Solar Energy Materials & Solar Cells 140 (2015) 464–476

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Limit of efficiency for photon-enhanced thermionic emission vs. photovoltaic and thermal conversion

Gideon Segev [a], Yossi Rosenwaks [a], Abraham Kribus [b,*]

[a] School of Electrical Engineering, Tel-Aviv University, Tel Aviv 69978, Israel
[b] School of Mechanical Engineering, Tel-Aviv University, Tel Aviv 69978, Israel

ARTICLE INFO

Article history:
Received 7 January 2015
Received in revised form
29 April 2015
Accepted 1 May 2015
Available online 22 May 2015

Keywords:
Shockley–Queisser limit
PETE
Thermionic emission
Spectral splitting
Multi-junction cells

ABSTRACT

Conversion of sunlight by photon-enhanced thermionic emission (PETE) combines a photonic process similar to photovoltaic cells, and a thermal process similar to conventional thermionic converters. As a result, the upper limit on the conversion efficiency of PETE devices is not the same as the Shockley–Queisser (SQ) limit that corresponds to the bandgap of the absorbing material, nor to the Carnot efficiency corresponding to its temperature. Here we analyze the upper limit on efficiency of ideal PETE devices in several possible configurations, in comparison to ideal photovoltaic cells and ideal solar thermal converters. Isothermal PETE converters are shown to be restricted to less than the SQ limit, but non-isothermal devices can exceed this limit. The limit of efficiency increases with the flux concentration reaching for example 52% at concentration of 1000 suns. Spectral splitting leads to a modest increase in conversion efficiency to 56% at 1000 suns. Addition of a secondary thermal cycle increases the efficiency limit for all PETE configurations, up to 69.8% and 70.4% for the cases of isothermal PETE and a dual bandgap PETE system at 1000 suns.

1. Introduction

Conversion of solar radiation to electricity is obviously subject to the laws of thermodynamics, which impose an upper limit on the conversion efficiency. However, different conversion paths lead to different limits on efficiency. These limits are well known for the two major paths of photovoltaic conversion and thermal conversion. The path of photon-enhanced thermionic emission (PETE) combines processes of both thermal and photovoltaic nature, and therefore the upper limit on its efficiency, and its relation to thermal-only and photovoltaic-only limits, needs to be clarified.

The maximum conversion efficiency of photovoltaic conversion in single-junction solar cells is subject to the Shockley–Queisser (SQ) limit [1]. This limit accounts for the three most important and inevitable losses in single-junction solar cells: transmission of sub-band gap photons, thermalization of high-energy electrons, and radiative recombination. The radiative recombination under non-equilibrium conditions considering photon recycling within the cell is described with a simple expression, derived by comparing the radiative recombination under equilibrium conditions to the absorption of environmental photons. According to this limit, the maximum conversion efficiency for a single-junction cell with optimal bandgap under standard illumination (AM1.5 spectrum, no concentration) is about 34%. Real cells have achieved efficiency of about 30% with optimal selection of the bandgap, close to this theoretical limit. Concentrating the solar radiation increases the maximum possible efficiency, for example to 41% at concentration of 1000 suns.

Surpassing the SQ limit requires lifting the fundamental assumptions leading to this limit. The most common approach is reducing the thermalization loss through the use of more than one bandgap, leading to spectral splitting and separate conversion of different parts of the solar spectrum. For example, in multi-junction solar cells, different sub-cells are arranged in a series optical arrangement, such that a photon transmitted through one material with higher bandgap may be absorbed in a subsequent material with lower bandgap [2]. For example, using the same assumptions as the SQ analysis, the upper limit on efficiency of a dual junction cell under 1000 suns is raised to 54.4%. In intermediate band solar cells, the absorber band gap is divided into two separate gaps for the same purpose [3]. Multi-junction cells achieve in practice efficiencies of over 43%, exceeding the SQ limit for a single-junction cell.

Solar thermal conversion usually requires three processes: conversion of radiation to heat, heat to mechanical work, and then work to electricity. This conversion path involves two unavoidable losses: blackbody emission from the radiation receiver in the first process, and heat rejection to the environment dictated by the second law of thermodynamics in the second process. The third

---

[*] Corresponding author. Tel.: +972 3 6405924.
E-mail address: kribus@tauex.tau.ac.il (A. Kribus).

