Research Article

Facile Fabrication of $\text{SrTiO}_3\text{@MoS}_2$ Composite Nanofibers for Excellent Photodetector Application

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Molybdenum disulfide (MoS_2), as a kind of transition metal dichalcogenide, has been widely studied for its excellent compatibility with most of inorganic nanomaterials. Nevertheless, its microscale and agglomeration limit the performance severely. Therefore, the special structure of V- MoS_2 has drawn a lot of interest, which can not only reduce the size of MoS_2 nanosheets but also improve the valence electron structure of the materials. In this work, $\text{SrTiO}_3\text{@MoS}_2$ composite nanofibers were synthesized by the simple electrospinning and hydrothermal method, and it was applied as a novel material for photodetector. SEM, TEM, EDX, XRD, I-T curves, and EIS analysis were used to study the structure and properties of the prepared $\text{SrTiO}_3\text{@MoS}_2$ composite nanofibers. Simulating under sunlight at a potential of 1.23 V, the prepared composite materials exhibited a superior photoelectric performance of photocurrent density of $21.4 \mu\text{A}$ and a resistance of 2.3Ω . These results indicate that the composite of SrTiO_3 nanofiber adhered with V- MoS_2 has a stable composite structure, good electrical conductivity, and photoelectric sensitivity and is a suitable material for photodetectors. This work provides new ideas for the preparation of self-assembled materials and their application in photodetectors.

1. Introduction

As we all know, water pollution, greenhouse effect, and fumes are hazardous to human beings, but few people notice that potential light pollution is also threatening our health [1–4]. Light is everywhere in our life; in fact, proper sunlight is useful for our health. However, excessive light may damage our eyesight, affect our emotions, and even induce cancer [5]. The light pollution mainly originated from assimilation lighting and massive use of architectural glass, particularly in the developed region. To solve this problem, photodetector has been widely studied as optoelectronic devices [6–8].

As a member of semiconductors, transition metal dichalcogenides (TMDCs) have shown perfect properties of its special band structure, fairly physical character, and

superconductive performance [9, 10]. Within all kinds of materials of TMDCs, molybdenum disulfide (MoS_2) has attracted more and more attention due to its special structure, excellent compatibility with abundant nanoscale materials, and attractive price [11]. Therefore, MoS_2 has been used in many fields such as nano-electronic devices and optoelectronics. However, the performance of MoS_2 was limited by the lamellae stacking and the lack of active sites [12]. Recently, vertical MoS_2 (V- MoS_2) has been reported frequently in the field of photoelectricity [13]. The photoelectric performance of MoS_2 nanosheets has been improved by building a V- MoS_2 structure at the nanoscale and changing MoS_2 from a multilayer structure to a single-layer structure. Moreover, high-quality V- MoS_2 structure has a stable reproducible optoelectronic performance and is easy to fabricate. In addition, V- MoS_2 with a single-layer

structure can form Mo-O bonds, which can further improve the sensitivity of the photodetector [14–16]. However, many efforts have been made to construct the V-MoS₂ structure, but most of them are still unsatisfactory for their poor performance and instability.

In this work, porous SrTiO₃ nanofibers embedded with MoS₂ nanosheets were constructed through electrospinning and hydrothermal method, which showed a V-MoS₂ structure [17–20]. The porous nanofibers can provide a stable substrate for delamination of MoS₂ to form a vertical monolayer structure. The prepared MoS₂-based material exhibited a sensitive optoelectronic performance through current density curves and Nyquist EIS plots characterization [21–23].

2. Materials and Methods

2.1. Materials. PVP (molecular weight = 1 300 000), thioacetamide (C₂H₅NS), tetrabutyl titanate (TBOT; C₁₆H₃₆O₄Ti), acetic acid (C₂H₄O₂), 2-methoxyethanol (C₃H₈O₂), strontium acetate (C₄H₆O₄Sr), sodium molybdate (Na₂MoH₄O₆), thioacetamide (C₂H₅NS), Pluronic F127, and hexadecyl trimethylammonium bromide (CTAB) were purchased from Aladdin Reagent Co, Ltd. All chemical reagents were of analytical grade (AR) and used without any further purification. The ultrapure water used throughout the experiments was extracted from a Milli-Q Millipore All Filter system (Millipore Co, Bedford, MA, USA).

