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Up-conversion luminescence from single vanadate through blackbody radiation harvesting broadband near-infrared photons for photovoltaic cells

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ABSTRACT

Up-conversion (UC) is a promising route to harvest near-infrared (NIR) sunlight and enhance the power conversion efficiency (PCE) of photovoltaic (PV) cells. However, most of the UC materials have some bottleneck problems associated with them, such as own only narrower excitation band matching with the sun spectrum, lower UC luminescence efficiency, and considerable heat losses. Thus, it is essential to design and find a UC material that can absorb broadband NIR photons through an attractive route named thermal radiation for photon energy UC. In this work, we investigated the UC luminescence properties of single $CeVO_4$ materials, in which the excitation bands can be augmented at least a range of 808 −1064 nm. We also confirmed that this kind of UC emission is triggered by the thermal absorption of VO_4^{3-}, which might be expanded to other single vanadate materials. The UC luminescence mechanisms were analyzed by power dependence and temperature modeling, and interpreted in terms of blackbody radiation theory. We demonstrated the possibility of photocurrent response in thin-film-hydrogenated amorphous silicon solar cell modified with $CeVO_4$ powders through blackbody radiation for harvesting NIR photons. Such single vanadate materials can absorb broader NIR photons for UC luminescence through blackbody radiation, will open a new door for the enhancement of the PCE in the next-generation concentrated PV cells.

1. Introduction

The utilization of solar energy has been made possible in different type of solar cells by directly converting it to electricity via photovoltaic (PV) effect, representing promising strategies to abundant, green and renewable energy generation and intriguing worldly scientific interests [1]. Most solar cells, such as amorphous silicon, polymer, dye-sensitized, and perovskite solar cells, have the spectrum response range below 800 nm and cannot directly exploit near-infrared (NIR) photons of the sunlight above 800 nm, of which the power conversion efficiency (PCE) are inhibited.

Photon energy up-conversion (UC) through rare-earth (RE) ions doped UC materials has been considered to be a promising way to the use of this portion of sunlight, which has potential to enhance the PCE in PV cells [2–5]. However, some bottleneck problems appear, such as lower UC luminescence efficiency, concentration-quenching, temperature-quenching and hold only narrower excitation band matching with solar spectrum, which is especially arduous to satisfy the requirement of solar spectrum conversion [4,6,7]. As a result, photonics UC goes broadband and very recently broadband UC as a hot topic of research has widely captured scientists' attention, and brought many interesting research works [8,9], such as introduction of NIR molecular dye sensitizers with broad NIR absorption range, design of core–shell composite nanostructure for multiple absorptions in the NIR region from different RE ions [10], investigation on UC materials upon simultaneous multi-wavelength even broadband NIR sunlight excitation [11–15], and expanding the excitation bands of lanthanide UC

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particles by compositing noble metal ions [16–18]. Nevertheless, all above systems are restricted to a major UC luminescence efficiency limiting factor termed heat losses [19–21]. Hence, it is much meaningful to synthesize UC materials for intense UC luminescence via bypassing or even benefiting from amounts of heat losses.

Here, we demonstrate photon energy UC luminescence in $CeVO_4$ powders taking advantage of blackbody radiation for harvesting broader NIR photons. $CeVO_4$ are chemically, photothermally, and photochemically stable, easy to synthesis, which has garnered widespread interest in recent years by virtue of its application as oxidation catalyst [22], photocatalyst [23], gas sensor material [24], and pigment [25]. More importantly, $CeVO_4$ can simultaneously absorb broader NIR photons to achieve UC luminescence than other materials consisting RE or noble metallic ions doping. However, to our knowledge the mechanism for the broadband UC luminescence in $CeVO_4$ is ambiguous up to now, and there might be something wrong with the previous interpreted luminescence mechanism in terms of photon avalanche or RE ions itself [26]. Here, we proposed that the broadband UC luminescence is rooting from blackbody radiation emission. In the present work, we studied the UC luminescence properties of $CeVO_4$ upon NIR laser of various wavelengths. The broadband UC luminescence of $CeVO_4$ can be observed in the visible to NIR region, and the excitation bands can be expanded at least a range of 808–1064 nm. The UC emission mechanisms were analyzed by power dependence and temperature modeling, and were elaborated in terms of blackbody radiation theory. The broadband radiation UC emission can also be observed in single YVO_4, which further validates our concept that the broadband UC luminescence is originated from the thermal accumulation from the VO_4^{3-}. The feasibility of photocurrent response was demonstrated in thin-film-hydrogenated amorphous silicon (a-Si:H) solar cell attached with $CeVO_4$ powders under irradiation of 808, 980, and 1064 nm. Such single vanadate materials, that can absorb broadband NIR photons through blackbody radiation without doping RE or noble metallic ions, have immense potential to improve the PCE in the concentrated PV cells in the near future.

