Hydrophilic MoSe$_2$ Nanosheets as Effective Photothermal Therapy Agents and Their Application in Smart Devices

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ABSTRACT: A facile poly(vinylpyrrolidone) (PVP)-assisted exfoliation method is utilized to simultaneously exfoliate and noncovalently modify MoSe$_2$ nanosheets. The resultant hydrophilic nanosheets are shown to be promising candidates for biocompatible photothermal therapy (PTT) agents, and they could also be encapsulated into a hydrogel matrix for some intelligent devices. This work not only provides novel insights into exfoliation and modification of transition metal dichalcogenide (TMD) nanosheets but also might spark more research into engineering multifunctional TMD-related nanocomposites, which is in favor of further exploiting the attractive properties of these emerging layered two-dimensional (2D) nanomaterials.

KEYWORDS: transition metal dichalcogenide, polymer-assisted exfoliation, photothermal therapy, dual-responsive, smart device

1. INTRODUCTION

Since the pioneering research on graphene, transition metal dichalcogenide (TMD) nanosheets as emerging layered two-dimensional (2D) nanomaterials have stimulated great research interest in recent years.$^{1,2}$ These nanosheets display a variety of extraordinary electronic, thermal, optical, mechanical, and catalytic properties, enabling their applications in electronic devices, energy storage, bioimaging, catalysis, and so on.$^{3-8}$ In particular, some nanosheets in this category (e.g., MoS$_2$ and WS$_2$) nanosheets) have been shown to be nontoxic and might have great potential as novel biomaterials. However, compared with effective modification techniques and various multifunctional nanocomposites of graphene,$^{11,12}$ it is obvious that TMD nanosheets have not yet realized their full potential.$^{13}$ For instance, facile preparation methods and various assemblies of functional materials related to graphene (or graphene oxide) expand the application range of pristine graphene; in particular, three-dimensional graphene hydrogels have been widely investigated in the fields of electrochemistry and biotechnology.$^{14}$ On the contrary, due to poor dispersibility in water and complex modification procedures for TMD nanosheets, it seems difficult to incorporate them in hydrogel matrices, which thus hinders their further applications.

Among reported top-down and bottom-up methods, scalable production of TMD nanosheets generally occurs through tert-butyl lithium intercalation and liquid exfoliation. However, both of these possess some drawbacks. In terms of chemical exfoliation of TMD materials by tert-butyl lithium intercalation, although as-prepared TMD nanosheets could be stable in water, it is difficult to get rid of excess Li ions, and complex postmodification is required to stabilize the nanosheets in phosphate-buffered saline solution (PBS), which limits their applications in biomedicine.$^{9}$ Besides, the ion intercalation process involves phase transition from semiconducting 2H phase to metallic 1T phase, which distorts the intrinsic properties of TMD nanosheets.$^{15,16}$ Although traditional liquid exfoliation enables relatively facile production of 2H-phase TMD nanosheets and their polymer-based composites,$^{17}$ it is also difficult to completely remove abundant high-boiling-point solvents, and the resultant nanosheets are water-insoluble.

Therefore, in order to investigate the intrinsic semiconducting properties of TMD nanosheets and develop multifunctional TMD-related biocompatible nanocomposites, it is of great concern to explore facile processing techniques and assemble TMD nanosheets with a variety of biocompatible and functional polymers, which might optimize their performance and further develop novel multifunctional materials.

Recently, some macromolecules are demonstrated to be able to assist exfoliating TMD nanosheets in aqueous solution.$^{18-20}$ It is worthwhile to note that, during the exfoliation process,
macromolecule chains tend to coat on the nanosheets and thus render them hydrophilic. Therefore, it inspires us to take advantage of noncovalent interactions between the nanosheets and macromolecules and further investigate the multifunctional application of these nanosheets. Among TMD materials, MoSe2 nanosheets possess an obvious absorption peak located at ~808 nm [21] (in contrast, MoS2 have only near-infrared (NIR) absorbance instead of an obvious absorption peak), indicating their great potential as NIR photothermal transducers. Therefore, it encourages us to explore more applications of hydrophilic and biocompatible MoSe2 nanosheets, for example, as photothermal therapy (PTT) agents in biomedicine. Furthermore, via the assemblies of hydrophilic TMD nanosheets, it might also be possible to develop some dual-responsive (i.e., thermo- and photoresponsive) smart hydrogels, which could expand the application range of these emerging 2D nanomaterials.

