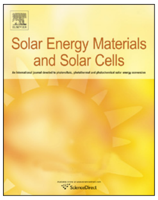
Solar Energy Materials & Solar Cells 121 (2014) 137–143

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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



Space charge effects on the maximum efficiency and parametric design of a photon-enhanced thermionic solar cell

Shanhe Su, Yuan Wang, Tie Liu, Guozhen Su, Jincan Chen*

Fujian Key Laboratory of Semiconductor Materials and Applications and Department of Physics, Xiamen University, Xiamen 361005, People's Republic of China

ARTICLE INFO

Article history:
Received 8 June 2013
Received in revised form
11 October 2013
Accepted 5 November 2013
Available online 24 November 2013

Keywords:
Photon-enhanced thermionic solar cell
Space charge
Cathode material
Maximum efficiency
Parametric design

ABSTRACT

With the help of the Langmuir space charge theory, the performance of a photon-enhanced thermionic solar cell (PETSC) limited by space charge is discussed. It is found that space charge effects become important for the PETSC when the gap width between two electrodes is a few microns or more. At these distances, near-field heat transfer effects are negligible because the gaps are larger than the characteristic wavelength of the thermal radiation, as given by Wien's displacement law. The effects of the energy band gap, electron affinity and temperature of the cathode on the efficiency of the PETSC are analyzed in detail. The maximum efficiency of the PETSC limited by the space charge is calculated under different constraint conditions. Although the maximum efficiency obtained here is much smaller than that calculated theoretically by Schwede et al., Nature Materials 9 (2010) 762, it may be higher than those of traditional solar cells and thermionic devices as long as the gap width of two electrodes is rationally designed.

1. Introduction

The photon-enhanced thermionic solar cell (PETSC) as a new solar-energy device, which has the potential to harness both the light and heat of the sun to generate electricity and increase the efficiency of solar power production, has attracted considerable interest [1–6]. Schwede et al. predicted that the efficiency of the PETSC may greatly exceed the theoretical limits of traditional single junction photovoltaic cells and rival those of multijunction cells by harvesting sub-band gap photons and thermalization losses as heat [1,7]. A GaAs/AlGaAs heterostructure was theoretically and experimentally investigated by combining the basic physics of photon-enhanced thermionic emission and photoemission mechanisms [2,3], which represents the prospect of practical applications based on the PETSC. In addition, compared with the standard thermionic emission device, the PETSC has the ability to emit electrons at lower temperatures and even when both electrode temperatures are the same, because the energy barrier for electrons in the cathode is reduced under illumination as a semiconductor material is used as the cathode [4,5].

In the standard thermionic emission device, the electrons emitted from the cathode do not travel instantaneously to the anode because they require a finite time for transmission. These electrons form a cloud around the cathode such that negative charges accumulate in the interelectrode space. Space charge effects are often considered in the investigation of thermionic emission devices and can be calculated by the Langmuir space charge theory [8–10]. Various methods have been proposed to moderate space charge effects. Neutralizing the space charge with cesium plasma [11,12] and reducing the interelectrode spacing to a few microns [13,14] are some of the most common ways. Koeck et al. developed a new approach that is to incorporate molecular assisted charge transport by introduction of methane in the inter electrode gap [15]. In addition, other techniques suggested employing diamond coating with a negative electron affinity [16,17] or using nanostructuring [18], which may increase the emitted current and may be beneficial independently of the space charge effect by inducing a localized field at the emitting surface. Similarly, the space charge effects in the PETSC cannot be ignored especially when there is a high electric field between the electrodes. Thus, the space charge effects in the PETSC urgently need to be further investigated.

In the present paper, the Langmuir space charge theory is used in the model of the PETSC. By self-consistently solving Poisson's equation, the electrostatic potential distribution is obtained to determine the number of the emitted electrons moving in the interelectrode space. The current density as a function of the voltage is calculated. The effects of the gap width, energy band gap, electron affinity and temperature of the cathode on the performance of the PETSC are discussed in detail. Interestingly,

---

* Corresponding author.
E-mail address: jcchen@xmu.edu.cn (J. Chen).

0927-0248/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.solmat.2013.11.008

the emission current equations obtained here correspond to those described in Ref. [4], where the behavior of a photon-enhanced thermionic emission device under variable voltage was discussed. But it is different from Ref. [4] that the model adopted here does not include the dependence of the cathode electron concentration on the barrier height. Electrons that are emitted from the anode and reflected due to the barrier in the interelectrode space have the possibility to be re-absorbed by the cathode and contribute to the conduction band population. This addition is important. However, similarly to Ref. [1], these two effects are neglected for simplicity.

2. Model description of a photon-enhanced thermionic solar cell

A PETSC consists of a p-type semiconductor as the cathode and a metal plate anode with a vacuum gap in the middle, as shown in Fig. 1 [1]. The PETSC combines photovoltaic and thermionic effects and can simultaneously harvest both photons and heat from the concentrated solar spectrum to generate electricity. By comparing with the Shockley–Queisser limit of an ideal single-junction solar cell, such a device is capable of sustainably increasing the solar energy conversion efficiency [1]. When photons impinge on the semiconductor cathode, electrons can be excited to the conduction band. After a rapid thermalising process, the excited electrons will spread over all the cathode material in an equilibrium distribution according to the cathode temperature T_C, and the electrons with energies greater than the electron affinity χ would transmit out of the cathode surface to produce a thermionic current. Consequently, each emitted electron can thus harvest photon energy to overcome the energy band gap and thermal energy to overcome the electron affinity of the material [1]. Schwede et al. derived the performance of the PETSC at the steady-state condition by considering a balance charge carrier generation, emission, and recombination in the cathode and using the following conservation equations [1,6]

$$R_S - R_P - R_r = 0, \tag{1}$$

where R_S is the rate of photon-induced electrons, R_r is the rate of photon-enhanced recombination, and R_P is the rate of thermionic emission in the semiconductor cathode. In Eq. (1), the conduction band population of the cathode contributed by the thermionic emission from the anode and reflected electrons due to the barrier is assumed to be negligible [1]. The balance equations can be solved to obtain the conduction band concentration n. The description of these equations can be found in Refs. [1,6].