http://dx.doi.org/10.1016/j.solmat.2015.05.001
0927-0248/

Nomenclature

A	Richardson constant [A/cm^2 K^2]
c	speed of light [cm/s]
$E_{f,n}$	conduction band quasi-Fermi level [eV]
$E_{f,p}$	valence band quasi-Fermi level [eV]
E_g	cathode band gap [eV]
G	optical generation [1/cm^3 s]
h	Planks constant [eV s]
H	cathode height [cm]
$h\nu$	photon energy [eV]
J_{em}	cathode emission current density [A/cm^2]
J_{rev}	anode emission current density [A/cm^2]
K_B	Boltzmann's constant [eV/K]
K_{PETE}	emission current coefficient [A cm]
K_R	radiative recombination coefficient [cm^3/s]
m_n	electron effective mass [kg]
n	cathode electron concentration [cm^{-3}]
n_{eq}	cathode equilibrium electron concentration [cm^{-3}]
P	cathode hole concentration [cm^{-3}]
p_{eq}	cathode equilibrium hole concentration [cm^{-3}]
P_{PETE}	power converted through PETE device [W/cm^2]
P_{rad}	radiative recombination losses [W/cm^2]
P_{sun}	input solar power flux density [W/cm^2]
P_{th}	power converted through secondary thermal cycle [W/cm^2]
q	electron charge [C]
Q	heat flux density to the thermal cycle [W/cm^2]
R	total radiative recombination [1/cm^2 s]
R'	non equilibrium radiative recombination [1/cm^2 s]
R_0	equilibrium radiative recombination flux density [1/cm^2 s]
S	electrodes aspect ratio
T_A	anode temperature [K]
T_C	cathode temperature [K]
V	operating voltage [V]
V_{mpp}	maximum power point voltage [V]
W	cathode width [cm]
ΔE	the difference between the conduction band quasi-Fermi level and the equilibrium Fermi level [eV]
δn	access carriers concentration [1/cm^3]
η	PETE efficiency
η_{sec}	secondary thermal cycle efficiency
η_{th}	ideal solar thermal converter efficiency
η_{total}	PETE and thermal cycle efficiency
σ	Stephan Boltzmann constant [W/cm^2 K^4]
ϕ_A	anode work function [eV]
ϕ_B	cathode electron emission barrier [eV]
ϕ_C	cathode work function [eV]
$\Phi_s(E>E_g)$	above band gap photon flux density [1/cm^2 s]
χ	cathode electron affinity [eV]

process can, in principle, be performed without loss. The concentration of sunlight is also assumed to be ideal with no optical losses. The upper limit on solar thermal conversion efficiency can then be expressed by the following simple expression [4]:

$$\eta_{th} = \left(1 - \frac{\sigma T_R^4}{P_{sun}}\right)\left(1 - \frac{T_{amb}}{T_R}\right) \tag{1}$$

T_R and T_{amb} are the temperatures of the radiation receiver and the ambient, respectively. P_{sun} is the flux density of incident solar radiation, determined by the optical concentration of sunlight. For each given concentration, the receiver temperature T_R can be optimized to yield the maximum conversion efficiency. For example, under concentration of 1000 suns (P_{sun} = 1000 kW/m^2) and T_{amb} = 300 K, the optimal receiver temperature is 1107 K and the upper limit on efficiency is 66.7%.

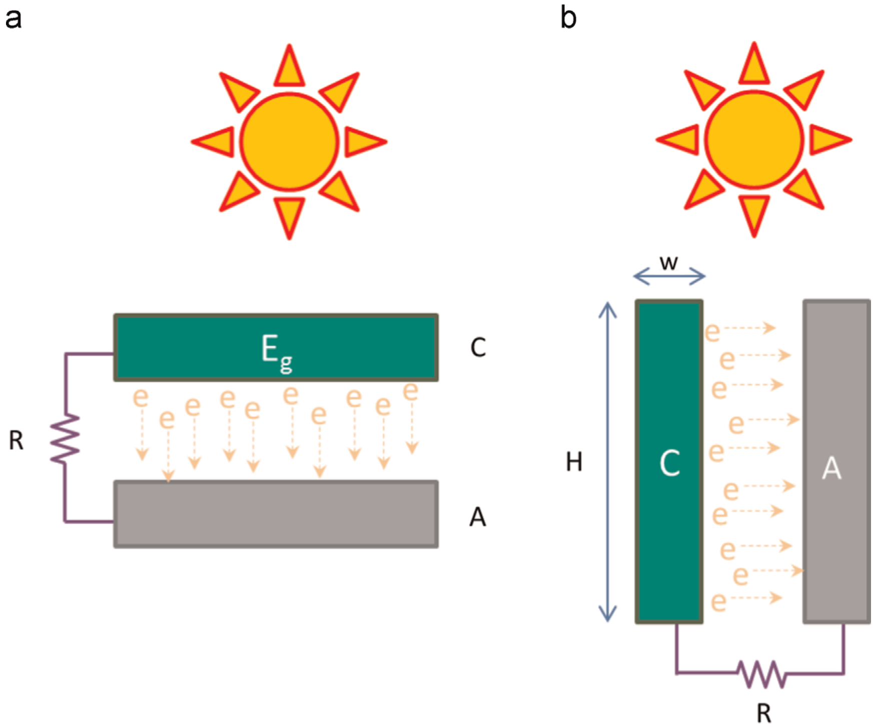

Fig. 1. Schematic of PETE converters (a) front illuminated, (b) side illuminated.