2.2. Synthesis of Porous SrTiO₃ Nanofibers. In brief, tetrabutyl titanate (TBOT) and strontium acetate were dissolved in 10 mL acetic acid at a mass ratio of 1.6:1. The mixture was vigorously stirred for 15 min until the solution transformed to transparent, and it was named solution A. Then, PVP, Pluronic F127, and CTAB were put into 6 mL 2-methoxyethanol at a mass ratio of 1:0.5:0.7 with vigorous stirring for 15 min, which has been deeply explored in previous work to ensure the proper ratio of these reagents [17]. When the mixture became transparent viscous liquid, solution A was dropped to the liquid slowly and stirred overnight. Next, the mixture was put into syringe and applied a 15 kV electric voltage at the distance of 20 cm. The ejected rate was set 0.5 ml h⁻¹ to obtain the nanofiber membrane. Then, the prepared membrane was under pyroprocessing at 700°C for 3 h at a ramp rate of 2°C min⁻¹ to obtain the porous SrTiO₃ nanofibers.

2.3. Synthesis of SrTiO₃@MoS₂ 2D Structure. Typically, C₂H₅NS and Na₂MoO₄·2H₂O with a mass ratio of 3:5 were dissolved in 15 mL ultrapure water. Then, 150 mg porous SrTiO₃ nanofibers were put into the solution. The mixed solution was then shifted to a 50 mL hydrothermal reactor and heated at 220°C for 24 h. Ultimately, the SrTiO₃@MoS₂ 2D structure was obtained through filtration separation and vacuum drying [24].

2.4. Photo(electro)chemical Measurements. 8 mg SrTiO₃@MoS₂ sample and 1 mg acetylene black were transferred to a

25 mL beaker with 10 mL absolute alcohol, and then, 10 μL PTFE was dropped into the mixture with vigorous stirring. The mixed solution was ultrasonic treated for about 30 min and shaken well at last 2 min. After that, the beaker was put into a vacuum drying oven to evaporate the alcohol for 3 h and then transferred the sediment to the nickel foam. Finally, put the nickel foam into a vacuum oven at 100°C overnight and obtain the working electrodes. The photo (electro) chemical test was performed using a CHI660 electrochemical workstation with a standard three-electrode system with a graphene rod, an Ag/AgCl electrode, and nickel foam, respectively. All the measurements were tested in 1 M KOH aqueous solution under simulated solar light, which was provided by a 300 W Xe lamp. The change in the current density curve with time was tested at a potential of 1.23 V under light on/off condition [25]. The electrochemical impedance spectroscopy (EIS) tests were measured in a frequency range from 100 kHz to 0.1 Hz with an amplitude of 5 mV at $\eta = -0.24$ V [26–30].

2.5. Characterizations. X-ray diffraction (XRD) analyses of the as-prepared samples were investigated with an X-ray diffractometer (SmartLab, Rigaku, Akishima, Japan). The morphologies of prepared samples were obtained by using transmission electron microscopy (TEM) (HT7700, Hitachi High Technologies Corporation, Ibaraki, Japan) and field-emission scanning electron microscopy (SEM, S-4800II, Hitachi, Japan). Elemental map results were investigated with an Oxford Link-ISIS X-ray EDXS microanalyzer at 200 kV with SEM. All the ultrapure water used in the experiment was purified in a Milli-Q Millipore All Filter system (Millipore Co, Bedford, MA, USA).