According to the theory of the statistical physics, the total emitted saturation current density from the cathode can be expressed as [1]

$$J_C = \int_{E_C+\chi}^{\infty} e v_x N(E) f(E) dE, \tag{2}$$

where E_C is the conduction band minimum, e is the elementary charge, v_x is the electron velocity perpendicular to the material surface, $N(E)$is the density of state as a function of the energy level, and$f(E)$ is the Fermi distribution. $N(E)$ is assumed to be parabolic in the conduction band. Because the work function is much larger than kT_C, $f(E)$ can be simplified into the Boltzmann distribution. By following the calculation in Ref. [1], Eq. (2) can be rewritten as

$$\begin{aligned} J_C &= \int_{E_C+\chi}^{\infty} e v_x \frac{4\pi(2m_e)^{3/2}}{h^3}\sqrt{E-E_C}\exp\left(\frac{-(E-E_{F,n})}{kT_C}\right)dE \\ &= en\sqrt{\frac{kT_C}{2\pi m_e}}e^{-\chi/kT_C}, \end{aligned} \tag{3}$$

where m_e is the effective mass of electrons, h is the Planck constant, k is the Boltzmann constant, and $E_{F,n}$ is the conduction band quasi-Femi level of photoexcited electrons. The electron current is regarded as positive in the following calculation. In Fig. 1, ψ_A is the anode work function and the work function of the cathode ψ_C is equal to $E_g+\chi-E_F$, where E_g is the cathode energy band gap, and E_F is the equilibrium Fermi level and can be numerically calculated by the charge neutrality in the semiconductor crystal [19].

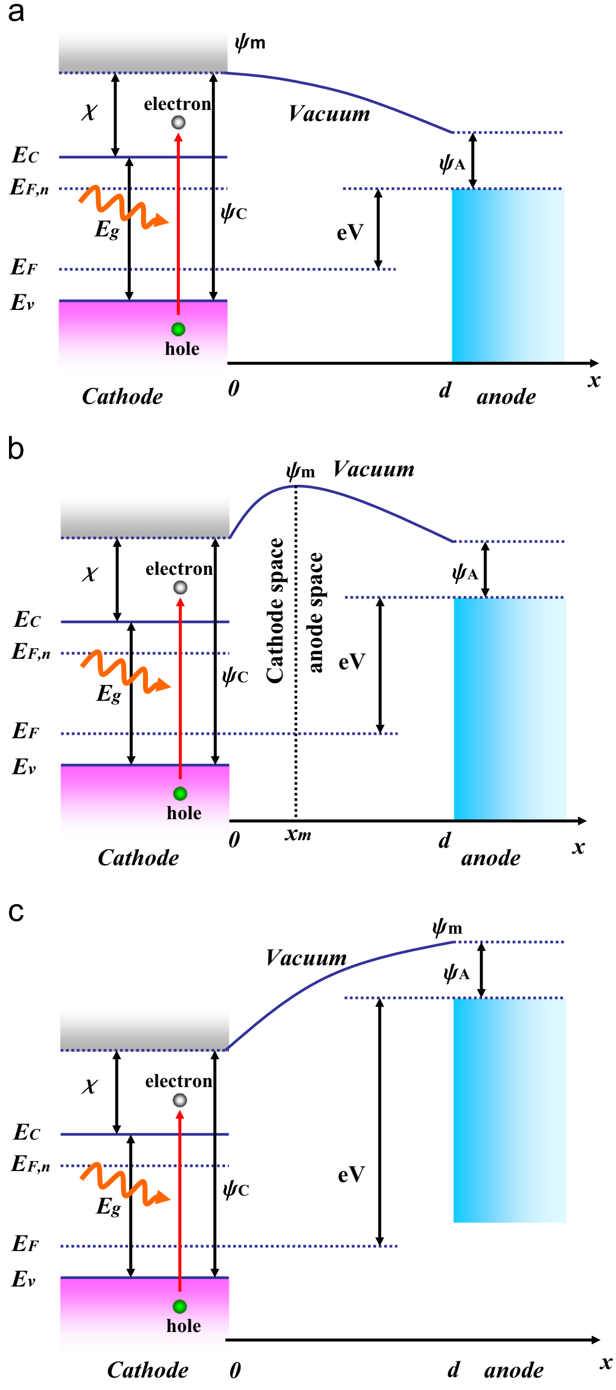


Fig. 1. The energy diagram of a PETSC and motive diagram corresponding to (a) the saturation point, (b) the space charge limited regime, and (c) the critical point.

3. Brief description of Langmuir space charge theory

Charge carriers can form a space charge region when carriers are moving between parallel-plane electrodes in vacuum [20]. This