Preparation of SnS$_2$ colloidal quantum dots and their application in organic/inorganic hybrid solar cells

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Abstract

Dispersive SnS$_2$ colloidal quantum dots have been synthesized via hot-injection method. Hybrid photovoltaic devices based on blends of a conjugated polymer poly[2-methoxy-5-(3',7''-dimethyloctyloxy)-1,4-phenylenevinylene] (MDMO-PPV) as electron donor and crystalline SnS$_2$ quantum dots as electron acceptor have been studied. Photoluminescence measurement has been performed to study the surfactant effect on the excitons splitting process. The photocurrent of solar cells with the hybrid depends greatly on the ligands exchange as well as the device heat treatment. AFM characterization has demonstrated morphology changes happening upon surfactant replacement and annealing, which can explain the performance variation of hybrid solar cells.

Introduction

Organic-inorganic hybrid bulk-heterojunction (BHJ) solar cell is an interesting alternative to the all-organic solar cells with replacement of the organic n-type material with inorganic nano-particles (NPs). This new kind of solar cell aims at combining the solution processability of conjugated polymers with high electron mobility and the relative environmental stability of inorganic semiconductors. Up to now, various NPs such as CdSe [1-3], PbS [4], TiO$_2$ [5], ZnO [6], or heterojunction nano-crystals [7-9] have been applied in organic-inorganic BHJ solar cells. The best solar cell adopting inorganic nano-phase as the electron acceptor demonstrated a power conversion efficiency exceeding 3% using CdSe tetrapods [3]. However, compared with this toxic material, a nontoxic, environmental-friendly alternative may be more attractive in the future application of this kind of cells.

Tin disulfide (SnS$_2$) is a fullerene-like semiconductor with a band gap of about 2.35 eV [10]. In this study, the consideration of SnS$_2$ as electron acceptor in BHJ solar cell is based on its several advantages. Comparing with Cd-containing inorganic nanoparticles, SnS$_2$ is easy to prepare, nontoxic, and environment-friendly, with an abundant content of row materials in the earth. Besides, it has an appropriate energy level distribution when forming hybrid with an electron donor such as MDMO-PPV; electrons transfer at the interface is convenient. Furthermore, as a fullerene-like semiconductor, it is easy to form a net-like interpenetrating connection between particles, which is greatly beneficial to electrons transportation. Up to now, extensive research has been focused on its application of gas-sensing [11], lithium batteries [12], and electrical switching [13]. As a photoconductive semiconductor, its potential application in solar cells is rear. Our previous study has shown that SnS$_2$ nano-particles with a crystalline/amorphous blended phase demonstrated obvious photovoltaic property as an electron acceptor when blending with an organic semiconductor poly[2-methoxy-5-(3',7''-dimethyloctyloxy)-1,4-phenylenevinylene] (MDMO-PPV) [14]. However, the conversion efficiency may be influenced due to the not well-dispersed and well-crystallized SnS$_2$ particles prepared at low temperature. Other commonly used methods such as solvothermal [15] or chemical and vapor deposition [16] usually generated very large particles, which is not suitable for hybrid BHJ solar cells. A dispersive and well-crystallized SnS$_2$ nanoparticle is of great necessity to form an interpenetrating electron tunneling path in the hybrid BHJ solar cells.

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Herein, SnS$_2$ colloidal quantum dot that is up to the role in organic/inorganic hybrid BHJ solar cell is prepared via hot-injection method [17,18]. The hybrid solution containing SnS$_2$ quantum dots and MDMO-PPV in chloroform or chlorobenzene is clear and transparency. Solar cells using these quantum dots as electron acceptor generate an improved photovoltaic property after replacing the insulating surfactant on the particles surface. The result of this research suggests this easy-prepared nontoxic semiconductor could be a promising candidate for BHJ solar cells.

