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A full-band sunlight-driven carbon nanotube/PEG/SiO_2 composites for solar energy storage

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ABSTRACT

Carbon nanotube/PEG/SiO_2 composites were prepared from multiwall carbon nanotubes, poly(ethylene glycol), and inorganic SiO_2, and found to be an efficient full-band sunlight conversion and storage device. Compared with traditional phase-change materials, the composite exhibited rapid and broadband visible light-harvesting characteristics, light-thermal conversion, thermal energy storage ability, form-stable effects, and high thermal conductivity. The results showed that the combination of a light–heat conversion agent and a phase change thermal storage material can effectively improve the efficiency of solar energy applications.

1. Introduction

The conversion, storage, and application of solar energy are attracting considerable attention because of the cleanliness and renewability of this type of energy [1–8]. In particular, the development of phase-change materials (PCMs) for storing solar thermal energy has become a hot research topic [9–14]. As solar thermal energy storing materials, form-stable PCMs are considered to have highly promising applications because of their excellent form-stable effects during phase transition [15,16]. Unfortunately, UV–vis light of the solar irradiation spectrum, which accounts for 45% of the total solar energy [17], cannot be directly or effectively applied by PCMs because of their low thermal efficiency [18,19]. The intermittence of time and space solar irradiation is also difficult to overcome [7]. Both these factors can significantly decrease solar energy utilization efficiency. Therefore, solar energy conversion materials with efficient full-band light-harvesting and photothermal conversion-thermal storage abilities are very promising for developing renewable and clean energy sources.

Our group has previously reported the introduction of an organic dye that selectively absorbs visible light into organic PCMs to improve the usage efficiency (η) of solar energy. This strategy has been proven to be promising [20,21]. η of visible light is >0.90 under corresponding single-band irradiation; for example, η of red solar energy materials is 0.956 under visible light irradiation from 550 to 650 nm. However, capturing and converting full-band solar irradiation are very difficult because the dye selectively absorbs visible light. η of solar energy materials with the ability of single-band selective absorption of visible light is <0.66 under visible light (from 400 nm to 700 nm). Accordingly, the present study aimed to capture and convert full-band solar irradiation. Multiwall carbon nanotubes (MWCNTs), which have a broad range of UV–vis light absorbance [22–28] and good light-thermal conversion capability [29–31], were introduced into a PCM system to obtain novel carbon nanotube/poly(ethylene glycol) (PEG)/SiO_2 composites capable of full-band light-driven reversible phase transition (Fig. 1). The novel form-stable PCM (MWCNT/PEG/SiO_2) was synthesized by a simple ultrasound-assisted sol–gel method (Fig. 2). MWCNTs were successfully introduced into MWCNT/PEG/SiO_2 composites as a photon antenna as an effective “photon capturer and molecular heater” of light-to-heat conversion [22–31]. The PCM in the MWCNT/PEG/SiO_2 composites stores heat energy through phase transition with high energy storage density [9,10]. The inorganic SiO_2 net of the MWCNT/PEG/SiO_2 composites serves as the supporting material and excellently maintains the form-stable effects. Thus, the novel sunlight-driven carbon nanotube/PEG/SiO_2 composites can realize highly efficient solar radiation applications.

The MWCNT/PEG/SiO_2 composites are advantageous over previously reported materials [20,21] because of their broadband harvesting conversion and high thermal conductivities. The visible-light-to-heat conversion and energy-storage efficiency of MWCNT/PEG/SiO_2 composites was determined to be $\eta=0.918$

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under full band visible light irradiation conditions (from 400 nm to 700 nm) using photothermal calculation methods. This result was higher than the ($\eta < 0.66$) value of our previously reported materials with single-band selective absorption of visible light (yellow, red, or blue). Additionally, the MWCNTs used to form the novel MWCNT/PEG/SiO_2 composites had a high thermal conductivity, [32] by which the heat storage and release time of MWCNT/PEG/SiO_2 composites could be shortened. So, our composites increased the energy utilization efficiency during the heat charging and discharging processes. The MWCNT/PEG/SiO_2 composites are essential prerequisites for the highly efficient use of solar radiation and extending their potential applications in renewable and clean energy sources.

2. Experimental

2.1. Materials

Tetraethoxyl silane (TEOS; 98% purity) was obtained from Sigma-Aldrich. PEG-6000 (PDI = 1.06) was purchased from Guoyao, Inc., China. MWCNTs (> 97% purity) was supplied by Shenzhen Nanotech Port Co. Ltd. (NTP, Shenzhen, PR China). Sodium dodecyl benzenesulfonate (SDBS) was obtained from Tianjin Fuchen Chemical Reagents Factory (Tianjin, PR China). All other materials were analytical grade and used without further purification.