Herein, poly(vinylpyrrolidone) (PVP), as a typical biocompatible polymer whose amphiphilic nature might contribute to the exfoliation and stabilization of the nanosheets in aqueous solution, is selected as a model polymer to develop MoSe2-related multifunctional nanocomposites. Through a facile PVP-assisted exfoliation process, simultaneous exfoliation and noncovalent modification of MoSe2 nanosheets is realized. PVP coating endows these nanosheets with good hydrophilicity and perfect opportunities to fabricate novel hybrid nanocomposites for multifunctional applications. For instance, PVP-coated MoSe2 nanosheets are researched for efficient PTT agents. Furthermore, the hydrophilic MoSe2 nanosheets are successfully encapsulated in a thermo-responsive hydrogel matrix. In this case, MoSe2 nanosheets in the hydrogel could absorb light and generate heat, and thus could remotely control stimuli-responsive behavior of the hydrogel at a specific time and location. The resulting dual-responsive hydrogel is then applied as a novel smart remote-controlled device and a promising matrix for drug encapsulation and release.

2. EXPERIMENTAL SECTION

2.1. Materials. Bulk MoSe2 powder was purchased from Alfa Aesar Co. Ltd. Poly(vinylpyrrolidone) (PVP, MW ~10 000) was purchased from Aldrich Co. Ltd. N-isopropylacrylamide (NIPAM, 99%) was purchased from J&K Chemical Co. Ltd. and purified by passage through an alumina column. N,N’-Methylenebis(acrylamide) (Bis) and ammonium persulfate (APS) were obtained from Aladdin Co. Ltd. and used without further purification. N2 and CO2 was purchased from Shanghai Jifu Gas Co. Ltd. Fetal bovine serum (FBS) and doxorubicin hydrochloride (DOX) were purchased from Energy Chemical Co. Ltd. Dulbecco’s modified Eagle medium (DMEM) and trypsin–ethylenediaminetetraacetic acid (EDTA) were purchased from Gibco. Phosphate-buffered saline solution (PBS, pH 7.4) and antibiotics (100 units mL⁻¹ streptomycin and 100 μg mL⁻¹ penicillin) were purchased from Invitrogen. Counting cell kit 8 (CCK-8) was purchased from Beyotime Institute of Biotechnology (Jiangsu, China). Calcium-AM and propidium iodide (PI) was purchased from Sigma–Aldrich. Mouse embryonic fibroblasts (MEF, normal cells) and HeLa cells (cancer cells) were originally obtained from the Cell Bank of Type Culture Collection of Chinese Academy of Sciences China (Shanghai, China).

2.2. Preparation of PVP-Coated MoSe2 Nanosheets. Typically, 1 g of bulk MoSe2 powder was first added in 250 mL of aqueous solution containing 0.5 g of PVP, and then the mixture was sonicated for 8 h [only bath sonication (QGS200DB) with an output power of 250 W, no need for probe sonication]. The supernatant containing PVP-coated MoSe2 nanosheets was collected after centrifugation at 3000 rpm for 30 min. The yield of MoSe2 nanosheets was determined by weighing method, about 34 μg mL⁻¹. In order to get rid of excess unbound PVP, the supernatant was further subjected to ultra-centrifugation (Hitachi, CS150FNX, SS0A) at 50 000 rpm for 30 min, and the sediments of PVP-coated MoSe2 nanosheets were collected (supernatant of unbound PVP was decanted). Then collected PVP-coated MoSe2 nanosheets can be redispersed in water at different concentrations.

