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Parametric characteristics and optimum criteria of a near-field solar thermophotovoltaic system at the maximum efficiency

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ABSTRACT

The model of a near-field solar thermophotovoltaic system (NF-STPVS) consisting of a solar concentrator, an absorber, an emitter, an optical filter, and a photovoltaic (PV) cell is proposed, in which the near-field radiation between the emitter and the PV cell, the radiation and reflection losses from the absorber to the environment, and the finite-rate heat transfer between the PV cell and the heat sink are taken into account. By using the fluctuational electrodynamics and irreversible thermodynamics, formulas for the power output and efficiency of the system are analytically derived. By solving energy balance equations, the operating temperatures of the emitter and the PV cell are calculated for given values of the output voltage of the PV cell and the vacuum gap. The concentration factor at the maximum efficiency of the system is optimally given. Furthermore, the maximum efficiencies of the system are calculated for two cases of the absence and presence of the Auger recombination and the corresponding optimum values of several key parameters are determined.

1. Introduction

A thermophotovoltaic (TPV) cell is an energy device that converts a part of heat into electricity via the radiated photons [1–3]. The advantages of TPV devices mainly include the easy maintenance, high portability, great fuel flexibility, waste heat recovery, high power density, high heat-to-electricity conversion efficiency, small size, no moving parts, low noise, etc. [4–6]. Traditionally, a basic TPV device consists of an emitter and a photovoltaic (PV) cell [7–9]. Photons are emitted due to thermal motion of charges in the emitter, which can be heated by external sources such as sun energy [10], industrial waste heat [11], or burning of fossil fuels [4,5]. Simultaneously, the PV cell can absorb some of these radiated photons and convert them into photocurrent by creating free charge carriers [12]. It is noteworthy that the performances of the materials including the emitter and PV cell are of great importance to improve the efficiency of TPV devices. The emitter should maintain the optical properties such as the wavelength, polarization, and direction at high temperatures [13]. Based on different physical mechanisms, many structures such as one-dimensional photonic crystals [14], one-dimensional complex gratings [15], single-defect phonic crystals [16], three-dimensional woodpile-like photonic crystals [17], random multilayer structures [18], resonant nano-optic cavities [19], two-dimensional grating/thin-film nanostructures[20], surface plasmons [21], one-dimensional trilayer films grating with W/SiO_2/W structure [22], and multilayer structures [23] have been proposed and investigated to achieve spectrally selective emission. In addition, the efficiency of TPV devices can be enhanced by returning subband photons back to the emitter by means of intermediate frequency filters such as rugate filters, photonic crystal filters, and plasma reflectors. More importantly, the near-field thermal radiation is mostly at near infrared and infrared frequencies due to the temperature of the emitter. In order to match the optical properties of the emitter, low band gap semiconductor materials such as GaSb, InAs, and InSb are usually used in PV cells [23]. Specifically, TPV cells can be divided into far-field [24–29] and near-field [30–35] TPV devices, which can be distinguished by comparing the vacuum gap between the emitter and the PV cell with the characteristic wavelength of thermal radiation given by Wien's displacement law. When the vacuum gap is at subwavelength, the near-field radiation is several orders of magnitude larger than the far-field radiation due to the contribution of evanescent waves. Thus, the performance of the TPV cell can be enhanced when the radiative heat transfer is in near-field regime. Recently, many theoretical and experimental studies have been focused on the near-field TPV devices [30–38]. Molesky et al. [30] established a model of the near-field TPV system by using the van Hove singularities presenting in carbon nanotubes. The results showed that both the spectral selectivity of thermal radiation and magnitude can be boosted and the energy-conversion efficiency can be dramatically improved. Some researchers

