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Parametric investigation of nano-gap thermophotovoltaic energy conversion

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ABSTRACT

Nano-gap thermophotovoltaic energy converters have the potential to be excellent generators of electrical power due to the near-field radiative effect which enhances the transfer of energy from one medium to another. However, there is still much to learn about this new form of energy converter. This paper seeks to investigate three parameters that affect the performance of nano-gap thermophotovoltaic devices: the emitter material, the thermophotovoltaic cell material, and the cell thickness. Furthermore, the temperature profiles in insulated thin films (cells exposed to below-band gap near-field radiation) are analysed. It was discovered that an effective emitter material is one that has a high generalised emissivity value and is also able to couple with the TPV cell material through surface polaritons while a cell material's electrical properties and its thickness has heavy bearing on its internal quantum efficiency. In regards to the temperature profile, the heat-flux absorbed causes a rise in temperature across the thin film, but is insufficient to generate a temperature gradient across the film.

1. Introduction

A thermophotovoltaic (TPV) device is an energy converter that converts heat into electricity. A basic configuration consists of an emitter and an absorber which are separated by a gap. The emitter is heated up by an external source and will then radiate energy in the form of electromagnetic waves or photons. These photons will then be absorbed by the photovoltaic (PV) cell (absorber) to produce electricity. The PV cell used in TPV systems will hereafter be referred to as TPV cells to differentiate them from their solar-dependent counterparts. The emitter is usually heated up to and maintained at a temperature between 1000–2000 K, while TPV cells with band-gaps below 1.1 eV are usually required [1,2].

TPV devices are considered more versatile when compared to conventional PV cells which can only be powered by the sun. A TPV device can generally be deployed anywhere where there is sufficient energy to raise the temperature of the emitter. It also shares some of the strengths of PV devices such as the ease of maintenance and portability. Despite these advantages, the efficiency of TPV devices are relatively low compared to other types of green energy generators [3].

In order to improve the performance of TPV devices, a modification to the existing design was proposed. DiMatteo [4], and Whale and Carvalho [5,6] were the first to propose the idea of reducing the gap size to lengths smaller than the characteristic wavelength in order to take advantage of the near-field effect. Within the near-field region, there exist evanescent modes which dominate heat transfer. There are namely three types of modes which are well-documented in the literature: evanescent waves, surface plasmon polaritons (SPPs), and surface phonon polaritons (SPhPs). When the TPV cell is brought close enough within the

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Nomenclature

$D_{(e,h)}$	diffusion coefficient of electron/hole [$m^2\,s^{-1}$]
e	electron charge ($=1.6022\times10^{-19}$ J eV^{-1})
f	distribution function
$\mathbf{g}$	generation rate of electron–hole pairs [$m^{-3}\,s^{-1}$]
g^E, g^H	electric/magnetic Weyl component of the dyadic Green's function [m]
$\hbar$	reduced Planck's constant ($=1.0546\times10^{-34}$ J s)
J	effective photocurrent [A m^{-2}]
J_{ph}	photocurrent generated [A m^{-2}]
k	wavevector [rad m^{-1}]
k_b	Boltzmann constant ($=1.3807\times10^{-23}$ J K^{-1})
k_v	wavevector in vacuum [rad m^{-1}]
k_z	wavevector in the z-direction [rad m^{-1}]
k_ρ	parallel wavevector [rad m^{-1}]
$n_{(e,h)}$	electron/hole concentration [m^{-3}]
N_a	acceptor concentration [m^{-3}]
N_c	effective density of states in the conduction band [m^{-3}]
N_d	donor concentration [m^{-3}]
N_n	number of spatial nodes in n-type region
N_p	number of spatial nodes in p-type region
Q	Heat energy [J]
q	radiative heat flux [W m^{-2}]
q'''	power density [W m^{-3}]
$S_{(e,h)}$	surface recombination velocity of electron/hole [m s^{-1}]
T	temperature [K]
t	time [s]
x	dimension of thin film in x-direction [nm]
y	dimension of thin film in y-direction [nm]
z	dimension of thin film in z-direction [nm]
ε_r	dielectric function ($=\epsilon'_r+i\epsilon''_r$)
$\eta_{q,\omega}$	internal quantum efficiency
κ	absorption coefficient [m^{-1}]
λ	wavelength [m]
Θ	mean energy of a Planck oscillator [J]
$\tau_{(e,h)}$	electron/hole lifetime [s]
ω	angular frequency [rad s^{-1}]

Subscripts and superscripts

dp	depletion region
e	electron
gen	generation
h	hole
l	lth layer
n	n-region
p	p-region
ph	phonon
pl	polarization
ref	reference
ρ,θ,z	polar coordinate system

influence of these evanescent modes, a phenomenon called radiation tunnelling occurs. This phenomenon increases the heat flux exchanged between the emitter and the absorber by a few orders of magnitude which will in turn increase the electrical output of the device [7], making it a very attractive power generator.

In this paper, a theoretical near-field TPV design which incorporates a gap size of 10 nm will be used. The nanometric gap will enhance the near-field effect even further. This device will thus be called a nano-gap TPV device. A numerical model based on Franceour's work [7] will be utilised to investigate the effects of the emitter material, the TPV cell material, and the cell thickness on the performance of a nano-gap TPV device. In the final section, thickness effects on the cell's temperature profile will be studied through the use of phonon Monte Carlo (MC) simulations.

2. Literature review

2.1. Near-field radiation heat transfer

Tien et al. [8,9] were one of the first to present a quantitative analysis of near-field radiation transfer between two solids. In their work, they introduced two phenomena that influence near-field radiative heat transfer, which are wave interference and radiation tunnelling. They then calculated the radiative heat-flux exchanged between two dielectrics separated by a vacuum gap. However, the source of the radiation is not well defined. They related the radiation emitted by the dielectric to the radiation emitted by a black body through Fragstein's relation. Furthermore, they only considered the total internal reflection as the source for evanescent waves without taking into account other possible modes.

The first accurate heat flux calculation was done by Polder and Van Hove [10]. They used the fluctuational electrodynamics (FE) formalism pioneered by Rytov [11] and the fluctuation-dissipation theorem (FDT) to describe the source of emission.

Mulet et al. [12] demonstrated that surface phonon–polaritons that can be generated in certain materials produce quasi-monochromatic radiative heat transfer between two objects while Lee et al. [13,14] introduced a way to visualise the Poynting vector which is used to calculate the near-field radiative heat flux. Furthermore, Narayanaswamy and Chen [15] studied near-field radiation in one-dimensional layered media and developed a general formulation to describe it. They used a combination of Maxwell's equations (ME) and the FDT to compute the thermal emission directly from the emitting structure.

2.2. TPV models

Whale [5] investigated the phenomenon of near-field radiation and provided an analysis of the performance of a microgap-TPV device. He proposed a way to