Photoacoustic and photothermal methods towards the characterization of solar energy conversion technologies: progress to date

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Despite the advancements in the field of solar energy production, there remains an acknowledged challenge associated to efficiency losses due to arguably low spectral overlap between that of the active material and the solar spectrum (Figure 1(a) for a crystalline single junction silicon solar cells (c-Si) [1-3]). As a consequence, a significant part of the incident sunlight energy is converted into heat, accounting for losses over 80% of the incident solar energy [1]. In response to this, significant efforts have been devoted to the realisation of novel materials with improved solar cell efficiency as well as reduced production costs. The achieved technological advances already resulted in new emerging technologies, such as the so-called 'Third generation solar cells" based on tandem, perovskite, dye-sensitized, organic, as well as spectral converters [1-3]. In fostering the development of superior active materials in such optoelectronic devices, the reliable determination of the photovoltaic efficiency is paramount, with photoacoustic and photothermal methods representing highly desirable techniques to do so. Both are based on the detection of heat induced in a sample after light excitation. These techniques can be applied to evaluate the photovoltaic efficiencies of the devices as well as the thermophysical parameters of related materials used in their construction. Motivated by this, herein we report on the utilisation of state-of-the-art photoacoustic and photothermal methods for the characterization of solar cell devices and their built-in materials. In addition, we comment on our views to shed light and pave the way for the development of superior technologies.

In this context, we deem as particularly relevant the use of photoacoustic spectroscopy for the determination of band gaps, evaluation of the photovoltaic effect as well as thin film thickness measurements. In short, we report on the use of thermal lens and thermal mirror methods to measure the fraction of the energy converted into heat in optical materials referred to as spectral converters. Such architectures are characterized by a pair of rare earth ions having the highly-desirable capability to undergo down-conversion processes, whereby high energy photons are converted into low energy ones in the infrared, at the c-Si band gap. As an example, Figure 1(b) illustrates pairs of ions (Eu^{2+} and Nd^{3+}) that could induce down-conversion processes, e.g. these ions can efficiently absorb UV and visible light with Yb^{3+} acting as the acceptor ion due to its emission around 980 nm matching to that of (c-Si) absorption (bandgap ~1.1 eV). In such processes, Eu^{2+} and Nd^{3+} are called activators and Yb^{3+} the sensitizer ions, respectively. Importantly, when coupled to single junction silicon solar cells, these spectral converters can enhance their PV efficiency.

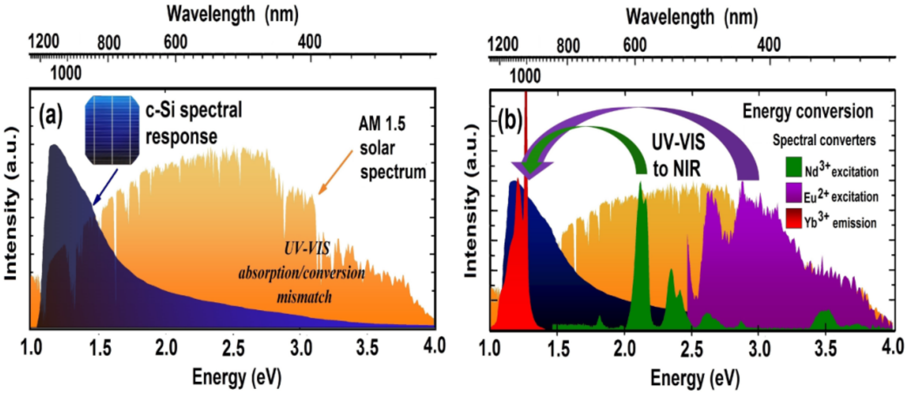

Fig. 1. (a) Solar spectrum (AM1.5G) in the UV-Vis-NIR regions and the spectral response of the c-Si solar cell. **(b)** Optical absorption coefficients of Eu^{2+} and Nd^{3+} activators and the Yb^{3+} sensitizer emission around 980 nm, close to the c-Si band gap [3].

In this work, we will be presenting a number of studies exemplifying the critical role that thermal lens and thermal mirror techniques can play in the quantitative characterization of these aforementioned processes. As a result, we strongly believe this work to be of significant interest to those engaged in the development of superior solar energy conversion technologies as well as the utilisation of photoacoustic and thermal methods as characterization alternatives.

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[2] E.L. Savi et al., Thin-film of Nd^{3+}–Yb^{3+} co-doped low silica calcium aluminosilicate glass grown by a laser deposition technique, J. Appl. Phys. 131 (2022) 055304-1-8. doi.org/10.1063/5.0067794.

[3] A.C. Bento et al., Photoacoustics and photothermics and the photovoltaic efficiency of solar cells: A tutorial, *submitted to J. Appl. Phys.*