2.3. Fabrication of PVP-MoSe2 Nanosheets/PolyNIPAM Hydrogel. The stimuli-responsive hydrogel was fabricated by a one-step polymerization reaction in the PVP-coated MoSe2 nanosheet dispersion. Typically, 0.5 g of NIPAM monomers, 0.01 g of cross-linker Bis, and 0.005 g of initiator APS were added into 5 mL of PVP-coated MoSe2 nanosheet dispersion of different concentrations, 0, 25, 50, 75, and 100 μg mL⁻¹, and the mixtures were then sealed in Teflon autoclaves at 180 °C for 4 h to obtain poly(N-isopropylacrylamide) (PNIPAM) nanocomposite hydrogel. The hydrogel was then washed with deionized water several times.

2.4. Characterization. Transmission electron microscope (TEM) images were recorded on a JEOL JEM2011 at 200 kV. Atomic force microscopy (AFM) images were obtained by a Multimode V8 in tapping mode. Dynamic light scattering (DLS) and ζ potential characterization were performed at a Malvern Zetasizer Nano ZS instrument (ZS90). X-ray diffraction (XRD) data were acquired on a Bruker D8 diffractometer (Germany) with Ni-filtered Cu Kα radiation (40 kV, 40 mA). Raman measurements were performed on an XploRA laser Raman spectrometer equipped with 532 nm helium/neon laser and charge-coupled device (CCD) detector. X-ray photoelectron spectra (XPS) were recorded by a RBD upgraded PHI-5000C ESCA system (PerkinElmer) with Mg Kα radiation (hv = 1253.6 eV). UV–vis–NIR spectra ranging from 1000 to 250 nm were recorded on a Lambda 750 spectrophotometer (PerkinElmer). The concentration of Mo within cells was measured by inductively coupled plasma–atomic emission spectrometry (ICP–AES; Hitachi, P4010). Field emission scanning electron microscope (FESEM) images were obtained by Zeiss Ultra 55 with energy-dispersive X-ray spectroscopy (EDS). Fourier transform infrared (FTIR) spectra were recorded on a Nicolet 6700 spectrometer. Dynamic mechanical properties of the hydrogels were measured by a Haake Paar rotary rheometer (Haake Mars III) with parallel plate geometry. Oscillatory frequency sweep testing was performed at constant 1% strain. Temperature sweep testing was performed at a temperature increase rate of 5 °C min⁻¹. Differential scanning calorimetry (DSC) measurements were performed on a Mettler-Toledo thermal analyzer at a scanning rate of 10 °C min⁻¹ from 15 to 60 °C. The hydrogels were sealed in alumina crucibles. Note that FTIR, FESEM, DSC, and rheology measurements were all performed on nanocomposite hydrogels with 25 μg mL⁻¹ (infrared concentration) Mo within cells was measured by inductively coupled plasma–atomic emission spectrometry (ICP–AES; Hitachi, P4010).

2.5. Cell Culture. All cells were cultured in DMEM with 10% PBS plus 1% penicillin/streptomycin and incubated in a humidified 5% CO2 incubator at 37 °C, with the medium changed every other day. Cytotoxicity assays of mouse embryonic fibroblasts (MEF) and human cervical cancer cells (HeLa) were seeded on 96-well plates (2 × 10³ cells/well) with growth medium in a CO2 incubator. After 12 h, the medium was replaced with fresh growth medium containing desired amount of samples (PVP or PVP-coated MoSe2 nanosheets) at different concentrations; for the control group, an equal volume of
PBS was added. Then cells were cultured for another 24 h. After that, the medium were removed and cells were gently washed with PBS once. Cell viability was measured by a standard CCK-8 assay as described before.25

2.6. In Vitro Photothermal therapy. HeLa cells were seeded on 96-well plates (2 × 10⁴ cells/well), and after 12 h of incubation the cells were treated with fresh medium containing MoSe₂ nanosheets at different concentrations (PVP-coated MoSe₂ nanosheets; PBS was used for the control group). After another 12 h, the medium was removed and cells were rinsed with PBS to remove free MoSe₂ nanosheets outside the cells. After addition of fresh medium, the cells were irradiated by an 808 nm laser at 2.5 W·cm⁻² power density for 15 min, with the laser fully covered the area of each well in a CO₂ incubator at 37 °C. Treated cells were incubated for another 12 h, and then photothermal therapy efficacy was measured by a standard CCK-8 assay. Meanwhile, the other treated cells were costained with 1 μg·mL⁻¹ calcein-AM and 50 μg·mL⁻¹ PI for 10 min, and after being washed with PBS once, the cells were observed and captured by an inverted fluorescence microscope (Olympus, Japan).

