Solar Energy Materials & Solar Cells 107 (2012) 125–130

Contents lists available at SciVerse ScienceDirect

Solar Energy Materials & Solar Cells

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

Efficiency of photon enhanced thermionic emission solar converters

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ARTICLE INFO

Article history:
Received 19 October 2011
Received in revised form
20 July 2012
Accepted 12 August 2012
Available online 5 September 2012

Keywords:
PETE
Thermionic emission

ABSTRACT

Photon Enhanced Thermionic Emission (PETE) is a recently proposed novel concept in solar energy conversion, combining thermal and photovoltaic carrier excitation with thermionic emission. A recent study has shown that PETE conversion efficiencies can theoretically rise above 40% at concentration of 1000 suns. We analyze two major aspects missing from previous treatment of PETE conversion efficiency: changes in the cathode's conduction band carrier concentration with the electrical operating point; and determination of the cathode temperature from a full thermal energy balance. The results show that the conversion efficiency is a monotonically increasing function of temperature, and a monotonically decreasing function of the cathode electron affinity. It is shown that PETE converter efficiency according to the modified model is higher than previously reported, but achieving very high efficiencies of over 40% requires high temperatures that may be difficult in practical implementation.

1. Introduction

When metal or semiconductor surfaces are exposed to vacuum or a rarefied vapor, electrons can be emitted from the surface, at a rate that depends strongly on the surface temperature. This phenomenon is called thermionic emission, and can be used as a method for converting heat directly into electrical power [1,2]. In its most elementary form, a thermionic converter will consist of a cathode receiving heat from a heat source (e.g., combustor or solar concentrator), an anode disposing waste heat to a heat sink, a vacuum gap between the two electrodes, and electrical connections that allow closing the circuit through an external load. Thermionic converters typically require high cathode temperatures, over 1000 °C, and even at these high temperatures the conversion efficiency from heat to electricity is usually less than 20%. The thermionic converter technology has therefore not been widely implemented.

In Photon Enhanced Thermionic Emission (PETE) [3], the cathode is illuminated with above band gap energy photons, increasing the cathode's conduction band electron population, and raising the conduction band quasi-Fermi level. As a result, the electrons' energy barrier to the vacuum is reduced, allowing electron emission at temperatures considerably lower than standard thermionic emission. The PETE conversion process can be divided into three steps. First, the cathode absorbs above band gap photons, adding electrons to the conduction band. The optically generated electrons then thermalize and those having energies higher than the vacuum level, are emitted to the vacuum and collected by the anode.

For the PETE process to work effectively with illumination by solar radiation, the cathode needs to be a semiconductor with suitable bandgap energy matching the energy of solar photons, e.g., in the range of 1–1.5 eV. Only a part of the energy in the incident solar radiation is converted to energy embodied in conduction band electrons: excess photon energy above the bandgap is converted to thermal energy by thermalization, and sub-bandgap photon energy may also contribute to the thermal energy if the cathode contains some means to absorb also these photons. PETE conversion can potentially be more efficient than conventional photovoltaic conversion, since it can extract electricity also from the part of the solar radiation that is expressed as thermal energy. PETE should also be more efficient than conventional thermionic conversion: the absorption of supra bandgap photons in a semiconductor cathode creates a larger conduction band electron population, resulting in a lower potential barrier for electron emission compared to a conventional ceramic cathode activated by heat only, leading to a higher emission current.

Smestad [4] has shown experimentally that combined heating and illumination produces electrical current and output power that are higher than the separate outputs of either heating only or illumination only. Under some conditions the combined power output was even higher than the sum of the separate outputs (Fig. 4 in [4]). This has demonstrated the synergy of the optical (photoelectric) and thermal (thermionic) conversion mechanisms. This work further discusses the limiting efficiency of the combined conversion process, following the analysis of Ross and Nozik [5], assuming that the electrons are hot, i.e., they are emitted before thermalization in the cathode. There is no experimental evidence in [4] to indicate whether

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http://dx.doi.org/10.1016/j.solmat.2012.08.006

the emitted electrons were hot or thermalized, and therefore this experiment can be viewed as a demonstration only in principle of the synergy of photonic and thermal excitation, but without specifying the process.

In more recent work, Schwede et al. [3] have experimentally characterized emitted electrons and have shown that they follow a thermal distribution rather than a 'hot electrons' distribution. The analysis in [3] has presented estimates of conversion efficiency significantly higher than for conventional thermionic emission, e.g., efficiency exceeding 40% for incident solar radiation concentration of $\times 1000$ and temperatures below 1000 °C. The conversion efficiency of a PETE device subject to concentrated solar radiation is therefore theoretically comparable to the best photovoltaic cells. Conversion efficiency may be even higher if the PETE device anode is allowed to reach moderate temperatures (but not high enough to create a significant reverse current), and the heat extracted from the anode can then be used to generate additional electricity, similar to a 'Combined Cycle' in conventional thermal power plants.

