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Efficiency limits for single-junction and tandem solar cells

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Abstract

Basic limitations of single-junction and tandem p–n and p–i–n diodes are established from thermodynamical considerations on radiative recombination and semi-empirical considerations on the classical diode equations. These limits are compared to actual values of short-circuit current, open-circuit voltage, fill factor and efficiency for amorphous (a-Si:H) and microcrystalline (μc-Si:H) silicon solar cells. For single-junction cells, major efficiency gains should be achievable by increasing the short-circuit current density by better light trapping. The limitations of p–i–n junctions are estimated from recombination effects in the intrinsic layer. The efficiency of double-junction cells is presented as a function of the energy gap of top and bottom cells, confirming the 'micromorph' tandem (a-Si:H/μc-Si:H) as an optimum combination of tandem solar cells.

Keywords: Amorphous and microcrystalline silicon; Single p–n and p–i–n junction solar cells; Tandem solar cells; Efficiency limits

1. Introduction

Thin-film silicon solar cells are regularly presented as a one of the main future options for cost-effective solar cells [1–3]. But, parallel to a price reduction, it is imperative to improve the efficiency of current solar cells. It is therefore useful to look in detail at the existing efficiency limitations, introducing estimated values for the dark current in the

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classical diode model for the solar cell and comparing them with values predicted by Ref. [4], as well as ultimate values predicted by Ref. [5].

The aim of this paper is, thus, to re-examine the fundamental limits for short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF) and efficiency (η) as a function of the energy gap (E_g) for single-junction and tandem solar cells, in the context of thin-film silicon solar cells.

Additional losses in V_{oc} and FF due to the p–i–n configuration generally used in thin-film silicon solar cells will be estimated considering two different effects: (a) the diminution of the photogenerated current in p–i–n solar cells due to additional recombination in the intrinsic layer and (b) the increased dark (reverse) current of thin-film silicon p–i–n diodes, as can be attributed to thermal generation current from mid-gap defect states (dangling bonds).

The efficiency limitations for tandem (double-junction) solar cells will then be considered; it will be shown that tandem 'micromorph' (a-Si:H/μc-Si:H) solar cells correspond to an optimum combination of band gap values.

2. Single-junction solar cells

2.1. Theoretical limit for short-circuit current, J_{sc}

An upper limit for the J_{sc} can be computed by considering the normalized AM 1. 5 spectrum (IEC 904-3) and assuming that all photons with $h\nu > E_g$ (where h is Planck's constant, $\nu = c/\lambda$ with c the speed of light and λ the wavelength, and E_g is the energy gap of the semiconductor material considered) are absorbed and converted into electron–hole pairs that can, in principle, be collected at short circuit conditions.

This results in J_{sc} (E_g) as presented in Fig. 1: microcrystalline (μc-Si:H) solar cells have an E_g of around 1.1 eV which corresponds to the limit $J_{sc} < 43.6\,\text{mA/cm}^2$, whereas amorphous (a-Si:H) solar cells have an E_g of 1.75 eV, corresponding to $J_{sc} < 21.1\,\text{mA/cm}^2$. At the moment, values of $J_{sc} \approx 20$–$30\,\text{mA/cm}^2$ for μc-Si:H solar cells and values of $J_{sc} \approx 12$–$17\,\text{mA/cm}^2$ for a-Si:H solar cells are obtained by most laboratories. A substantial gain in short-circuit current can therefore still be obtained, mainly by improving light trapping techniques [3].

2.2. Limits for single-junction cells: V_{oc}, FF and η

2.2.1. Open-circuit voltage, V_{oc}

According to the standard diode equation, the $J(V)$ characteristic of a single-junction solar cell under illumination can be written as the linear superposition of the dark characteristics of the cell and the photogenerated current

$$J = J_L - J_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right], \tag{1}$$

where J_L is the photogenerated current, J_0 is the reverse saturation current, q is the elementary charge, k the Boltzmann constant, T the absolute temperature and n the ideality factor with $n = 1$ standing for ideal p–n junctions, whereas $n \approx 2$ stands for p–i–n junctions.