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Enhanced Conversion Efficiency of Hybrid Solar Cells by using Alloyed Silicon-Tin Nanocrystals via Quantum Confinement Effect

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Abstract

This work presents the first report of hybrid solar cells using alloyed semiconducting silicon-tin nanocrystals (SiSn-ncs) with quantum confinement effect that allow additional absorption. The conversion efficiency of hybrid solar cells is enhanced by tuning the shorter wavelengths into infra-red absorbed in the active layer.

1. Introduction

Hybrid solar cells have focused much of attention from researches because they offer a possibility of low cost and large area devices. Conjugated polymers, which are the main material of hybrid solar cell devices, were intensively developed to reach a high absorption in the visible range of the solar spectrum, a good conductivity, and can be easily integrated in industrial process.

To further enhance the global conversion efficiency of those hybrid solar cells, we propose to use silicon nanocrystals (Si-ncs) or alloyed silicon-tin nanocrystals ($Si_{1-x}Sn_x$-ncs) that allow an additional modification absorption via quantum confinement effect [1,2]. Particularly, the SiSn alloy is a promising candidate for infra-red absorption by tuning the shorter wavelengths into infra-red with an adjustable bandgap below 1.12 (Si) down to 0.46eV depending on the concentration of Sn [3]. Furthermore, SiSn alloy can turn into a direct bandgap material that greatly enhances the absorption. Previous reports of the synthesis of SiSn-ncs using a highly non-equilibrium and spatially confined short pulsed laser process [1] revealed the feasibility of SiSn alloy with quantum confinement effect [4]. In this study, we successfully synthetized SiSn-ncs by the nanosecond pulsed laser fragmentation in liquid media technique and realized hybrid solar cell devices to underline their photovoltaic properties. This work presents the first report of hybrid solar cells using alloyed silicon-tin nanocrystals with quantum confinement size and absorption peaks at 0.85 and 0.64eV.

2. Experimental details and discussions

Synthesis of silicon nanocrystals

Si-ncs were produced by electrochemical etching of a silicon wafer (p-type boron doped, ⟨100⟩, 0.1Ωcm, thickness of 0.525mm) and subsequent mechanical pulverization [5]. A dry powder of Si-ncs is obtained that includes Si-ncs aggregates of different sizes with diameters up to the micrometer range.

Synthesis of alloyed silicon-tin nanocrystals

The synthesis of SiSn-ncs is achieved by laser ablation in water of a $Si_{0.9}Sn_{0.1}$ target using a nanosecond pulsed laser (KrF, 245nm, 20Hz) [1]. The target is placed at the bottom of a glass container and immersed in 6mL of deionized water. The SiSn-ncs in liquid suspension were put on hot plate in air condition and then collected after water evaporation. The synthetized SiSn-ncs have a quantum confinement size about 7nm.

Material analysis

The colloidal dispersions of Si-ncs and SiSn-ncs were analyzed by absorbance measurements using a UV/vis spectrometer (PerkinElmer Lambda 950). Figure 1 displays the absorbance spectra of synthetized SiSn-ncs compared to Si-ncs. As we can see the SiSn-ncs display a clear shift in absorption with the presence of two peaks down to 0.85 and 0.64eV in comparison to Si-ncs. This prove the feasibility of the fabrication of alloyed semiconducting silicon-tin nanocrystals, which are difficult to obtain by chemical fabrication process with metallic behavior [6].

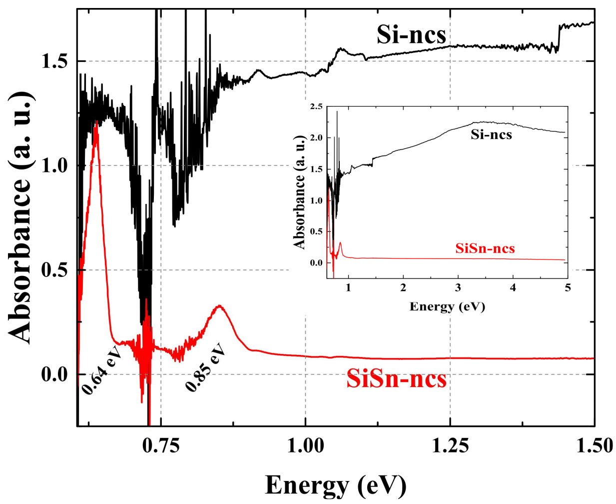

Fig. 1 presents the absorbance spectra of SiSn-ncs (red line) compared to Si-ncs (black line) dispersed in ethanol. The embedded graph corresponds to the same absorbance spectra at wider energy scale from 0.6 until 5eV.