We consider here two physical effects that were not addressed in previous analyses, and their impact on the conversion efficiency of PETE devices. The first is the behavior of a PETE device under variable voltage, and identification of the maximum power point. The model in [3] assumed that the carrier concentration in the cathode is independent of the electrical working point, leading to the conclusion that the PETE IV curve follows closely the IV curve of standard thermionic emission devices, and the maximum power point is then found at the flat band condition voltage (the difference in the cathode and anode work functions). However, when increasing the voltage above the flat band condition, the electrons in the inter-electrode space experience a decelerating force. Electrons that do not have sufficient energy to reach the anode are turned back by the electric field and are reabsorbed by the cathode. Since the electrons absorbed by the cathode are at the vacuum level energy, it can be assumed that they will add to the conduction band population (for a cathode with non-negative electron affinity; when the electron affinity is negative, not all the "turned back" electrons have sufficient energy to be reabsorbed in the conduction band; this case is not addressed here). A similar argument applies to the reverse emission electrons that are emitted from the anode and absorbed by the cathode. The electron concentration in the conduction band therefore increases. These electrons may then recombine or be emitted back into the vacuum, and both mechanisms will occur at a higher rate due to the higher concentration. The result is that the decrease in the emission current with voltage above the flat band condition will not be as steep as in conventional thermionic converters, and the maximum power point may be above the flat band voltage. Hence, the maximum conversion efficiency should be evaluated taking this effect into consideration. We show that this effect leads to a significant change in the behavior of the efficiency compared to the previous model.

The second effect considered here is the thermal balance of the cathode. We consider here a configuration where the cathode is thermally isolated and has no additional heat transfer means. As a result, a thermal energy balance determines the cathode temperature for a given input radiation flux, and given the electrical working point. We use a coupled thermal and electrical energy balance and present the cathode temperature and device efficiency as a function of the input flux concentration.

2. Analysis

2.1. Constant cathode temperature

In order to take into account the carrier concentration effect on the maximum power point, a balance of charge carrier generation and loss is performed. It is assumed that the charge carriers' concentration, the temperature and the electrostatic potential are all uniform across the cathode. The effects of negative space charge region are also not considered. It is also assumed that the reverse current emitted from the anode to the cathode contributes to the conduction band electron concentration. Under steady state conditions the difference between the cathode's total optical generation and recombination is the net current

$$L(G-R') = \frac{J_{em}-J_{rev}}{q} \tag{1}$$

where G is the optical generation, R' is the total non-equilibrium recombination per unit volume, J_{em} and J_{rev} are the cathode and anode emission currents respectively, L is the cathode thickness and q is the fundamental charge. Inserting the proper expression to each of the terms in Eq. (1) allows solving for the conduction band electron concentration n.

The optical generation, G, is calculated according to the number of incident photons with energy above the band gap averaged over the entire cathode

$$G = \frac{\Phi(E > E_g)}{L} \tag{2}$$

where $\Phi(E > E_g)$is the flux of all solar photons with energy above the cathode band gap, E is the photon energy and E_g is the cathode band gap.

The emission current follows the derivation suggested by [3]

$$\begin{aligned} J_{em} &= qn\langle v_x\rangle e^{-\frac{\chi}{K_B T}},\ V \le \phi_C-\phi_A \\ J_{em} &= qn\langle v_x\rangle e^{-\frac{\chi+(\varphi_A+V-\varphi_C)}{K_B T}},\ V > \phi_C-\phi_A \end{aligned} \tag{3}$$

where K_B is the Boltzmann constant in eV K^{-1},$\langle v_x\rangle = \sqrt{qK_BT/2\pi m_n}$ is the average electron velocity perpendicular to the surface, m_n is the electron effective mass and χ is the electron affinity. We note that the emission current is linear with the electron concentration and can be written as $J_{em} = K_{PETE}n$. V is the operating voltage and ϕ_C, ϕ_A are the cathode's and anode's work functions, respectively. Assuming that the cathode is connected to the external circuit through a perfect ohmic contact, the valence and conduction band quasi-Fermi levels converge into the equilibrium level at the contact. Hence, the operating voltage is defined as the difference between the cathode's equilibrium Fermi level and anode's Fermi level. Note that in PETE the electron concentration is determined by Eq. (1), and varies with the voltage. Therefore, the emitted current is not purely exponential for voltages above the flat band condition. In conventional thermionic converters, on the other hand, the cathode is typically made of metal or a non-metal at very high temperature, and the electron concentration n is very high and close to the equilibrium concentration determined by the cathode temperature. The number of emitted electrons then does not affect n significantly. Therefore, the emitted current will show an exponential decline with voltage above the flat band condition.

For voltages higher than the flat band condition, inserting $\phi_C = \chi+E_g-E_f$ eliminates the dependence on electron affinity

$$J_{em} = qn\langle v_x\rangle e^{-\frac{\varphi_A+V-(E_g-E_f)}{K_B T}} \tag{4}$$

Eq. (4) implies that for voltages above the flat band condition, the emission current is independent of the electron affinity. The reverse current follows the standard formulation for vacuum thermionic converters [1]

$$\begin{aligned} J_{rev} &= AT_A^2 e^{-\frac{\varphi_C-V}{K_B T}},\ V \le \phi_C-\phi_A \\ J_{rev} &= AT_A^2 e^{-\frac{\varphi_A}{K_B T}},\ V > \phi_C-\phi_A \end{aligned} \tag{5}$$

$A = 120$ A/cm^2 K^2 is the Dushman–Richardson constant and T_A is the anode temperature. Following [3], we assume that radiative recombination is the dominant recombination mechanism. The radiative