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Tandem perovskite solar cells

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ABSTRACT

Progress made in perovskite solar cells (PSCs) in tandem with silicon, thin films, and organic solar cells has been reviewed. Tandem configurations are comprised of two or more cells and are designed to absorb the entire range of the solar light by the successive cells. Such configurations are considered as the most sought-after remedies to generate cheaper solar electricity by increasing the efficiency beyond the theoretical limits of single junction cells. The current market leader i.e. state of the art single junction silicon solar cells have a laboratory scale efficiency ~ 25% achieved as a result of the over 60 years of research. Further research is expected to enhance their efficiency close to the theoretical limits. PSCs may be the next desired choice as the top solar cell due to its higher absorption edge (~ 2.23 eV) in comparison to its Si counterpart (~ 1.48 eV). Beginning with a brief introduction of the PSC, studies regarding its suitability for tandem devices, comparison of single and multiple junction solar cells, and the progress made so far employing different perovskite absorbers, have been reviewed. The advantages and disadvantages of PSCs, including losses of various tandem solar architectures have been discussed. Finally, the review has been concluded with a summary of the current developments and commercialization potential of this technology for real-life applications.

1. Introduction

The quest for clean and sustainable energy has been instrumental in initiating research to explore sun's energy in all forms. Among these, its incessant radiant energy as heat (solar thermal), differential heating (wind), and photonic energy transfer by a semiconductor (photovoltaics) have been the most popular protocols. Investments in fossil fuels add up to $2.1 trillion through 2040 but nearly quadruple of this amount ($7.8 trillion) is projected for renewables. Here again, the solar ($3.4 trillion) and wind ($3.1 trillion) take up the major share [1]. It is expected that by 2027, building new solar fields and wind farms will be cheaper than running coal and gas generators [2].

For an electronic device, the one-dimensional current density (J_n) of a solar cell can be expressed as

$$J_n(x) = n\mu_n \nabla E_{Fn}(x)$$

where $\nabla E_{Fn}(x)$ is the gradient in Fermi energy of the material across which the photocurrent flows and this determines the open circuit voltage (V_{OC}) of the cell, here n is the electron density, and μ is the charge mobility. The same relationship holds for the holes as well. The total current density in a solar cell under standard conditions follows the Shockley equation given as follows:

$$J = J_p + J_n = J_S(e^{\frac{eV}{K_B T}} - 1)$$

where J_S is the saturation current density, J_p and J_n represent the current density of holes and electrons respectively, e is the electronic charge, K_B is the Boltzmann Constant and T denotes the temperature.

The current density under illumination is given by,

$$J = J_S\left(e^{eV/k_B T} - 1\right) - J_{\text{photo}}$$

In addition to the above parameters, absorption cross-section and band gap of the absorbers further limit the short circuit current density (J_{SC}) and V_{OC}. In the absence of nonradiative recombination, the Shockley-Queisser limit for a single p-n junction with bandgap (E_g) of 1.1–1.4 eV is ~ 33% (Fig. 1a). This indicates that about 67% of the energy coming from the sun does not contribute to solar electricity. The two main sources of loss are, (i) transmission of photons with energies lower than the E_g of the material without absorption and (ii) the loss of energy by photons of energy higher than the E_g of the material via

Abbreviations: PSC, Perovskite solar cells; DSSC, Dye sensitized solar cells; PCE, Power conversion efficiency; PV, Photovoltaic; 2T, Two terminal; 4T, Four terminal; NREL, National Renewable Energy Laboratory

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Nomenclature

J	Current density	n	Electron density
J_{SC}	Short circuit current density	J_p	Current density of holes
V_{OC}	Open circuit voltage	J_n	Current density of electrons
μ_n	Charge mobility	K_B	Boltzmann's constant
		E_g	Bandgap
		eV	Electron volt

