Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 130 (2016) 139–147

SOLAR ENERGY

www.elsevier.com/locate/solener

Tabulated values of the Shockley–Queisser limit for single junction solar cells

Sven Rühle

Solar Energy Consulting, Tel Aviv 62095, Israel

Received 8 October 2015; received in revised form 1 February 2016; accepted 8 February 2016

Communicated by: Associate Editor Frank A. Nüesch

Abstract

The detailed balance limit for solar cells presented by Shockley and Queisser in 1961 describes the ultimate efficiency of an ideal *p–n* junction solar cell illuminated by a black body with a surface temperature of 6000 K. Today the AM 1.5G spectrum is the standard spectrum for non-concentrated photovoltaic conversion, taking light absorption and scattering in the atmosphere into account. New photovoltaic materials are investigated every day, but tabulated values to estimate their performance limits are difficult to find. Here values of the maximum short circuit current density (J_{sc}), open circuit voltage (V_{oc}), light to electric power conversion efficiency (η) as well as current density (J_{mpp}) and voltage (V_{mpp}) at the maximum power point are presented as a function of the light absorbers' band gap energy.

Keywords: Maximum photovoltaic conversion efficiency; Detailed-balance limit; ASTM G173-03; AM 1.5G; Standard conditions

1. Introduction

The maximum light to electric power conversion efficiency η of a single junction solar cell for a given illumination spectrum is known as detailed balance limit or Shockley–Queisser limit. Based on detailed balance considerations William Shockley and Hans-Joachim Queisser presented in 1961 for the first time the calculation of the maximum conversion efficiency of a *p–n* junction solar cell illuminated by the sun, where the sun spectrum was approximated by the emission of a black body with a surface temperature of $T_s = 6000$ K (Shockley and Queisser, 1961). They assumed that in an ideal solar cell the only recombination path which cannot be reduced to zero is radiative recombination, which defines the upper limit for the minority carrier lifetime (Queisser, 2009). For the generation of electron–hole pairs it was assumed that photons with an energy below the energy band gap do not interact with the solar cell while photons with an energy above the band gap are converted into electron-hole pairs with a quantum efficiency of 100%. Shockley and Queissers calculated the efficiency limit for a single junction solar cell at a cell temperature of $T_c = 300$ K.

Today the sun spectrum on earth is defined by the American Society for Testing and Materials (ASTM International Standard), which defines in the document ASTM G173-03 two terrestrial spectral irradiance distributions, the 'direct normal' and 'hemispherical on 37° tilted surface' (ASTM G173-03), which will be abbreviated as AM 1.5D and AM 1.5G throughout this article. Both

E-mail address: sven.ruhle@solarenergy-consulting.com
URL: http://www.solarenergy-consulting.com

http://dx.doi.org/10.1016/j.solener.2016.02.015
0038-092X/

terrestrial solar spectral irradiance distributions are shown in Fig. 1 together with the extraterrestrial irradiance distribution AM 0 just outside the earths atmosphere, where AM is the abbreviation for air mass and is defined by $1/\cos(\theta)$. Furthermore, the black body spectrum is shown that was used by Shockley and Queisser in their original work. The AM 1.5D spectrum is relevant for solar conversion systems based on light concentration with mirrors or lenses because it consists only the direct sunlight while the AM 1.5G spectrum includes also scattered light from the atmosphere and is relevant for PV systems without light concentration. Further details about their exact definition can be found elsewhere (Reference Solar Spectral Irradiance). The integrated power density is 900.1 W/m^2 for AM 1.5D and 1000.4 W/m^2 for the AM 1.5G spectral irradiance, which is substantially lower compared to 1576.7 W/m^2 corresponding to Shockley and Queissers approximation of the sun as a black body with a surface temperature of 6000 K. The ASTM G173 standard was adopted in January 2003 and has replaced the previous standard ASTM G159.