Meanwhile, we investigated time-dependent therapy efficacy of PVP-coated MoSe₂ nanosheets. HeLa cells were incubated with medium containing 100 μg·mL⁻¹ MoSe₂ nanosheets for different times: 0, 3, 6, 12, and 24 h. Afterward, the medium was removed and cells were rinsed with PBS once to remove free MoSe₂ nanosheets outside the cells. After addition of fresh medium, the cells were irradiated by an 808 nm laser at 2.5 W·cm⁻² power density for 15 min; for the control group, there was no NIR irradiation (laser off). All of the cells were incubated for another 12 h, and then photothermal therapy efficacy was measured by a standard CCK-8 assay.

2.7. Drug Encapsulation and Release Protocol. For encapsulation, 0.1 g of dehydrated hydrogel (nanocomposite hydrogel prepared with 100 μg·mL⁻¹ MoSe₂ nanosheets was investigated and had been incubated at 70 °C for 2 h to dehydrate) was incubated with 50 μg of DOX in 1 mL of water and kept for 24 h at 4 °C. The supernatant with free DOX was subjected to UV–vis measurements to estimate the amount of drug loaded into the hydrogels. For the release of drug, samples loaded with DOX were placed in quartz cells with 1 mL of PBS in each at 25 °C. They were further subjected to NIR irradiation (808 nm, 2.5 W·cm⁻²) for different times, 0, 5, 10, 30, and 60 min, and the release of DOX in supernatant was also recorded by measurement of UV–vis spectra. For the control group, there was no NIR irradiation and the release of DOX at 25 °C in supernatant was also recorded after 0, 5, 10, 30, and 60 min. Note that all drug encapsulation and release experiments were performed three times.

3. RESULTS AND DISCUSSION

3.1. Preparation and Characterization of PVP-Coated MoSe₂ Nanosheets. According to TEM images in Figure 1a–d, few layers, good crystallinity, and polymer-coated features of the exfoliated nanosheets are observed. Selected area electron diffraction (SAED) with single-crystalline hexagonal spot pattern confirms the retained good crystallinity of the exfoliated MoSe₂ nanosheets. The lateral profile in Figure 1b suggests the few-layer morphology of the nanosheets. The clear lattice fringe in Figure 1c,d confirms the exfoliated nanosheets retain crystalline hexagonal honeycomb structure of MoSe₂ and the lattice spacing is about 0.285 nm, which corresponds to the (100) face of 2H-MoSe₂.26 In addition, the blurred boundary
around the clear lattice fringe (as indicated by red arrows) reveals the nanosheets with good crystallinity are coated with some amorphous polymers, probably due to simultaneous PVP modification of MoSe₂ nanosheets in the liquid exfoliation process. AFM analysis in Figure 1e,f further confirms the ultrathin and polymer-coated features of the MoSe₂ nanosheets. The height of the MoSe₂ nanosheets is 1−7 nm, indicating fewer than 10 layers of the MoSe₂ nanosheets (about one to seven layers). The rough surface of the nanosheets is ascribed to the hydrophilic PVP coating, which thus results in excellent stability of the nanosheet aqueous dispersion. In addition to microscopic observations, Raman spectrum (Figure S1a) and XRD pattern (Figure S1b) of the PVP-coated nanosheets also confirm their highly exfoliated features. Compared with bulk MoSe₂ powder, an apparent red shift and decreasing intensity of out-of-plane A₁₅g mode and in-plane E₁²₆g mode confirm the successful exfoliation and few-layered structure of the nanosheets. Peak spacing between the two modes increases as the layer number decreases, which is also consistent with a previous report. According to XRD patterns, the decreasing and broad diffraction peak at ~13.5° corresponds to the (002) face of 2H-MoSe₂ (JCPDF 29-0914). Its lower-angle shift might be due to the fact that some polymers intercalate into and bond with the MoSe₂ nanosheets and thus enlarge their interlayer distance. In addition, the average lateral size of the PVP-coated MoSe₂ nanosheets is ~161 nm (Figure S2) and their ζ potential is −23.9 mV, revealed by DLS measurements. After drying at room temperature, as shown in Figure S3a, plenty of aggregate nanosheets with relatively uniform size are observed. According to qualitative analysis of element mapping, Mo and Se elements are identified, while C, O, and N elements are ascribed to the PVP coating on the nanosheets. According to XPS analysis (Figure S4) of the PVP-coated MoSe₂ nanosheets (excess unbound PVP was washed away by ultracentrifugation), the binding energies of Mo 3d₃/₂ and Mo 3d₅/₂ are 231.8 and 228.6 eV, respectively, indicating the +4 oxidation chemical state of Mo. Se 3d₃/₂ and Se 3d₅/₂ are located at 55.1 and 54.2 eV which are in line with a previous report.
Therefore, the as-prepared MoSe2 nanosheets are in a stable chemical state.