**Experiment**

**Synthesis of SnS$_2$ colloidal quantum dots via hot-injection method**

All chemicals are used as-received without further treatment. In a typical reaction, 0.26 g of tin (IV) chloride anhydrous (SnCl$_4$, 99.0±%, Sinopharm, Beijing, China) is added to 20 ml of oleylamine (OLA, 80+%, Aladdin, Shanghai) in a 50-ml three-neck flask. The mixture is purged with N$_2$ for 30 min at 120°C and heated to 200°C. Then 3 ml of OLA containing 0.22 g of thioacetamide (TAA, 99.0±%, Sinopharm, Beijing, China) is injected into the mixture quickly. The reaction is kept at 200°C with N$_2$ purging for 12 h and then cooled down to room temperature. The as-formed nanocrystals are isolated by precipitation with ethanol followed by centrifugation. The final product, SnS$_2$ quantum dot, is washed three more times with solvent/antisolvent precipitation with chlorobenzene/ethanol.

For a better application in hybrid BHJ solar cell, the OLA ligands on the surface of SnS$_2$ colloidal quantum dots are partly replaced by stirring the final product in anhydrous pyridine at 60°C for 1 h and ultrasonicated at 40°C for 1 h. After that, the particles are precipitated with hexanes at room temperature, recollected by centrifugation, and then dispersed into a mixture of chlorobenzene/pyridine (90:10, vol/vol) for further use.

**Fabrication of hybrid bulk-heterojunction solar cells**

The fabrication process of hybrid BHJ solar cells is as follows. Poly(thiophene) (3,4-ethylenedioxythiophene)/poly(styrenesulfonate) (PEDOT:PSS) is spin coated at 2400 rpm onto the ITO substrates those are precleaned by soap water followed by deionized water, and then ultrasonicated in acetone and isopropanol. After the ITO/PEDOT:PSS is annealed at 140°C for 1 h, it is transferred into a glove box together with the organic/inorganic-blended solution. The mixture is prepared by blending SnS$_2$ and MDMO-PPV in chlorobenzene with different mass ratios and then ultrasonicated for about 1 min to form a transparent solution. Hybrid BHJ films with an optimized thickness of about 120 nm are achieved by spin-coating the mixture on PEDOT:PSS at 1500 rpm for 30 s in a N$_2$ atmosphere in a glove box. Afterward, onto the hybrid film, a ZnO buffer layer of about 20 nm is obtained by spin-coating a ZnO methanol solution (30 mg/ml, 3000 rpm) [19]. The solar cells fabrication is then finished by thermally depositing a 100-nm aluminum cathode on top.

The crystalline phase pattern of SnS$_2$ particles is characterized by X-ray diffraction (XRD) on a Rigaku D/ max-ga X-ray diffractometer with Cu Kα radiation. Its morphology is given by a transmission electron microscopy (TEM) on a Hitachi H-800 at an acceleration voltage at 80 kV. Absorption spectrum (Abs) and photoluminescence (PL) measurements are carried out on Varian U-3000 model ultraviolet-visible spectrophotometer and Varian Cary Eclipse fluorescence spectrophotometer, respectively. The surface morphology of hybrid MDMO-PPV:SnS$_2$ films is characterized on Solver P47 scanning probe microscopy (SPM). The current-voltage (I-V) measurements on the MDMO-PPV: SnS$_2$ BHJ solar cells are performed on Keithley 2400 source in forward bias mode under AM 1.5 100 mW/cm$^2$ illumination.

**Results and discussion**

**Characterization of SnS$_2$ and its hybrid with MDMO-PPV**

The TEM images and SEAD measurement of SnS$_2$ nano-particles distilled at different reaction times are shown in Figure 1. Corresponding to morphology in Figure 1a, SEAD in Figure 1 (1) exhibits an amorphous phase and the beginning reaction. It turns to a formation of polycrystalline when further increasing reaction time, and then again, amorphization formed. It reveals such a reaction process as precursor decomposition (Figure 1a) followed by quantum dot precipitation (Figure 1b,c) and then redissolving into the solution (Figure 1d). In fact, after the TAA-OLA solution was injected, a phenomenon was observed that the reaction mixture first turned from turbid orange to semi-transparent yellow and then becomes clearly transparent yellow. When the reaction temperature was increased, just less time was needed for this variation. It can be seen from Figure 1 that an optimal reaction for SnS$_2$ colloidal quantum dots was happened at 12 h, which generated a dispersive SnS$_2$ quantum dot about 5-7 nm in size. The crystalline phase of SnS$_2$ particles is demonstrated by XRD in Figure 2 from which the crystalline transformation process can also be observed. All the characteristic diffraction peaks corresponding to a berndtite-4 type (PDF card 21-1231) appear when the reaction persists for 12 h. Nano-size of SnS$_2$ at this time is about 5.3 nm, which is obtained from the Scherrer equation $D = K \lambda/\beta \cos \theta$ where $D$ is the diameter of the synthesized crystals, $\beta$ is the full-width half-maximum, and $\theta$ is the diffraction angle. Further reaction up to 30 h caused dissolving of
SnS$_2$ particles through forming coordinated organic compound with OLA. Thus, diffraction signal mainly demonstrate an amorphous phase in the longer time reacted product.