Fabrication process of hybrid solar cell devices

Glass substrates with an indium tin oxide electrode were used for the fabrication of solar cells. The conjugated polymer Poly(3,4-ethy-lenedioxythiophene):poly(styrene sulfonic acid), namely the PEDOT:PSS, was deposited by spin-coating (3min at 3000 rpm, dried at 135°C for 15min). Subsequently, the conjugated polymer poly-thieno[3,4-b]thiophenebenzodithiophene, namely the PTB7, mixed with SiSn-ncs or Si-ncs as active layer was deposited by spin-coating under nitrogen condition (2min at 1500rpm, dried at ambient temperature for 20min). Then, an alumina top electrode of 100nm thick was deposited on top of the active layer by vacuum evaporation. The active area of hybrid solar cell devices is $4mm^2$.

Photovoltaic properties

Hybrid solar cell devices with SiSn-ncs or Si-ncs inside the active layer can display photovoltaic properties. In both cases introduction of nanocrystals formed bulk heterojunction and nanocrystals served as electrons accepting material, which underlines the quality of SiSn-ncs with low defect concentration. To emphasis the photovoltaic properties of SiSn-ncs/Si-ncs, we investigated the role of the ratio nanocrystals/ PTB7 polymer by increasing the concentration of nanocrystals up to 60% in weight. Figure 2 presents the current-voltage characteristics of hybrid solar cells using 25 mg of PTB7 mixed with 40% in weight of SiSn-ncs or Si-ncs under standard AM1.5G illumination (solid lines) and dark condition (dashed lines). Under AM1.5G illumination we could see an improvement in the short circuit current density (Jsc) of devices using SiSn-ncs over those using Si-ncs due to enhanced absorption in near infrared. Enhanced current density at negative bias voltage underlines an effective separation of the photo generated excitons. Under dark condition the current density is very low about 3.1×10^{-4} and 4.7×10^{-4} mA/cm^2 at 0.8V for devices using Si-ncs and SiSn-ncs, respectively. This underlines a low leakage current with our synthetized SiSn-ncs close to Si-ncs and confirmed a low defect concentration. Our results indicate that, in the case of SiSn-ncs, the preservation of lower mass of electrons compared to holes results in minor changes of the valence band position which leads to open-circuit voltage (Voc) rather identical for both devices (0.8V).

3. Conclusions

The feasibility of alloyed semiconducting silicon-tin nanocrystals was underlined using a highly non-equilibrium and spatially confined short pulsed laser process. Photovoltaic properties could be obtained, which is the first report of hybrid solar cells using SiSn-ncs with quantum confinement effect. It is believed that use of direct bandgap, environmental friendly and low cost silicon based nanocrystals with quantum confinement could lead to a crucial enhancement of the conversion efficiency not only for hybrid solar cells but allow the formation of new types of solar cell structures with strong absorption below the Si energy bandgap.

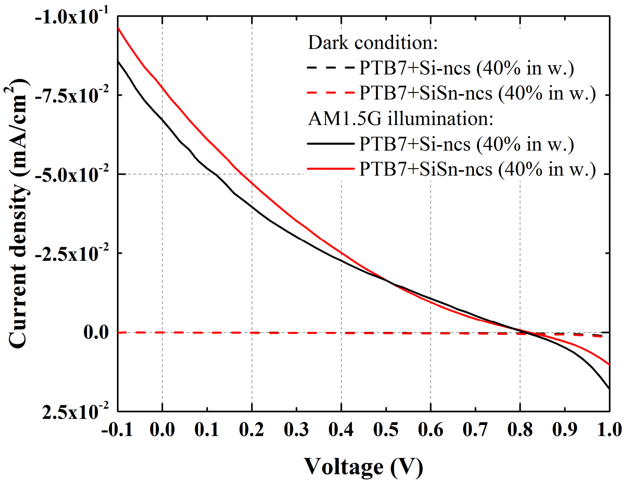

Fig. 2 presents the current-voltage characteristics of hybrid solar cells using 25mg of PTB7 mixed with 40% in weight of SiSn-ncs or Si-ncs as active layer under AM1.5G (solid lines) and dark condition (dashed lines).

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