3.2. Optical and Photothermal Properties of PVP-Coated MoSe2 Nanosheets. Although bare TMD nanosheets are hydrophobic and cannot uniformly disperse in water, PVP coating renders them hydrophilic and very stable in water, PBS, and cell culture medium (DMEM). As shown in Figure S5, after storage at 4 days and further centrifugation at 3000 rpm for 5 min, the nanosheets are still stable and no obvious sediment forms. Besides, stability tests of PVP-coated MoSe2 nanosheets at different pH values and temperatures were also performed. As shown in Figures S6 and S7, PVP-coated MoSe2 nanosheets are very stable in water at different temperatures (Figure S6) and at different pH values (Figure S7). After 24 h, the nanosheets are still stable and no obvious sediment forms.

According to UV–vis–NIR spectra of PVP-coated MoSe2 nanosheets, a distinct NIR absorption peak located at around 800 nm is identified in contrast to other TMD nanosheets, which highlights that MoSe2 nanosheets have great potential to be applied as efficient PTT agents. On the basis of Beer–Lambert law (Figure 2b), the mass extinction coefficient (ε) of PVP-coated MoSe2 nanosheets at 808 nm is calculated to be 11.1 L·g⁻¹·cm⁻¹, much higher than that of graphene oxide (GO) nanosheets and comparable to that of black phosphorus quantum dots. Photothermal transduction of the PVP-coated MoSe2 nanosheets is further investigated by measuring the dispersion temperature as a function of time under 808 nm NIR irradiation over a range of concentrations. In contrast to negligible temperature fluctuation of pure water (Figure 2c), a significant temperature increase of 12.5 °C is generated even with very low concentration of 25 μg·mL⁻¹ after 2.5 W·cm⁻² irradiation for 20 min. At a higher concentration (100 μg·mL⁻¹), the dispersion temperature is increased by 29.3 °C, indicating favorability for thermal ablation therapy. With laser power density increasing from 1.25 to 5 W·cm⁻², the temperature elevation of PVP-coated MoSe2 nanosheet dispersion is also remarkably improved. Based on the total energy balance of the system (Figure 2e,f), photothermal conversion efficiency (η) of PVP-coated MoSe2 nanosheets is calculated to be 57.9% (details are available in Supporting Information), which is significantly higher than that of Au nanorods (21%) and black phosphorus quantum dots (28.4%) and comparable to that of Cu₂Se nanocrystals (56.7%). Moreover, the photothermal stability of PVP-coated MoSe2 nanosheets is also assessed by monitoring temperatures with laser on/off cycles. As shown in Figure S8, the dispersion shows no deterioration of photothermal effect after cycling, confirming their stability as photothermal agents.
3.3. Cytotoxicity and In Vitro Photothermal Therapy.