The absorption spectra of SnS$_2$ nano-particles in chlorobenzene are shown in Figure 3. SnS$_2$ sample reacted for 0.25 h does not show an obvious absorption near its bandgap energy region. It is due to the presence of an amorphous precursor that is not crystallized. Samples at 2 and 5 h exhibit obvious absorption peaks at 450 nm, suggesting the formation of nano-particles. The absorption of SnS$_2$ with a final reaction time of 12 h is a little intensified and shows a slight red-shift, which is caused by an enlarged particle size. From the absorption spectrum, the optical bandgap of SnS$_2$ particles can be obtained which is shown as the inset in Figure 3. SnS$_2$ nano-particles reacting for 12 h generated a band-gap value of about 2.66, 0.3 eV larger than its bulk phase due to the quantum size effect. The absorption properties of SnS$_2$ and MDMO-PPV blends in chlorobenzene are given in Figure 4. It is simply a superposition of the respective absorption spectra of pure MDMO-PPV and SnS$_2$ nano-particles at longer and shorter wavelength. The absorption of SnS$_2$ at 450 nm in the blends is not obvious; this is probably due to its weaker absorbance comparing to MDMO-PPV. The introduction and increasing weight ratio of SnS$_2$ in organic/inorganic hybrids cause more obvious absorption enhancement in ultra-violet region, mainly because of the intensive absorption property of nano-particles [20-22]. Although light absorption enhancement is commonly existed in organic-inorganic hybrid systems due to the introduction of inorganic nano-particles, its contribution to the photocurrent of hybrid solar cells is not confirmable because of many other caused variations such as excitons splitting and so on.

Photoluminescence (PL) spectrum is used to research how the addition of SnS$_2$ affects the photo-generated charge transfer in the hybrid. Figure 5 shows the PL quenching of MDMO-PPV following the increasing concentration of SnS$_2$. Indeed, the spectra show that the PL intensity is increasingly lost upon addition of SnS$_2$ due to the formation of coordination compounds.
to the fast, sub-picosecond forward electron transfer from MDMO-PPV to SnS2. At 50 wt% SnS2, about 40% of the PL is quenched, and at 90 wt% SnS2, 80% of the PL is quenched. Further increasing of the concentration of SnS2 will not obviously quench the PL. This is attributed to a saturated organic/inorganic interface, which will further decrease the lifetime of photo-generated excitons [23]. Inset in Figure 5 shows the PL spectrum of SnS2 reacted for 12 h. It exhibits two strong emission peaks at 545 and 490 nm. The former is corresponding to radiative recombination of quantum confined electron-hole pair that in energy is a little smaller than the energy bandgap of nanocrystals [24]. The latter is not clear for us at present. We suppose it may be due to radiated recombination of excitons’ absorption-generated electrons lying at higher excited energy levels.

The surfactant on the SnS2 particles affects the electron transfer from MDMO-PPV to SnS2 so that the PL quenching intensity may be influenced. This can be demonstrated by replacing the long insulating OLA ligands with pyridine. As is shown in Figure 6, comparing with that of SnS2 with OLA ligands on surface, the PL intensity is obviously further decreased after treating with pyridine, suggesting a more efficient charge transfer between the organic and the inorganic materials. This is of great importance for the use of active layers in hybrid solar cells.

