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Di-functional nanocomposite films for efficient conversion and storage of solar energy



Solar Energy Material

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ABSTRACT

There is no doubt that renewable sources, such as solar energy, have played an important role in the future renewable energy system. And solar heat has great potential and a high contribution towards the future energy supply. How to directly collect, fast convert and efficiently store solar heat is still a problem to be solved in solar energy application. Herein, the di-functional nanocomposite film was designed and fabricated toward efficient conversion and storage of solar thermal energy. The di-functional nanocomposite film was feasibly prepared by uniformly imbedding phase change materials (PCMs) and Au nanoparticles into PVA matrix uniformly through the hydrogen-bonding interactions. The Au nanoparticles, as photothermal nanoabsorbers, with a low concentration (~0.23% m/m), can instantly and intensely realize solar-to-heat conversion by utilizing surface plasmon resonance. Subsequently, efficiently conversion heat could be stored into the PCMs is observed due to the strong hydrogen-bonding confinement at interface between PCMs and the film matrix. This kind of difunctional nanocomposite films is of great importance and wide usage in the fields of solar thermal energy conversion and storage, thermal interface materials, protective layers and sensing, etc.

1. Introduction

Efficient conversion and storage of solar energy is particularly attractive since the solar power is the most plentiful, clean and lasting renewable energy source [1]. Utilization of solar energy is considered to be the most promising technology in the future energy system, in which solar heat has great potential in future solar energy usage [2]. The key is how to directly collect, fast convert and efficiently store the solar thermal energy for the further application. Plastic thin films, such as protective films, are excellent materials for solar thermal applications in agriculture due to their ability to regulate solar/heat transmission [3–5]. In recent years, to improve light absorption, some efforts have been made to improve light absorption by doping photo-selective additives in plastic materials during the process of conversion of solar energy. For example, organic dye molecules were integrated into poly (ethylene glycol) matrix to collect, absorb and convert visible light into heat [6-8]. Meanwhile, to improve the overall thermal conductivity of solar thermal thin films, high thermal conductivity fillers, including metal/metal oxide particles [9,10] and a variety of carbon materials [11–15], were used considering that these fillers can accelerate the thermal diffusion from light absorber [16–20]. The inherent defects of thermal thin films, such as low thermal conductivity and low thermal storage, may restrict its partial practical application. Therefore, a well-designed di-functional nanocomposite films toward fast solar-to-heat conversion and their efficient storage of solar energy is remained in urgent demands.

Herein, different from previous work, we designed and fabricated a di-functional nanocomposite film by combining rapid photo-thermal conversion and efficient thermal storage. The photothermal effect of Au nanoparticles (Au NPs) is attributed to the plasmon resonance, which speeded up the heating rate of organic plastic film matrix. Meanwhile, illuminating this kind of film by sunlight or a low-power pulsed laser, the generated heat could be charged into PCMs for storage. What's more, the PCMs exhibit a highly film-interior reversible phase change, in which neither leakage of PCMs nor change of film shape is observed due to the strong hydrogen-bonding confinement between PCMs and the matrix. Compared with ordinary films, the thermal storage efficiency of the di-functional nanocomposite film was enhanced by 201%, exhibiting an outstanding ability to store thermal energy. The current obtained di-functional nanocomposite films have great poten-

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Scheme 1. The design concept of the di-functional nanocomposite film combining rapid solar-to-heat conversion and thermal storage and release.

tial in wide application fields involving photo thermal energy conversion and storage.

Firstly, the design concept we proposed is illustrated in Scheme 1. The Au NPs were chosen as photothermal nanoabsorbers, in that the incident light excites Au NPs to transfer energy to lattice vibrations on a picosecond timescale. As a result, energy absorbed at or near the plasmon resonant frequency is rapidly converted to heat [21–23]. It is a prerequisite for fabricating a film with rapid photothermal conversion. The Au NPs of small size were confirmed to have the best performance of photothermal conversion efficiency and conversion stability compared with other materials at the same conditions, including PbS NPs, organic dyes and carbon black [24]. Secondly, PCMs can store and release more latent heat than other sensible heat materials. Therefore, the ability to absorb heat from environment offers a strong thermal energy function [25].

2. Results and discussion

2.1. Structure of the films

To achieve and obtain a homogeneous di-functional nanocomposite film, Fig. 1A describes the simple procedure for fabricating the difunctional films. Spherical Au NPs were synthesized by coating citrate ions as the stabilizing agent [26] and used as numerous photothermal nanoabsorbers to fast convert solar energy to thermal energy (Experimental Section S1.2, Supplementary materials). The obtained Au NPs can be easily dispersed into PVA solution (1) due to the

effective surface protection of citrate ions. The strong hydrogen-bond interactions between the carboxyl groups of citrate ions and the hydroxyl groups of PVA molecules, will thus drive the selective hostguest interaction at the surface of the Au NPs. As PEG molecules (2) were added into above suspended solution, PVA molecules also played the role to form hydrogen-bond with C-O groups (the ether bond) of the PEG molecules simultaneously. Herein, the hydrogen-bond from interaction of PEG and PVA molecules can tightly lock phase change PEG molecules and prevent leakage after phase transition. (The hydrogen-bond interactions were characterized using IR spectroscopy. as shown in Fig. S2, Supplementary materials). The TEM image of Fig. 1B shows that the synthesized Au NPs are near monodisperse and spherical with an average diameter of ~25 nm (particle size distribution histogram was shown in Fig. S3, Supplementary materials). The mixing solutions were highly stable and homogenous. As the concentration of Au NPs increased, the color of solutions changed from colorless to pink to dark red gradually (Fig. 1C). UV-Vis spectra (Fig. S4, Supplementary materials) show the same absorption peak centered at 532 nm and the peak intensity increased with the increasing concentration of Au NPs. Finally, the relevant di-functional nanocomposite films were made by facial drying under air/vacuum condition (Fig. 1D). The color of the obtained films was similar with the color of the mixing solutions and the di-functional nanocomposite films exhibit high optical transparency. Those results indicated that the Au NPs were equally distributed into PVA matrix. No aggregation of Au NPs is critical for both penetration of incident light source and the highefficiency excitation of plasmonic nanoparticles.

2.2. Laserlight-to-heat conversion

Before solar-to-heat conversion measurements, the photothermal properties of the obtained di-functional films were systemically studied to deeply understand the essence of utilizing surface plasmon resonance to quickly implement photo-to-heat conversion and efficiently charge thermal into PCMs. As is well known, when the Au NPs size matches the plasmon wavelength, a strong and resonant excitation of surface plasmon can be produced quickly to generate heat [22,23]. A green low-power pulsed laser (~532 nm of wavelength) was chosen to coincide with the plasmon resonance frequency of Au NPs (absorption peak centered at 532 nm). Proof-of-concept experiments were performed by rapid photothermal conversion, collecting/storing heat energy from a green laser to excite the Au NPs at near their plasmonic resonance wavelength. The laser excited surface plasmons of Au NPs, which transfer resonant energy to lattice vibrations for producing heat



Fig. 1. (A) The simple procedure for fabricating the di-functional nanocomposite film. (B) The TEM image of the Au NPs. (C) Digital photograph of the mixture solutions containing different amounts of Au NPs. Left-to-right: 0, 0.139, 0.406 and 0.677 nM, respectively. (D) Digital photograph of the corresponding nanocomposite films fabricated from the solutions in Fig. 1(C).

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