the pristine PbI2 and the PbI2 from the heterostructure. Compared with pristine PbI2, the PL peak of PbI2 from the heterostructure is significantly enhanced, accompanied by redshift and broadening. Considering that the quality of interface in the heterostructure is not systematically optimized in this work; therefore, the broadened PL peak of PbI2, maybe, contains band-edge emission and interfacial defect emissions. Even so, the PL integrated intensity of the PbI2 from the heterostructure is still obviously enhanced about eightfold compared with pristine PbI2. To conclude it, the photostability and PL intensity of PbI2 could be effectively enhanced via constructing type-I heterostructure with the ZnO nanowire.

3. Conclusion

In summary, we have successfully realized the improvement of photostability of PbI2 at different excitation wavelengths, including 320, 405, and 532 nm, via constructing type-I heterostructure with ZnO nanowire. In the heterostructure, ZnO nanowire synthesized by hydrothermal method offers a desired path of heat dissipation for PbI2, which is attributed to the high thermal conductivity of ZnO that is two orders of magnitude higher than organic polymers. In addition, due to the type-I band alignment between PbI2 and ZnO, the photogenerated electrons and holes in the ZnO nanowire can be transferred to the PbI2 flake to enhance the PL intensity of PbI2, which is proved to obtain nearly eightfold enhancement in the heterostructure based on the PL spectra analysis. Our work not only provides a feasible strategy to improve the photostability and PL intensity of PbI2, but also gives possibilities for propelling the progress of practical applications.

4. Experimental Section

Fabrication: A recrystallization reaction method was used to synthesize PbI2 flakes. First, PbI2 powder (99.9%) was dissolved in secondary deionized water (1 mg mL\(^{-1}\)) and heated with stirring at 110 °C for 1 h to guarantee PbI2 powder was dissolved completely. Subsequently, the PbI2 aqueous solution was kept 1 h at room temperature and then dropped on a cleaned SiO\(_2\)/Si substrate (1 cm \(\times\) 1 cm) via using a high-precision pipette. After several minutes, the excess undried liquid was absorbed by a dropper and finally PbI2 flakes of various shape and thickness grow. ZnO nanowires were prepared by a typical hydrothermal process. Zinc acetate and hexamethylenetetramine (HMT) were separately dissolved in water with adequately stirring, and then were mixed to get 20 mmol L\(^{-1}\) ZnO precursor solution. The mixture was poured into a reactive kettle in which the sapphire substrate was facing down. Finally, the reactive kettle was heated for 2.5 h at 95 °C in an oven to obtain ZnO nanowires. The ZnO nanowires were mechanically exfoliated from the sapphire substrate and then accurately transferred onto the pregrown PbI2 flakes by PDMS-assisted dry transfer technique.

Characterization: The tapping mode of AFM (Dimension Icon, Bruker) was used to monitor the surface morphology of ZnO nanowires and PbI2 nanoflakes. All steady-state PL spectra and mappings were measured with a micro-PL system (Metatess, ScanPro) equipped with a monochromator, a charge-coupled device (CCD), and three different excitation sources, including 320, 405, and 532 nm CW laser. The Raman spectra were collected by a spectrophotometer system equipped with a Si-based CCD (HR Evolution, Horiba). The excitation source is a 488 nm CW laser with an output power of 1 μW, and the laser spot size is focused to a spot diameter of ~1 μm. A Hitachi UV-4150 spectrophotometer is used to measure the steady-state absorption spectra.

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.

Data Availability Statement

Research data are not shared.

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