3. Results and Discussion

3.1. Characterization of SrTiO₃@MoS₂. The morphologies of as-prepared materials were obtained by transmission electron microscopy (TEM) and scanning electron microscopy (SEM). Figure 1(a) shows the SEM image of electrospun nanofibers before calcined, which mainly consisted of PVP, F127, and other ions. The diameter of nanofibers is approximately 1–3 μm and evenly distributed with a network structure. Figure 1(b) shows the image of nanofibers after being calcined at 700°C, and the surface of fibers becomes rough and shows many pores. It can be clearly observed that the diameter of fiber reduced to about 300 nm with 10–20 nm aperture gap uniform distributes on the surface. This special morphology is mainly caused by the synergistic effect of F127 and CTAB, which has been studied systematically in the earlier works. This special structure can greatly increase the surface area of SrTiO₃ NFs and provide suitable sites for loading MoS₂ [31–36]. In addition, the pores in the nanofibers can magnify the contact area between electrodes and electrolytes and optimize the structure of valence electron transmission. Figure 1(c) exhibits the result of SrTiO₃@MoS₂ composite nanofibers. It can be found that the triangular MoS₂ nanosheets firmly embed in the aperture gap of SrTiO₃ nanofibers to form a V-MoS₂ structure. TEM is carried out to further

FIGURE 1: SEM images of (a) nanofibers before calcination, (b) porous SrTiO_3 NFs, and (c) $\text{SrTiO}_3@\text{MoS}_2$ composite nanofibers. TEM images of (d) nanofibers before calcination, (e) porous SrTiO_3 NFs, and (f) $\text{SrTiO}_3@\text{MoS}_2$ composite nanofibers.

explore the structure of MoS_2 on $\text{SrTiO}_3@\text{MoS}_2$ hybrids, as shown in Figures 1(d)–1(f). From Figure 1(d), the diameter of as-spun nanofibers is about 200 nm, which corresponds to the SEM images. As shown in Figure 1(e), it can be observed that the calcined nanofibers are highly porous due to the different electron penetrability of various positions [37–46]. Figure 1(f) shows the composite nanofibers of $\text{SrTiO}_3@\text{MoS}_2$, and it can be clearly seen that the MoS_2 nanosheets and porous nanofibers combine tightly. Furthermore, the sample was under ultrasonic treatment for about 15 min before TEM operation, and the MoS_2 nanosheets were still adhered in the nanofibers. This phenomenon can convincingly demonstrate the stability of $\text{SrTiO}_3@\text{MoS}_2$ composite nanomaterials. The mesoporous structure in NFs provided an excellent adhesion environment to form the V- MoS_2 structure [47].

The elemental map is one of the most commonly used techniques to observe the morphology of elements distribution. The SEM mapping of bare SrTiO_3 nanofibers and $\text{SrTiO}_3@\text{MoS}_2$ hybrids is shown in Figure 2. Figures 2(a)–2(d) illustrate that the elemental map of SrTiO_3 nanofibers includes Ti, Sr, and O elements. The distribution of elements matches well with the shape of nanofibers, which indicate that the porous SrTiO_3 nanofibers have been successfully prepared. Figures 2(e)–2(j) show the presence of Ti, Sr, O, Mo, and S elements on the surface of $\text{SrTiO}_3@\text{MoS}_2$ hybrids, proving that the MoS_2 nanosheets have been successfully adhere to the nanofibers.

The crystallographic structure of the prepared materials is shown in Figure 3, illustrated by the XRD profiles. The porous SrTiO_3 nanofibers and pure MoS_2 are precisely indexed to the JCPDS 35-0734 and JCPDS 37-1492, respectively. For 2D $\text{SrTiO}_3@\text{MoS}_2$ composite nanofibers, the XRD peaks of SrTiO_3 appeared at 23° , 32° , 40° , 47° , 52° , 58° , 68° , and 77° can be assigned to the (100), (110), (111), (200), (210), (211), (220), and (310) planes, respectively. Nevertheless, the peaks of

MoS_2 are very weak or deviated in the composite XRD patterns. The V- MoS_2 delaminated in the porous nanofibers may be due to the crystalline form changed. Interestingly, we can see some heteropeaks in the composite XRD patterns, and we discovered that the heteropeaks can fit well with the elemental sulfur. Thus, we inferred that not all the thioacetamide transferred to the MoS_2 , a small amount of thioacetamide transferred to elemental S and adhered to the nanofibers, and causes some heteropeaks.