**Performance of BHJ solar cells with MDMO-PPV:SnS2 hybrid**

Detailed influence of pyridine-processed SnS2 concentration in the hybrid film on the photovoltaic performance
is given in Figure 7 in which several characteristics can be noted. Figure 7a shows that current density (Jsc) initially increases with increasing amount of SnS₂, reaches the maximum at 50 wt% SnS₂, and then decreases with further increasing the SnS₂ concentration. This trend might be related to the increased formation of free charges inferred from the PL quenching and/or the formation of more percolation pathways of SnS₂ particles that facilitate electrons transport at initial amount increasing of SnS₂ [25]. On the other hand, high SnS₂ concentrations may induce large-scale phase separation due to particles aggregation [26], so that the donor-acceptor contact is affected, which is deleterious to device photocurrent. The open circuit voltage (Voc) decreases slightly when the amount of SnS₂ increases. This might be due to the formation of shunts that may conduct charges from electrode to electrode. This likelihood increases once increasing the SnS₂ concentration. Generally, the value of fill factor (FF) is enlarged from 0.23 to 0.45 by increasing the amount of SnS₂ in the blend. This trend can be analyzed by reasoning that FF is a measure for the balance between free electrons and holes transport. While keeping the polymer concentration unchanged, increasing the SnS₂ concentration will increase the electrons transport efficiency so that more balanced charge transportation is achieved. The overall trend, when all parameters are combined into the transformation efficiency (Eff) is that it reaches the largest of about 0.26% at 50 wt% SnS₂ concentration. This concentration is different from the optimal amounts required for ZnO in MDMO-PPV:ZnO blends (67%) [6] and CdSe in PCPDTBT: CdSe blends (90%) [3]. From the curve shape, we can see that the efficiency variation is derived mostly by photocurrent.

To study the effect of surfactant on the photovoltaic performance, solar cells with and without pyridine treatment are fabricated and characterized. Also researched is the MDMO-PPV:pyridine-SnS₂ solar cell annealed at an optimized temperature of 150°C. The performances of solar cells with the same SnS₂ weight ratio of 50% in the three devices are shown in Figure 8. All the solar cells exhibit good diode behaviors in dark. Compared with the cell without pyridine treating, solar cell with pyridine exchange shows enhanced short circuit current density from 0.65 to 0.73 mA/cm² while keeping the open circuit voltage and fill factor nearly the same, about 0.88 V and 0.4, respectively. The Jsc exhibits further enhancement up to 0.88 mA/cm² through annealing. The opt-electric transformation efficiency of solar cell with pyridine is 0.263%, larger than that without pyridine, 0.204%, and this parameter goes up to 0.31% when the device with pyridine was annealed. The increasing in photocurrent upon surfactant exchange can be explained that charge transfer process at the interface of MDMO-PPV and SnS₂ could be more suited to happen, followed by a convenient free electrons transport among SnS₂ particles because of the benzene ring and small size of the pyridine molecule. However,
an additional dominant reason that induces the $J_{sc}$ enhancement after annealing might be optimized organic and inorganic phase separation as well as continuous electron transport through compact SnS$_2$ connections after the remain solvent’s elimination. This can be demonstrated by characterizing the surface morphology of different hybrid films, which are shown in Figure 9.

Compared with the homogeneous and flat MDMO-PPV film as shown in Figure 9A and a, the hybrid film containing OLA-linked SnS$_2$ shows clearly two phases (Figure 9B). The SnS$_2$ phase that is present as small protrusions (no higher than 20 nm shown in Figure 9b) are well dispersed and immersed into the homogeneous organic phase, which demonstrates that the OLA-linked SnS$_2$ particles can form good contact with MDMO-PPV. The SnS$_2$ particles show more enlarged aggregation and protrusion after pyridine treating, so that phase separation as caused is clearly observed (Figure 9C). The hybrid film surface becomes rougher due to large SnS$_2$ aggregation (Figure 9c). This will cause decreased interface between SnS$_2$ and PPV. However, $J_{sc}$ characteristic of solar cells with pyridine-SnS$_2$ as acceptor is superior to that of solar cells with OLA-SnS$_2$. One can get the supposition that the exciton splitting efficiency should be compensated upon ligand exchange so that it will not be weakened due to phase separation and interface decreasing. The supposition can be demonstrated through photoluminescence property in Figure 5b that PL quenching happens more intensively than that without pyridine treatment. On the other hand, transportation process of free charges, especially electrons, may be favored from suitable phase separation due to enlarged and connected inorganic phase. After heat treatment, previous small SnS$_2$ aggregates, formed during pyridine exchange, will further connect and partly fuse with the
adjacent ones (Figure 9D). Thus, electrons can find a more convenient way to transport themselves to the electrode through interpenetrating networks. Besides, the film surface becomes much flatter after annealing (Figure 9d), which is beneficial to form a good contact between the active layer and the electrode. This is why the cell performance has an improvement after annealing. Noticed is that, the efficiency of our solar cell using SnS2 as the electron acceptor is relatively low comparing with other hybrid solar cells such as CdSe [3] and PbS [4]. This is mainly attributed to un-optimized particle morphology as well as the particle aggregation in the hybrid film, increasing the series resistance and decreasing current. On the other hand, SnS2 particles enhanced light absorption in the hybrid film is not obvious. Maybe this is our further study to improve the device performance in next step.