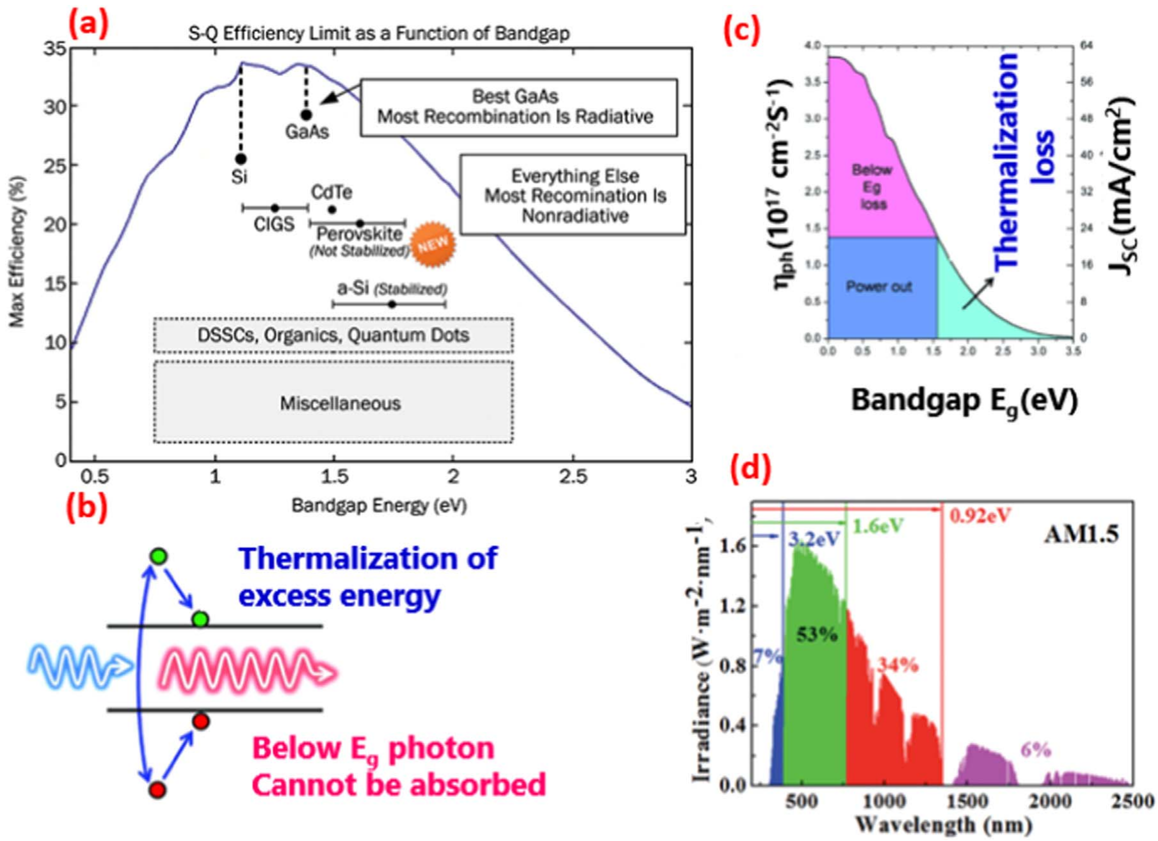

Fig. 1. (a) Calculated maximum theoretical efficiency of a single junction solar cell according to Shockley-Queisser limit. Si and GaAs based single junction solar cells currently hold the record for the highest efficiency. CIGS systems are tuneable via control of the In/Ga ratio, adopted from Ref. [8]. Copyright 2011 Wiley, (b–c) thermalization of the photoinduced electron and photon with lower energy than the E_g, and (d) response of various materials to solar spectrum. Adopted from Ref. [9] Copyright 2017 Wiley.

phonon emission at the rotational and vibrational energy levels which lie at the continuum band (Fig. 1b). These two phenomena are explained in a more elegant way in Fig. 1c showing the efficiency of photon and photocurrent versus E_g. Materials such as quantum dots, having discrete energy levels in comparison to the continuum band, have been reported to uplift the Shockley-Queisser limit over 70% [3]. Recent reviews on this topic can be found elsewhere [4–7]. Considering the solar spectrum (Fig. 1d), role of the absorber's band gap becomes clearer; i.e., a material of band gap ~ 0.92 eV can absorb up to ~ 94% of the solar light whereas a material of band gap ~ 1.6 eV can absorb only up to 60% of the solar light.

A number of attempts have been made to minimize the two major losses occurring in single junction solar cells i.e., the sub band gap transmission and thermalization of hot carriers. Consequently, several advanced approaches have been devised to reduce spectral losses such as multiple exciton generation, hot carriers, and tandem designs. Among these, tandem solar cells have demonstrated the potential to conceive practical performance better than the Shockley-Queisser limit [10]. A tandem cell is a unique combination of two or more sub-cells which converts much of the sunlight into electricity and minimizes spectral losses. In single-junction devices (Fig. 2a), photons with energy < E_g will not be absorbed by the material, while those with energy higher than E_g will generate hot carriers. These hot carriers get thermalized to band edge due to phonon interaction and emit surplus energy as heat. In this way, a significant amount of energy is lost through the optical spectral losses. On the other hand, tandem device is comprised of two different solar cells or materials coming from the same family with different E_g. Strategically, the tandem device consists of a top sub-cell with wide E_g and a bottom sub-cell with narrow E_g. The top sub-cell with wide E_g absorbs higher energy photons (yield higher voltage and lower photocurrent) and the narrow E_g bottom sub-cell absorbs the lower energy photons (yield lower voltage and higher photocurrent) as shown in Fig. 2b. Therefore, a tandem device absorbs a wide spectral range to gain a high photocurrent as can be seen from the top and bottom cells response to the electromagnetic radiation (Fig. 2c). In parallel, the radiative losses in silicon single junction due to thermalization of high energy photons (hot carriers) well above the silicon optical E_g are reduced. The radiative losses accounts for more than 50% of the overall losses in a single junction silicon. The tandem solar cells concept was established as early as 1978, and a device made using AlGaAs/GaAs showed a very large V_{OC} ~ 2.0 V, J_{SC} ~ 7 mA cm^{-2}, and fill factor ~ 07–0.8 with power conversion efficiency PCE ~ 9% [11]. Such a large V_{OC} demonstrated that the two cells are electrically connected in series and the voltage of the individual cells are added via a connecting diode, while the band gap difference between the top cell and bottom cell was only ~ 0.2 eV. Under standard