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Efficiency enhancement in solar cells using photon down-conversion in Tb/Yb-doped tellurite glass

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ABSTRACT

Management of the solar spectrum incident on a solar cell was studied using tellurite glasses doped with Tb^{3+} and Yb^{3+} ions as a cover slip. From the transmittance measurements through the doped glass, a red-shift of the solar spectrum was observed and the mechanisms involved in this phenomena were investigated through the absorption spectra and luminescent measurements. Energy transfer of the UV radiation into VIS and IR radiation was elucidated by analyzing the emission spectra. From the results, the power dependence of the Yb^{3+} IR luminescence on the pumping laser intensity at 482 nm revealed that the energy transfer mechanism involving a virtual state was predominant in these samples. Total quantum efficiency higher than 100% was obtained for the sample co-doped with 1% of Tb^{3+} ions and 5% of Yb^{3+} ions. The efficiency of commercial Silicon and Gallium Phosphide (GaP) solar cells, covered with tellurite glasses doped with Tb^{3+} and Yb^{3+} ions, was measured and compared to the efficiency with an un-doped the cover glass. Efficiency enhancement was observed with a dependence on the rare earth ions concentrations, and the results were attributed to the modification of the spectral profile of the incident radiation in the IR region.

1. Introduction

Solar energy is a renewable source of energy with low negative impact on the environment. Its growing market is driven by the technological improvements and the policies supporting renewable energy sources [1]. Two approaches are usually explored to increase the efficiency: one is based on the search for new materials or techniques that can explore efficiently the photovoltaic effect, and the second one is related to the solar spectrum modification in order to match it with the solar cell spectral efficiency. In the first case, novel materials such as organic solar cells and thin-films technologies were studied and their potentialities were addressed [2,3]. Also, the Multiple Exciton Generation process has been proposed to increase the internal efficiency in more than 100% as demonstrated using quantum dots [4]. Alternative techniques such as the texturization of silicon solar cells, the use of scattering particles, and the improvement of the fabrication process are also exploited to optimize the efficiency of the solar cells [5]. In another approach, the use of different multi-junction configuration is employed in order to efficiently explore the solar spectrum [6]. On the other hand, the degradation of the solar cell due to the incidence of UV radiation is an important detrimental factor that reduces its efficiency. It can be avoided by converting the UV radiation to near of the band gap frequencies of the solar cell, usually in the near infrared [7]. In this last case, the down-conversion and up-conversion processes in photonic materials, particularly those doped with rare earth ions [8], can be used to manage the solar spectrum. An interesting mechanism to be explored using rare earths doped materials is the quantum cutting. In this process, photons of high energy are converted into photons with low energy, which can lead to quantum efficiencies higher than 100%. Then, the main idea is to convert the UV photons of the solar radiation to photons with energies around 1,1 eV, which is the band gap of silicon solar cells. This process will avoid losses due to thermalization and will produce photons that can be used to create more charge carriers [9]. Photon conversion layers have been proposed in the literature to increase the efficiency of solar cells, but the material's optimization is necessary for further development of the photon conversion concept applied to photovoltaics [10].

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Optical properties of glasses doped with Tb^{3+} and Yb^{3+} ions are widely studied in the literature and the results reveal that they are potential candidates for solar cell applications due to their ability to transfer energy from the UV/VIS region to the NIR region [11–18]. However, a few number of papers report the application of these materials to improve the solar cell efficiency [19].

In this work, we study the down conversion process in tellurite glasses doped with Tb^{3+} and Yb^{3+} ions, and explore its application to modify the solar spectrum to increase the efficiency of commercially available silicon and GaP solar cells.

2. Experimental procedure

Samples of tellurite glasses were prepared using $85.0TeO_2-15.0ZnO$ (TZO glass)composition (in wt%) by the melting-quenching technique [20]. The doping species were Tb_4O_7 (1 and 2 wt%) and Yb_2O_3 (5 and 7 wt%). Reagents were melted at 835 °C in a platinum crucible for 1 h, quenched in a pre-heated brass mold, annealed at 325 °C for 2 h, and then cooled to room temperature in the furnace to reduce internal stress. Samples with approximately 3 mm thickness were cut and polished.

Absorption spectra and luminescence measurements were performed to characterize the optical behavior of the samples. The absorption spectra were obtained using a spectrophotometer (Agilent CARY 5000 UV-VIS-NIR) operating in the range of 350–2500 nm. The luminescence measurements were carried out using the third harmonic generation from a 1064 nm pulsed nanosecond Nd: YAG laser (QuantelUltra 50) and an OPA (Coherent Libra) tuned at 482 nm operating in a quasi-continuous (quasi-cw) mode as excitation lasers. The luminescence of the samples was collected using lenses and recorded with a spectrometer (ACTON SP-500i) coupled to a silicon and InGaAs CCD cameras for the VIS and IR measurements, respectively. The temporal measurements were obtained using a Si photodetector (THORLABS PDA100A) attached to a monochromator.

Modification of the solar spectrum was obtained from the measurements of the solar radiation transmittance emitted by a solar simulator (LCS-100 Newport) through the samples using a portable spectrometer (HR4000 Ocean Optics) and a calibrated reference solar cell (91,150 V Newport).