In order to illustrate the high photoelectric conversion capacity of the $\text{SrTiO}_3@\text{MoS}_2$ composite nanofibers, the mechanism illustration is shown in Figure 4. Under simulate sunlight illumination, the porous SrTiO_3 nanofibers produce photogenerated electrons, and the holes were left in the nanofibers. For the pure SrTiO_3 , the electrons and holes will recombine quickly and decrease the photoelectric performance immensely. However, after composing the V- MoS_2 , the conduction band position of SrTiO_3 is much higher than MoS_2 . The photogenerated electrons will transfer to MoS_2 and restrain the recombine of electrons and holes, which make the electrons more mobile and promote the photoelectric performance. Therefore, the V- MoS_2 structure can enlarge the surface area of materials and increase the active sites. In addition, the particular structure can retard the recombination of electrons and holes and then enhance the prolong of photoelectrons.

3.2. Optoelectronic Performance Test. Photocurrents and the electrochemical impedance spectroscopy (EIS) were used to explore the photoelectric conversion sensitivity and electronic transmission rate of the as-prepared samples. Figure 5(a) shows the I-T curves tested in the condition of the on-off cycle simulated sunlight for the pure SrTiO_3 nanofibers and $\text{SrTiO}_3@\text{MoS}_2$ heterostructure. The result of

FIGURE 2: SEM image of (a) porous SrTiO₃ nanofibers with (b–d) Ti/S/Sr elemental mapping and SEM image of (e) SrTiO₃@MoS₂ composite nanofibers with (f–j) Mo/S/Ti/Sr/O elemental mapping and (k) EDX images of SrTiO₃@MoS₂ composite nanofibers.

FIGURE 3: XRD patterns of pure MoS₂ nanosheets, porous SrTiO₃ nanofibers, and SrTiO₃@MoS₂ composite nanofibers.

SrTiO₃@MoS₂ indicates the photocurrent density is 21.4 μA , which is nearly twice higher than the pure SrTiO₃ nanofibers (10.1 μA). These results can prove that the adhering of MoS₂ improves the conductivity of materials and promotes the electron transfer rate. In addition, the V-MoS₂ nanosheets can increase the surface area of nanofibers and improve the photosensitivity and the separation of photo-induced carriers. It is also worth noting that photocurrent curves show a

regular rectangle shape, indicating the stability of composite materials. The EIS results in Figure 5(b) were applied to confirm the conductivity of the prepared composite. Moreover, the Rct of SrTiO₃@MoS₂ is lower than that of porous SrTiO₃ nanofibers, indicating that the V-MoS₂ on the nanofibers can accelerate the interfacial transfer and separation of charge carriers and then improve the optoelectronic performance. The use of MoS₂ to improve the

FIGURE 4: Schematic diagram of the photoelectric conversion mechanism of $\text{SrTiO}_3/\text{MoS}_2$ composite nanofibers.

FIGURE 5: (a) The current density curves as a function of the time for SrTiO_3 and $\text{SrTiO}_3/\text{MoS}_2$ at 1.23 V in 1 M KOH electrolyte; (b) Nyquist plots of samples at -0.24 V versus RHE measured from EIS in the frequency range from 100 kHz to 0.1 Hz.

performance of materials can be included in two reasons: first, the MoS_2 improves the electronic orbital structure of the SrTiO_3 and prolongs the life of photoelectrons. Then, constructing the structure of V- MoS_2 enlarges the surface area of materials, which means a larger contact area between electrodes and electrolytes.

4. Conclusions

In summary, new $\text{SrTiO}_3/\text{MoS}_2$ composite materials were successfully synthesized. The structure and morphologies of the prepared composite were studied by SEM, TEM, EDX, XRD, I-T curves, and EIS analysis. The large surface area of

the obtained SrTiO_3 NFs can provide suitable sites for loading MoS_2 . Under simulate sunlight at a potential of 1.23 V, the prepared composite materials exhibited a superior photoelectric performance of photocurrent density of $21.4 \mu\text{A}$ and a resistance of 2.3Ω . This study provides new clues for the preparation of MoS_2 -based composite materials and is widely used in the field of photodetector.

Data Availability

The experimental data used to support the findings of this study are included in the manuscript. The other data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

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