This work presents the theoretical maximum limit of the solar cell parameters (J_{sc}, V_{oc}, η, etc.) of single junction photovoltaic (PV) cells as a function of the band gap energy of the light absorber under illumination with the AM 1.5G spectrum and a solar cell temperature of 298.15 K (25 °C), corresponding to standard solar cell test conditions (Taylor et al., 2010). The maximum light to electric power conversion efficiency for AM 1.5G illumination, based on Shockley and Queissers detailed balance considerations is 33.16% and requires a semiconductor band gap of 1.34 eV (928 nm). Small deviations from this value can be found in the literature which might origin from a different standard spectrum which was used before the year 2003, a different cell temperature (e.g. 300 K), a different cell configuration including a reflector at the back side or from different numerical methods (Brown and Green, 2002; Peter, 2011; Ruppel and Wurfel, 1980; Kirchartz and Rau, 2008; Levy and Honsberg, 2006; ten Kate et al., 2013; Green et al., 2011; Thomas et al., 2012). Photovoltaic (PV) systems which can reach higher light to electric power conversion efficiencies beyond the single junction detailed balance limit are often referred to as 3$^{\mathrm{rd}}$ or 4$^{\mathrm{th}}$ generation PV. Even though detailed balance theory has been applied to a number of PV systems such as cells with light trapping (Yablonovitch and Miller, 2010), excitonic solar cells (Kirchartz et al., 2008), organic bulk heterojunction solar cells (Kirchartz et al., 2009), molecular PV devices (Nelson et al., 2004), thermophotovoltaic solar energy conversion (Harder and Würfel, 2003), multi-junction PV cells (De Vos, 2000), or quantum well solar cells (Barnham et al., 2002) up to now there are no tabulated values available for single junction solar cells that cover the spectral range from IR to UV. This information is of particular interest to estimate the performance limit of existing (Nayak and Cahen, 2014; Nayak et al., 2011) and novel photovoltaic materials based on the optical absorption onset like organo-metal halide perovskites (Kojima et al., 2009), quantum dot (Rühle et al., 2010), polymer (Helgesen et al., 2010) or metal oxide based solar cells (Rühle et al., 2012) and it shows to which extent existing photovoltaic absorbers can be improved until they reach their theoretical limit.

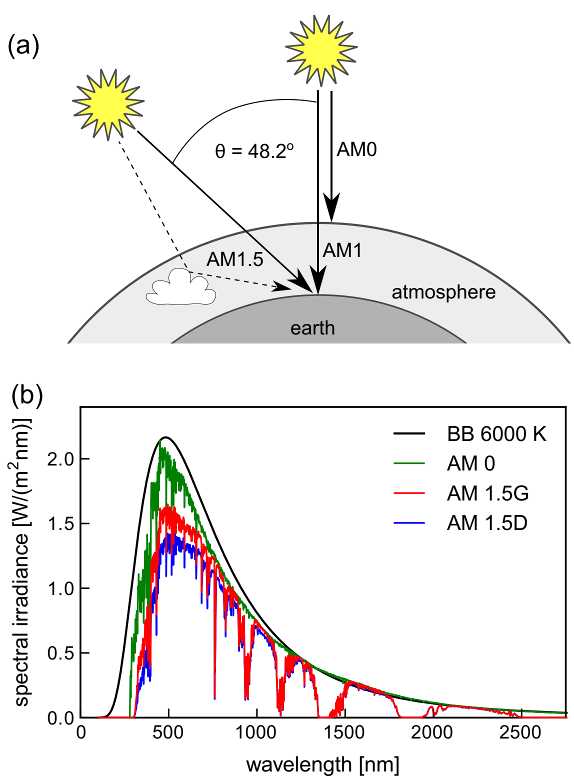

Fig. 1. (a) Schematic representation of the spectral irradiance outside the earths atmosphere (AM 0) and on the earths surface for direct sunlight shown by a solid arrow (AM 1.5D) and the direct sunlight together with the scattered contribution from atmosphere (solid and dashed arrow) integrated over a hemisphere (AM 1.5G). (b) Spectral irradiance according to ASTM G173-03 in comparison to the spectrum used by Shockley and Queisser of a black body with a surface temperature of 6000 K (BB 6000 K).

2. Calculations

For the calculation of the maximum photocurrent density $J_{\max}$ the AM 1.5G spectral irradiance was converted into an incident spectral photon flux ϕ^{i} according to

$$\phi^{\mathrm{i}} = \frac{q\lambda}{hc}\mathrm{AM\,1.5G} \tag{1}$$

with the elementary charge q, the vacuum wavelength λ, the Planck constant h and the vacuum speed of light c. $J_{\max}$ was calculated by integration the spectral photon flux ϕ of the AM 1.5G irradiance from the band gap energy E_{g} up to the UV edge of 280 nm (4.43 eV), which is the shortest reported wavelength in the ASTM G173-03 standard:

$$J_{\max}(E_{\mathrm{g}}) = \int_0^\infty a(E)\,\phi^{\mathrm{i}}(E)dE = \int_{E_{\mathrm{g}}}^\infty \phi^{\mathrm{i}}(E)dE \tag{2}$$