Electrical characterization was performed using a solar simulator (LCS-100 Newport) with a AM 1.5 filter and a sourcemeter (Keithley 2420) coupled to a PC. Efficiency, fill factor (FF), short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) and the current and voltage (I_{mp}, V_{mp}) at the maximum power were obtained from the Voltage-Current (V-I) curves obtained under 1000 W/m^2 irradiance of commercial silicon (BPW34 Vishay Semiconductors) and GaP (FGAP71 Thorlabs) semiconductors.

3. Results and discussion

The absorption spectra of tellurite glasses doped with 1% and 2% of Tb^{3+} co-doped with 2% and 5% of Yb^{3+} are shown in Fig. 1 (a) and (b). From these figures, the absorption bands corresponding to the $Tb^{3+}$and Yb^{3+}ions excited from the $^7F_6$ and $^2F_{7/2}$ ground states, respectively, are identified and represented in the energy level diagram in Fig. 2. Also, the band gap of the tellurite glass around 380 nm is observed.

In order to understand the role of the UV excitation in the VIS-IR emission, the emission spectra under laser excitation at 355 nm and 482 nm are shown in Figs. 3 and 4, respectively. From these figures, the visible emission in the region of $500-700$ nm was observed and assigned to the electronic transitions of $^5D_4 \rightarrow {}^7F_j$ (j=6, 5, 4, 3) of Tb^{3+} ions. For the sample prepared with 1% of

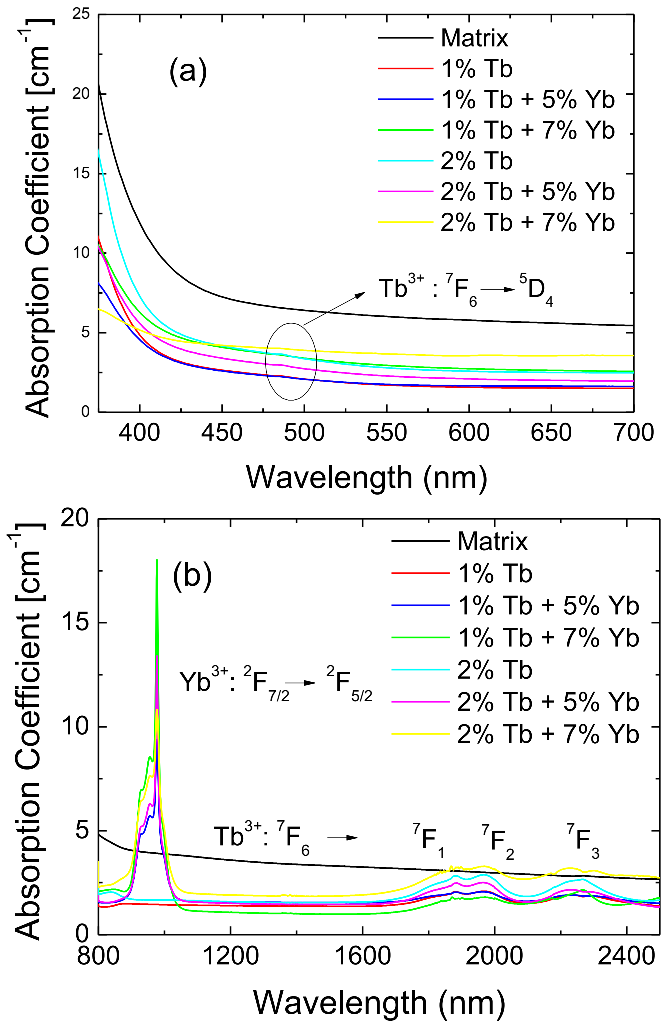

Fig. 1. Absorption spectra of the tellurite glasses doped with 1% and 2% of Tb^{3+} ions and co-doped with 5% and 7% of Yb^{3+} ions. a) VIS spectrum, and b) NIR spectrum.

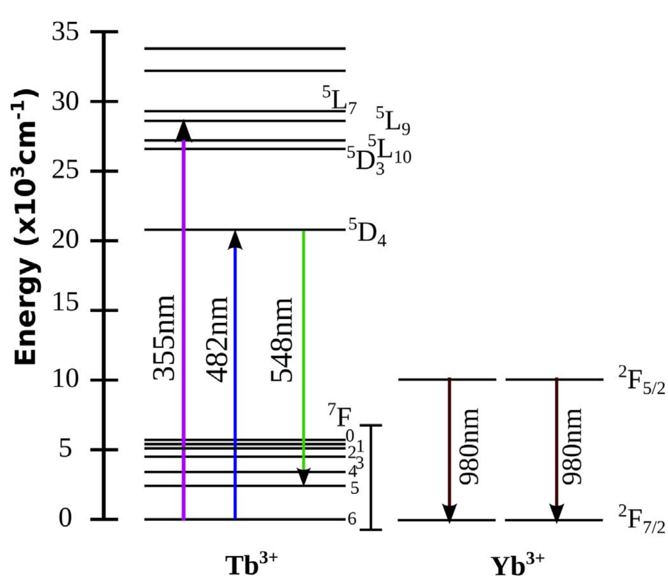

Fig. 2. Diagram of the energy levels of Tb^{3+} and Yb^{3+} ions.