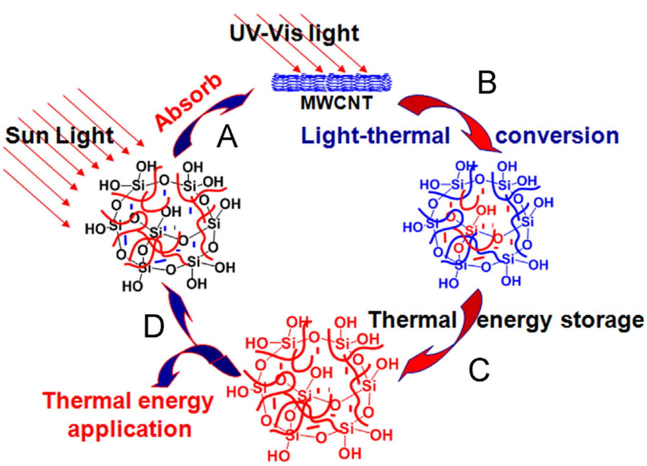

Fig. 1. Schematic of light-to-heat conversion and storage.

2.2. Synthesis of PEG/SiO_2/MWCNT by an ultrasound-assisted sol–gel method

Approximately 0.092 g of MWCNT and an equal amount of SDBS were mixed with 9.2 g of water. The mixture was ultrasonicated under 300 W of power for 4 h at 50 °C to obtain a well-dispersed suspension. After 20 min, the melted PEG was added to the mixtures under magnetic stirring.

The mixture of 6.5 g of TEOS and 5.6 g of deionized water (1:10 mol/mol) was pretreated under 300 W of ultrasound power for 10 min at 50 °C. A hydrochloric acid solution (c_{HCl} = 0.5 mol/L, V_{HCl} = 0.8 ml) was then added to the mixture. After 20 min, the dispersed MWCNT solution was added to the silica sol, and Na_2CO_3 ($c_{Na_2CO_3}$ = 100 g/L) aqueous solution was used to adjust the pH to ~7.0. A gel formed within a minute after adding aqueous Na_2CO_3 solution. The product was placed in a vacuum oven at 50 °C for 24 h. Finally, the hybrid form-stable PCMs were obtained.

2.3. Characterization of PEG/SiO_2/MWCNT

UV–vis absorption spectra (ranging from 220 nm to 1000 nm) were recorded with a UV 1801 spectrophotometer (Beijing Rayleigh Analytical Instrument Corporation) at 25 °C.

Infrared spectra of PEG/SiO_2 composite were recorded on a Perkin-Elmer 1600 FT-IR spectrometer.

Powder X-ray diffraction (XRD) patterns were obtained on a Rigaku D/MAX-2400 with Cu-Kα radiation. The scanning step size was 0.02°, and the 2θ range was from 5° to 80°.

Differential scanning calorimetry (DSC) was performed in N_2 atmosphere using an American TA Instruments 910S DSC thermal analyzer from 0 to 80 °C at a heating rate of 5 °C/min, N_2 flow rate of 20 mL/min, calorimeter precision of ±2.0%, and temperature measurements of ±2.0 °C. The samples were measured in a sealed

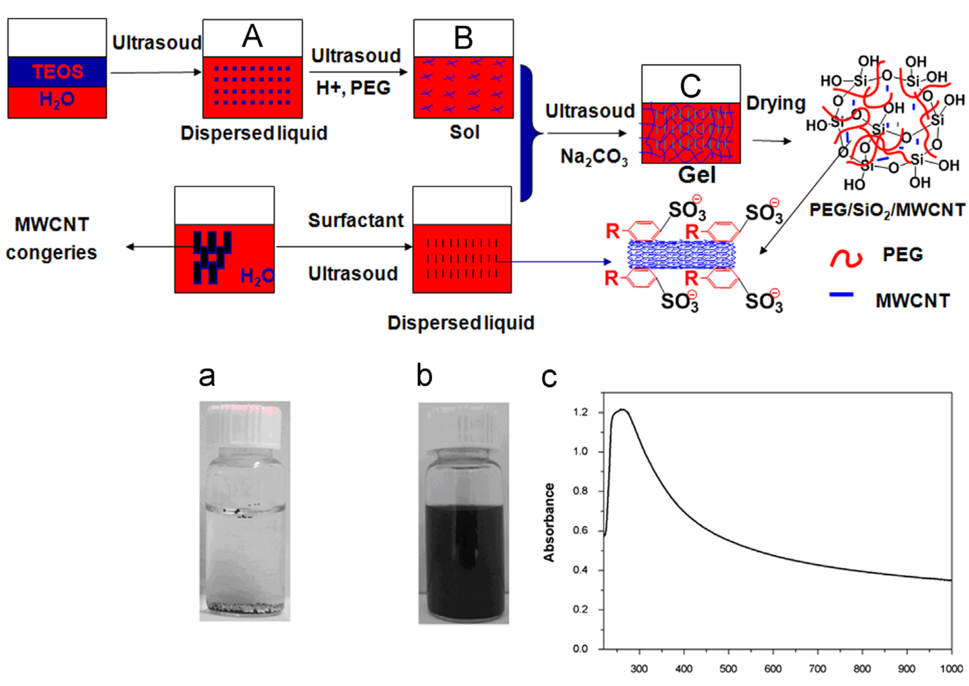

Fig. 2. Schematic of the synthesis of PCM assisted by ultrasound.