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Nomenclature

A	area (cm^{-2})
c	speed of light (cm s^{-1})
C	concentration factor
d	vacuum gap (cm)
e	elementary positive charge (C)
E_g	PV cell bandgap (eV)
h	Planck constant (eV s)
i	current density (A cm^{-2})
I	spectral incident solar radiation (W m^{-2} nm^{-1})
k	wave vector (cm^{-1})
K_B	Boltzmann constant (eV K^{-1})
m	Auger recombination coefficient (cm^6 s^{-1})
N	concentration (cm^{-3})
n	refraction index of the PV cell
P	power output (W)
P^*	power output density (W cm^{-2})
q	heat flow (W)
q^*	heat flow density (W cm^{-2})
r	Fresnel reflection coefficient
R	Auger recombination rate (cm^{-2} s^{-1})
G	photon generation rate (cm^{-2} s^{-1})
T	temperature (K)
t	thickness of PV cell (cm)
U	heat transfer coefficient (W K^{-1} cm^{-2})
V	voltage (V)

Greek symbols

α	absorptance
β	transverse wave vector (cm^{-1})
ε	dielectric function
η	efficiency
λ	radiation wavelength (cm)
ξ	emittance
$\prod$	coupling coefficient (cm^{-1})
ρ	conductivity
σ	Stefan-Boltzmann constant (W cm^{-2} K^{-4})
Ω	solid angle
τ	electron relaxation time (s)
Θ	photon mean energy function
ω	Frequency (rad s^{-1})
θ	fitting constant (eV K^{-1})
μ	fitting constant (K)

Superscript

E	emitter
P	photovoltaic
V	vacuum

Subscript

A	absorber
C	cold side
d	doping
E	emitter
Evan	evanescent
g	band-gap
H	hot side
I	imaginary part
i	intrinsic
max	maximum
oc	open circuit
oe	optical efficiency
opt	optimum
p	*p*-polarized wave
P	PV cell
Prop	propagating
R	real part
Rad	radiation
Ref	reflect
S	solar
s	*s*-polarized wave
V	vacuum
z	a component of the wave vector

Abbreviations

NF	near-field
PV	photovoltaic
STPVS	solar thermophotovoltaic system
TPV	thermophotovoltaic

investigated graphene-assisted near-field TPV systems [31–34]. Tong et al. [35] proposed a new approach to significantly improve the performance of TPV systems by using a thin-film Ge emitter and an ultra-thin GaSb cell supported by back surface reflectors. Svetovoy et al. [36] proposed a graphene-Si Schottky junction based near-field TPV system. The effects of the emitter temperature and vacuum gap on the performance of the TPV system were discussed. Recently, Fan et al. [37] investigated a high-efficient Schottky junctions-based near-field TPV system, in which the Schottky junctions are composed of silicon and metallic films. Through the optimization of the thermal radiation spectrum, the system can achieve high thermal-electricity conversion efficiency and power density. The fluctuation-dissipation theorem and fluctuation electrodynamics approach are usually used to investigate the performance of TPV devices [12,21,38–41]. Elzouka et al. [38] estimated the performance of the near-field solar TPV cell composed of a solar concentrator, an InGaSb PV cell, a photonic absorber, and a tungsten emitter. Moreover, the effects of the distance between the emitter and the PV cell, emitter temperature, and emitter/absorber area ratio on the overall solar-to-electrical conversion efficiency were discussed. Bright et al. [39] reported the parametric study of near-field TPV cells consisting of an InGaSb PV cell, a gold mirror, and a tungsten emitter. It was demonstrated that the performance of the TPV cells can be enhanced by adding a gold mirror in the system. Chen et al. [41] proposed a way to suppress the sub-bandgap phonon-polariton heat transfer and recover the low-quality waste heat by using a near-field TPV device consisting of an emitter made of refractory metal and a PV cell made of semiconductor Ge. Zhai et al. [42] analyzed the performance of far- and near-field ideal TPV systems with an equivalent cut-off blackbody emitter under a generic fluctuational electrodynamics model.

Based on the previous works, we propose a new model of the near-field solar thermophotovoltaic system (NF-STPVS) composed of a solar concentrator, an absorber, an emitter, an optical filter, and a PV cell. The concrete contents are organized as follows: In Section 2, a model of the NF-STPVS including the main irreversible losses is briefly depicted. In Section 3, the power output and overall efficiency of the system are derived. Moreover, energy balance equations are used to determine the operating temperatures of the emitter and the PV cell. In Section 4, the performance characteristics of the NF-STPVS are investigated through numerical calculation, the parametric optimum problems of the system are discussed in detail, and several of the important parameters are optimally designed. Finally, the main conclusions are summarized.