Conclusions

Dispersive SnS2 colloidal quantum dots are synthesized and considered as electrons acceptor in hybrid heterojunction solar cells containing a conjugated polymer (MDMO-PPV). It shows a best performance at the SnS2 weight ratio of 50%. OLA ligand on the particles should have an influence on the charges separation in the blends when characterizing through photoluminescence. Surfactant exchange using pyridine causes increased PL quenching, which suggests the enhanced excitons splitting efficiency. Thus, an obvious improvement in photocurrent as well as energy transversion efficiency is realized. Annealing treatment of the devices produces further increase in efficiency due to the enhancement of photocurrent. AFM studies have provided the insights into the variation of devices performance. Comparing with the uniformly distributed two phases in the OLA-SnS2:MDMO-PPV blended film, a phase separation in pyridine-SnS2:MDMO-PPV blending is appreciated on the photocurrent increase due to the pyridine ligand. Besides, not the isolated aggregates but the connected SnS2 networks after annealing are the best for the solar cells performance.

Abbreviations

Abs: absorption spectrum; BHJ: bulk-heterojunction; SnS2: disulfide; NPs: nano-particles; PL: photoluminescence; TEM: transmission electron microscopy; XRD: X-ray diffraction.

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Authors' contributions

FT participated in the design of the study, carried out the total experiment, performed the statistical analysis as well as drafted the manuscript. SQ participated in the guidance of experiment. JW and SL helped to give the corrections of the manuscript. ZW helped to give the theoretical guidance of the experiment. KL gave some help on the obtaining of the reading papers. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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References