Biocompatibility and in vitro photothermal therapy of PVP-coated MoSe2 nanosheets are further examined to explore their potential application in biomedicine. The cytotoxicity of nanosheets is evaluated in both normal and cancer cells through a standard CCK-8 assay as described before.25 As shown in Figure 3a, after 24 h of incubation, the cell viabilities of both MEF (normal cells) and HeLa (cancer cells) stay >93% with the addition of PVP-coated MoSe2 nanosheets up to 100 μg·mL−1, approximating the effect of PVP group at the same concentration. Moreover, as illustrated in section 3.2, PVP-coated MoSe2 nanosheets possess relatively higher photothermal conversion efficiency than other common PTT agents; thus low-cytotoxicity and high-efficiency MoSe2 nanosheets might have great advantages for biomedical applications. The PTT efficacy of PVP-coated MoSe2 nanosheets in cancer cells is further investigated. As shown in Figure 3c–g, after careful removal of free PVP-coated MoSe2 nanosheets outside the cells, under NIR irradiation (808 nm, 2.5 W·cm−2) for only 15 min, the viabilities of HeLa cells significantly decline. At the concentration 100 μg·mL−1, PVP-coated MoSe2 nanosheets can effectively kill HeLa cells with only 8.7% viability.

According to fluorescent microscopic images of HeLa cells incubated with different concentrations of MoSe2 nanosheets, live/dead cells were distinguished by calcein-AM (green fluorescence, live cells) and PI (red fluorescence, dead cells) costaining. After NIR irradiation for 15 min, almost no dead cells with red fluorescence can be observed in the absence of PVP-coated MoSe2 nanosheets, which is in contrast to the fact that dead cells increase with increasing concentration of PVP-coated MoSe2 nanosheets. Upon PTT treatment, cancer cells that have probably ingested MoSe2 nanosheets begin to dehydrate, shrink, and finally decrease as shown in Figure 3f; their morphology is obviously different from the expansive state as shown in Figure 3e.

To investigate time-dependent therapy efficacy of PVP-coated MoSe2 nanosheets, viabilities of HeLa cells incubated with 100 μg·mL−1 MoSe2 nanosheet suspensions for different times (0, 3, 6, 12, and 24 h) were also investigated. After incubation for different times, the medium was carefully washed to remove free MoSe2 nanosheets outside the cells. As shown in Figure 3d, with prolonged incubation time, cell viabilities without NIR irradiation (laser off) are almost unchanged, while the PTT efficacy is significantly enhanced. This indicates more...
MoSe₂ nanosheets are ingested by cells with longer incubation time, and thereby the cell viabilities obviously decline after NIR irradiation (laser on).

Furthermore, ICP-AES was also utilized to analyze the Mo concentration within the cells. HeLa cells were incubated with MoSe₂ nanosheets at a concentration of 100 μg·mL⁻¹. After the allotted time, the cells were carefully washed and collected by centrifugation. As shown in Figure S9a, with longer incubation time, the as-collected cells manifest darker color, probably due to more ingestion of MoSe₂ nanosheets. As shown in Figure S9b, after 6 h of incubation, the Mo concentration within the cells is significantly higher than the background, indicating remarkable uptake efficiency of the nanosheets by HeLa cells. Moreover, with prolonged incubation time, the Mo concentration within the cells also increases, which also suggests the uptake is time-dependent. After 12 h of incubation, the Mo concentration within the cells increases up to 1.19 × 10⁻⁸ mg/cell, which is higher than the cell uptake efficiency previously reported for Au nanoparticles.⁵⁵ Therefore, as a result of their excellent biocompatibility and good PTT efficiency previously reported for MoSe₂ nanosheets, nanocomposite hydrogels also exhibit photothermal conversion after a critical temperature that is close to the VPTT determined by DSC, suggesting their rheological behaviors are also thermo-responsive. Besides, with the incorporation of MoSe₂ nanosheets, nanocomposite hydrogels also exhibit photothermal conversion. Under NIR irradiation, MoSe₂ nanosheets lead to rapid photothermal heating of the hydrogel, and thus the PNIPAM network shrinks with volume phase transition. We recorded a group of time-dependent temperature rise curves of the nanocomposite hydrogels. As shown in Figure S10, there is only slight temperature fluctuation for the PNIPAM hydrogel without MoSe₂ nanosheets. On the contrary, nanocomposite hydrogels show an obvious temperature rise under NIR irradiation. Thus, MoSe₂ nanosheets impart remote-controlled photothermal responsiveness to these nanocomposite hydrogels, and this dual-response behavior could facilitate many applications. For example, upon exposure to NIR laser (808 nm, 2.5 W·cm⁻²), intriguingly, the nanocomposite hydrogel with the incorporation of 25 μg·mL⁻¹ MoSe₂ nanosheets gradually shrinks and climbs to the top of the quartz tube, as shown in Figure 5d. The nanocomposite hydrogel is irradiated at the bottom of the quartz tube in the initial state. When the hydrogel climbs along the quartz tube, it is no longer under NIR irradiation but can still arrive at the top of the quartz tube. This phenomenon is very different from other reported NIR-responsive hydrogels, which just shrink and swell at the bottom of the tube.³⁶ This might due to the fact that high photothermal conversion efficiency of PVP-coated MoSe₂ nanosheets enables effective temperature increase with only a small amount of MoSe₂ nanosheets in the hydrogel network; thus the shrinking hydrogel possesses lower density (closed to polymer) than surrounding water, which results in their self-motion in water. After the laser is switched off, the hydrogel would gradually swell and finally fall off. This nanocomposite hydrogel can also be used as a remote microvalve. As shown in Figure 5e, red rhodamine solution and pure water are on the two sides of the nanocomposite hydrogel, and it could effectively block the flow of liquid, while after NIR irradiation, the nanocomposite...
hydrogel shrinks and thus allows the flow of liquid. Therefore, this novel nanocomposite hydrogel, which combines the excellent photothermal properties of MoSe₂ nanosheets with the PNIPAM thermoresponsive network, can be remotely manipulated and valuable in the fields of intelligent materials.

