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Material optimum choices and parametric design strategies of a photon-enhanced solar cell hybrid system

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ABSTRACT

A novel design concept of the solar hybrid system consisting of a solar concentrator, a photon enhanced thermionic emission device (PETED), and a thermoelectric generator (TEG) is proposed. The main irreversible losses in the system are taken into account. The energy balance equations of the cathode and anode of the PETED are directly used to expound that the cathode and anode temperatures of the PETED may be changed through the different choices of the energy bandgap and electron affinity of the cathode material, the reduced electric current of the TEG, and the structure parameter of the hybrid device. Analytic expressions for the power output and efficiency of the hybrid system are derived. The maximum efficiency of the hybrid system is calculated and it is proved that the hybrid system can effectively enhance the conversion efficiency of solar energy. The optimal values of some important parameters, such as the energy bandgap and electron affinity of the PETED, the reduced electric current of the TEG, the structure parameter of the hybrid device, and the solar concentration of the hybrid system, are determined. The results obtained here will be helpful for the reasonable choice of cathode materials and the optimum design of practical hybrid devices.

1. Introduction

The ever increasing demand of energy is causing a great decrease in fossil fuels like coal, oil, and natural gas, which will threaten to the development of human activities. Developing renewable energy is an issue of critical importance for a sustainable future [1–5]. Solar energy has obvious advantages in comparison with the conventional energy sources, such as environment friendly, indispensable, and reliable for long term supply [6,7]. At present, the thermodynamic systems of utilizing solar energy mainly include solar photovoltaic devices and solar thermal collectors. Photovoltaic technologies employ solar semiconductive panels to directly convert sunlight into electricity [8,9], while solar thermal technologies are used for the heating [10,11] and electricity generation [12,13]. However, each of these systems has a relative low efficiency. For example, the commercial multicrystalline Si solar cell has the efficiencies of around 14–19% [14]. Photon enhanced thermionic emission device (PETED) as a new concept of thermionic emission mechanism has the advantage of combining light and thermal processes and has attracted considerable interests [15–21]. Using the photon enhanced thermionic emission as solar cell under concentrating circumstances can theoretically obtain the efficiency greater than the Shockley–Queisser (SQ) limit [15]. Obviously, it is very important to deeply investigate the performance of the PETED. Moreover, the anode temperature of PETED is usually much higher than the environmental temperature and the waste heat in the PETED has not been utilized [15,18]. Thus, it is more important to design some novel hybrid devices to efficiently recover the waste heat in the PETED and further enhance the conversion efficiency of solar energy.

In the present paper, we will propose a new model of the solar hybrid system which is composed of a solar concentrator, a PETED, and a thermoelectric generator (TEG) and discuss the optimum choices of the cathode material and the parametric design strategies of the hybrid system. The concrete contents are organized as follows: in Section 2, a new model of the solar hybrid system including main heat losses is briefly described. In Section 2.3, the energy balance equations are used to determine the operating temperatures of the cathode and anode of the PETED. The power output and efficiency of the hybrid system are derived. In Section 3, the performance characteristics of the hybrid system are determined by numerical calculation. The optimal design problems of the system are discussed in detail. The optimal values of the energy bandgap and electron affinity of the PETED, the reduced electric current of the TEG, the structure parameter of the hybrid device, and the solar concentration of the hybrid

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system are obtained. Finally, some significant conclusions are summarized in Section 4.

2. The model of a novel solar cell hybrid device

The novel solar cell hybrid device shown in Fig. 1 mainly consists of a PETED on the top and a series-connected semiconductor TEG attached to the bottom of the cell. When a ray of concentrated solar radiation is incident on the PETED, a part of the radiation will be selectively absorbed by the *P*-type semiconductor cathode material and converted into electrical energy. A layer of solar selective absorber material is coated on the surface of the cathode so that sub-bandgap photons can be absorbed to heat the cathode. Electrons in the cathode will thermalize to an equilibrium thermal distribution rapidly [15]. One part of these electrons crosses the vacuum gap, arrives at the anode, and returns to the cathode through the load resistance. The waste heat in the anode of the PETED may be used to drive a TEG so that the conversion efficiency of solar energy can be further increased. Below, the thermal and electrical performance evolution of individual part and overall device in the hybrid system will be discussed.

2.1. The power output and efficiency of a photon enhanced thermionic device

Thermionic device uses the heat-induced flow of charge carriers over a potential-energy barrier to realize the thermal-electric conversion. Unlike traditional thermionic devices, the PETED combining simultaneously photovoltaic and thermionic effects, which is also called as the photon enhanced thermionic emission solar cell and was first put forward in 2010 [15], can harvest both the photon and heat of the concentrated solar spectrum to generate electricity. Such a device is capable of sustainably increasing the efficiency of solar energy conversion. As shown in Fig. 1, a PETED consists of a *P*-type semiconductor as the cathode and an anode metal plate with a vacuum gap in the middle. When photons impinge on the semiconductor cathode, electrons can be excited to the conduction band. After a rapidly thermalizing process, the excited electrons will spread all over the cathode material with an equilibrium distribution according to the cathode temperature T_C. The electrons with energies greater than the electron affinity χ can transmit out of the cathode surface to produce thermionic current. Consequently, the emitted electrons contain the photon energy and thermal energy at the same time.