1. Huynh WU, Dittmer J, Alivisatos AP: Hybrid Nanorod-Polymer Solar Cells. Science 2002, 295:2425.
2. Sun B, Snith HJ, Dhoit AS, Westenhoff S, Greenham NC: Vertically segregated hybrid blends for photovoltaic devices with improved efficiency. J Appl Phys 2005, 97:041941.
3. Dayal S, Kopidakis N, Olson DC, Gimley DS, Rumbles G: Photovoltaic devices with a low band gap polymer and CdSe nanostructures exceeding 3% efficiency. Nano Lett 2010, 10:239.
4. Watt AA, Blake DJ, Warner JP, Thomsen EA, Tavenner EL, Dunlop HR, Meredith P: Lead sulfide nanocrystal: conducting polymer solar cells. J Phys D 2005, 38:2006.
5. Zeng TW, Lin YY, Lo HH, Chen CW, Liu SC, Huang HY, Su WF: A large interconnecting network within hybrid MEH-PPV/TiO2 nanorod photovoltaic devices. Nanotechnology 2006, 17:3387.
6. Beek WJ, Wierk MM, Janssen RAJ: Efficient hybrid solar cells from zinc oxide nanoparticles and a conjugated polymer. Adv Mater 2004, 16:1009.
7. Lee H, Yoon SW, Kim EJ, Park J: In-situ growth of copper sulfide nanocrystals on multilayer carbon nanotubes and their application as novel novel solar cell and amperometric glucose sensor materials. Nano Lett 2007, 7:778.
8. Tang AW, Fong F, Wang Y, Hou YB, Han WY, Xi LX, Gao MY: Investigation on photovoltaic performance based on matchstick-Like Cu2S-In2S3 heterostructure nanocrystals and polymer. Nano Res Lett 2008, 3:502.
9. Wang Y, Hou YB, Tang AW, Feng ZH, Feng B, Li Y, Fong F: Effect of ZnCdTe-Alloyed Nanocrystals on Polymer-Fullerene Bulk Heterojunction Solar Cells. Nano Res Lett 2009, 4:674.
10. Domingo G, Itoya RS, Cannawurf CR: Fundamental Optical Absorption in SnS2 and SnSe2. Phys Rev 1966, 143:S6.
11. Shi WD, Luo H, Wang HS, Zhang HJ, Yang JH, Wei PH: Hydrothermal growth and gas sensing property of flower-shaped SnS2 nanocrystals. Nanotechnology 2006, 17:3218.
12. Abraham KM, Pasquariello DM, Martin F: Mixed Ether Electrolytes for Secondary Lithium Batteries with Improved Low Temperature Performance. J Electrochem Soc 1986, 133:661.
13. Patil SG, Fredgold RH: Electrical and photoconductive properties of SnS2 crystals. J Pure Appl Phys 1971, 4:718.
14. Tan FR, Qu SC, Zeng XB, Yang CS, Shi MJ, Wang ZJ, Jin L, Bi Y, Cao J, Wang ZG, Hou YB, Feng T, Feng ZH: Photovoltaic effect of tin disulfide with nanocrystalline/amorphous blended phases. Solid State Commun 2009, 150:S4.
15. Hai B, Tang K, Wang C: Synthesis of SnS2 nanocrystals via a solvothermal process. J Cryst Growth 2001, 225:92.
16. Aora SK, Patel DH, Agarwal MK: Dielectric behaviour of tin disulphide single crystals. Mater Chem Phys 1996, 4:563.
17. Raha SC, Parkinson BA, Prieto AL: Solution-Based Synthesis and Characterization of Cu2ZnSnS4 Nanocrystals. J Am Chem Soc 2009, 131:12054.
18. Jamie HW, Cao H: Shape control of PbS nanocrystals using multiple surfactants. Nanotechnology 2008, 19:35065.
19. Pacholaki C, Korniawski A, Weller H: Self-assembly of ZnO from nanodots to nanorods. Angew Chem Int Ed 2002, 41:1188.
20. Kim SJ, Kim WJ, Singh R, Samoc M, Cartwright AN, Prasad PN: Enhancement of the photovoltaic performance in PbS nanocrystal/P3HT hybrid composite devices by post-treatment-driven ligand exchange. Nanotechnology 2009, 20:05202.
21. Dayal S, Kopidakis N, Olson DC, Ginley DS, Rumbles G. Photovoltaic devices with a low band gap polymer and CdSe nanostructures exceeding 3% efficiency. Nano Lett 2010, 10:239.

22. Zeng TW, Lin YY, Lo HH, Chen CW, Chen CH, Liou SC, Huang HY, Su WF. A large interconnecting network within hybrid MEH-PPV/TiO2 nanorod photovoltaic devices. Nanotechnology 2006, 17:5387.

23. Beek WJE, Wienk MM, Kemerink M, Yang XN, Janssen RAJ. Hybrid Zinc Oxide Conjugated Polymer Bulk Heterojunction Solar Cells. J Phys Chem B 2005, 109:9505.

24. Yang Q, Tang K, Wang C, Zuo J, Zhang D, Qian Y. A hexane solution deposition of SnS2 films from tetrabutyltin via a solvothermal route at moderate temperature. Thin Solid Films 2003, 436:203.

25. Van-Duren JK, Yang X, Loos J, Bulle-Lieuwma CWT, Sieval AB, Hummelen JC, Janssen RAJ. Relating the morphology of poly(phenylene vinylene)/methanofullerene blends to solar-cell performance. Adv Funct Mater 2004, 14:425.

26. Hoppe H, Niggemann M, Wender C, Kraut J, Hiesgen R, Hirsch A, Meissner D, Sariciftci NS. Nanoscale Morphology of Conjugated Polymer/Fullerene-Based Bulk-Heterojunction Solar Cells. Adv Funct Mater 2004, 14:1005.

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