2. Experimental

2.1. Fabrication of samples

The starting materials are CeO_2 (99.99%) and V_2O_5 (AR). The $CeVO_4$ powders were synthesized by solid–state reaction in air, and the stoichiometric mixture (CeO_2: V_2O_5 in a molar ratio of 2:1) was heated in a corundum crucible at 800 °C for 50 h [27].

2.2. Measurements and characterization

The crystalline phase of the samples were identified by X-ray diffraction (XRD) on an X'Pert PRO X-ray diffractometer (PANalytical, Netherland) using Cu K_α (λ = 1.5418 Å) radiation. The Raman spectrum was measured using a Raman spectrometer (Renishaw inVia, UK) using a 532 nm laser as an excitation source. Diffuse reflectance spectrum (DRS) was recorded using a Cary 5000 UV–vis–NIR spectrophotometer (VARIAN, USA) equipped with a double out-of-plane Littrow monochromator using $BaSO_4$ as a standard reference. UC emission spectra were measured with a spectrofluorometer (iHR 320, Jobin-Yvon, France) equipped with 808, 980 and 1064 nm laser diodes (LDs), respectively. Photocurrent responses of the PV-UC device were measured using a Keithley Series 2400 source meter (Keithley, USA). All the measurements were carried out at room temperature.

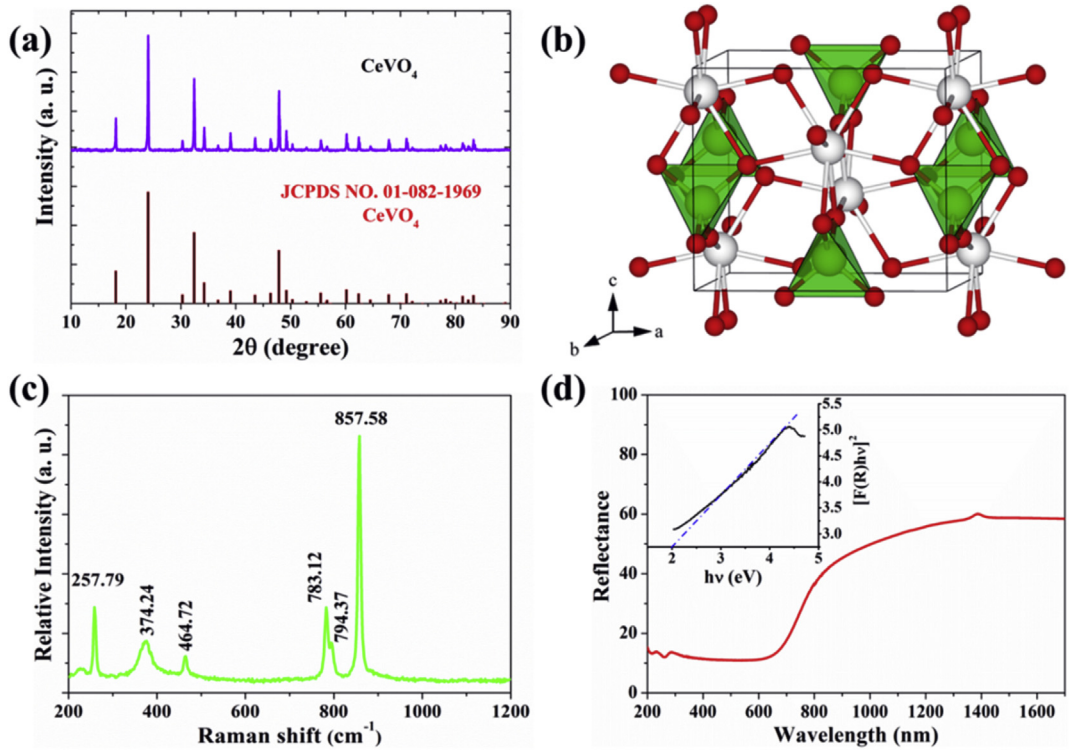

Fig. 1. (a) XRD patterns, (b) Unit cells structures, (c) Raman spectrum and (d) Diffuse reflectance spectrum of as-made $CeVO_4$ powders. In Fig. 1(b): Ce, V, and O atoms are colored silver, green, and red, respectively. The inset in Figure 1(d) shows the band gap of $CeVO_4$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)