Moreover, we also investigate potential applications of this smart hydrogel in biomedicine, that is, their drug loading and release efficacy under remote control of NIR laser. As shown in Figure 6, a nanocomposite hydrogel with incorporation of 100 μg·mL⁻¹ MoSe₂ nanosheets shows good drug (DOX) loading capability. After 24 h of incubation, ~45.8 μg of DOX is loaded in the initial dehydrated nanocomposite hydrogel, with the DOX loading percentage achieving ~92%. As for drug release evaluation, obviously, with remote photo control (laser on, NIR irradiation, 808 nm, 2.5 W·cm⁻²), the temperature of the nanocomposite hydrogels rises under NIR irradiation (Figure S10) and drug release efficacy of the nanocomposite hydrogels in PBS is obviously improved, while drug release without NIR irradiation (laser off) is sluggish. In particular, the DOX release of hydrogels with NIR irradiation significantly precedes that of hydrogels without NIR irradiation in the initial 5 min. After 60 min, the DOX released in PBS achieves almost constant concentration, and nanocomposite hydrogels release ~1.2 times the amount of DOX when exposed to NIR laser.

4. CONCLUSIONS

In summary, hydrophilic PVP-coated MoSe₂ nanosheets are obtained by using a facile polymer-assisted exfoliation technique. Simultaneous noncovalent modification of the nanosheets enables them to be applied as efficient PTT agents with high photothermal conversion efficiency and good biocompatibility. Moreover, when the hydrophilic nanosheets are encapsulated in PNIPAM network, a novel hydrogel with dual photo- and thermo- response behavior is formed that might have promising applications in intelligent materials. We believe that facile modification and various assemblies of TMD-related nanocomposites presented here might inspire further research into engineering multifunctional nanocomposites via assemblies of emerging layered 2D nanomaterials.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.6b07326.

Additional text and 6 equations describing calculation of photothermal conversion efficiency; 13 figures showing Raman spectra and XRD patterns of bulk MoSe₂ powder and PVP-coated MoSe₂ nanosheets, DLS result and ζ potential of diluted nanosheet dispersion, FESEM images of PVP-MoSe₂ nanosheets, XPS spectra of PVP-coated MoSe₂ nanosheets, stability of MoSe₂ nanosheets in different aqueous solutions, photostability, uptake assay of HeLa cells, time-dependent temperature rise curves of nanocomposite hydrogels under NIR laser irradiation, FTIR spectra and FESEM images of PVP-MoSe₂ nanosheets/PNIPAM hydrogel, and standard calibration curve for DOX at 480 nm in UV–vis spectra (PDF)

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Notes

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REFERENCES