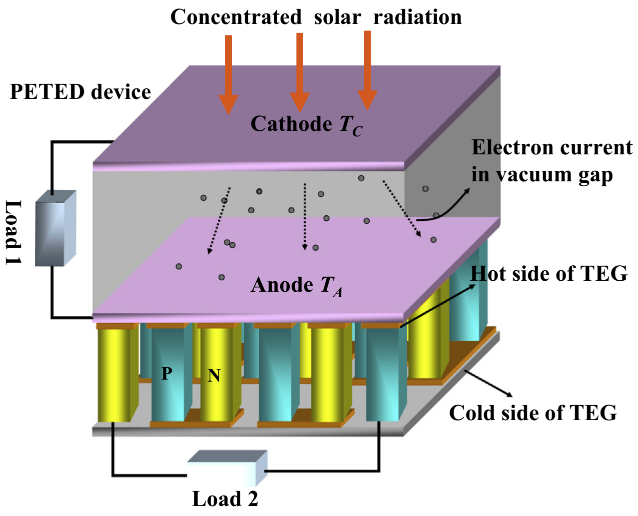

Fig. 1. The schematic diagram of a high efficient solar cell hybrid device.

It is significant to note that, based on the model of Ref. [15], the authors in Ref. [17] further considered that electrons reflected in the gap return to the cathode's conduction band and expounded that the cathode thermionic currents are different under different biases. Although the updated model in Ref. [17] can give a little improvement and is closer to the actual situation than the model in Ref. [15], but it is more complex than the model in Ref. [15], because the thermionic currents from the cathode and anode and the work function of the cathode in Ref. [17] need to be simultaneously determined by the electron affinity, energy bandgap of the cathode material, cathode temperature, and anode temperature. In order to simply and conventionally show the potential of improving energy conversion by employing a hybrid energy harvesting system, we will adopt the model in Ref. [15] rather than the model in Ref. [17] in the following discussion.

According to the theory of Boltzmann statistics and the supplementary information of Ref. [15], the cathode thermionic current density can be expressed as [19–21]

$$J_C = eN\sqrt{\frac{kT_C}{2\pi m_e}}\,e^{-\chi/kT_C} \tag{1}$$

where N is the conduction band population of photoexcited electrons in units of cm^{-3}, e is the absolute value of the electron charge in units of C (i.e., Coulomb), k is the Boltzmann constant in units of eV K^{-1}, and m_e is the effective mass of electrons in units of eV/cm^2/s^2. The conduction band population N can be determined by solving the particle balance equation as described by the supplementary information in Ref. [15]. Thus, the cathode thermionic current density is dependent on the cathode temperature T_C and the electron affinity χ, which are two important parameters to be optimized below. For the anode electrode, a traditional Richardson's equation [22, 23]

$$J_A = A_A T_A^2 e^{-\phi_A/kT_A} \tag{2}$$

is used to calculate the current density emitted by the metal surface with a work function $\phi_A = 0.9$ eV at a temperature T_A, where A_A is the Richardson constant, which is equal to 120 A cm^{-2} K^{-2}.

According to the analyses above, the power output and efficiency of the photon enhanced thermionic solar cell can be expressed as [15]

$$P_P = (J_C - J_A)(\phi_C - \phi_A - V_{bias})\,A_S \tag{3}$$

and

$$\eta_P = \frac{(J_C - J_A)(\phi_C - \phi_A - V_{bias})}{P_{sun}} \tag{4}$$

where P_{sun} is the concentrated AM1.5 direct circumsolar spectrum, A_S is the surface area of the PETED, V_{bias} is the bias voltage between the two electrodes, $\phi_C = \chi + E_g - E_F$ indicates the cathode work function, E_F is the equilibrium Fermi level of the semiconductor without photoexcitation and can be calculated by charge neutrality in the semiconductor [24], and E_g is the energy bandgap of the cathode material. In Eqs. (3) and (4), $\phi_C - \phi_A - V_{bias}$ determines the voltage output of the PETED. When V_{bias} in the gap is not considered, the voltage output of the PETED is simply given by the difference $\phi_C - \phi_A$ between the cathode and anode work functions [15]. It shows clearly that the power output and efficiency of the PETED are closely dependent on the material parameters χ and E_g of the cathode material and the temperatures T_C and T_A of two electric plates.

2.2. The power output and efficiency of a thermoelectric generator

Semiconductor thermoelectric generators can directly convert a part of heat into electricity and is playing an important role in the global sustainable energy issue [25,26]. A practical device contains