Renewable Energy 45 (2012) 245–250

Contents lists available at SciVerse ScienceDirect

Renewable Energy

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

Technical note

One-dimensional metallic-dielectric (Ag/SiO_2) photonic crystals filter for thermophotovoltaic applications

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ARTICLE INFO

Article history:
Received 2 March 2011
Accepted 2 March 2012
Available online 24 March 2012

Keywords:
TPV
Filter
Photonic crystals
Metal
Dielectric

ABSTRACT

In this article, the performance of one dimensional metallic-dielectric photonic crystals (1D MDPCs) filter for improving the performance of thermophotovoltaic (TPV) systems is studied. The reflectance and absorbance of Ag/SiO_2 filters are calculated using the transfer matrix method. The spectral efficiencies and the above-bandgap transmissions of the filters are calculated for different choices of number of periods and layer thicknesses. Furthermore, an optimized stack design that exhibits better spectral efficiencies and better above-bandgap transmission is presented.

1. Introduction

The thermophotovoltaic (TPV) technology is a promising approach that directly converts thermal energy, emitted from a radiated source, into electricity. The potential applications of TPV systems include remote electricity supplies, transportation, cogeneration, electric-grid independent appliances, and aerospace power applications [1]. The TPV system consists of a thermal radiator (emitter) assumed to be an ideal blackbody (BB), a selective filter and a photovoltaic (PV) cell. In contrast to solar photovoltaics, the radiation spectrum absorbed in the PV cells of a TPV system can be adapted to the spectral sensitivity of the PV cells, and losses of unusable radiation can be minimized in order to achieve high efficiency and high power output [2]. The PV cell absorbs the photons having energies greater than the cell bandgap energy, E_g, and generates electron–hole pairs that can be collected as a current through a connected load. The usual range of bandgaps using temperatures (1000–2000 K) blackbody is between 0.5 eV and 0.75 eV or slightly higher [3]. GaSb has a direct bandgap energy of $E_g = 0.7$ eV, or equivalently the bandgap wavelength $\lambda_g = 1.78$ µm, making it a good choice for spectral matching to emitter temperature at 1500 K. GaSb is an inexpensive material fabricated using well established processes that ensure good device quality. An ideal filter in a TPV system works as a perfect high pass filter. It transmits photons having energies higher than the bandgap energy ($R_{filter} = 0$ for $E > E_g$ i.e. $\lambda < \lambda_g$) and reflects back to the emitter photons having energies lower than the bandgap of the PV cell ($R_{filter} = 1$ for $E < E_g$ i.e. $\lambda > \lambda_g$). The investigation on a TPV system mainly focuses on increasing its efficiency. For such purpose, the spectral control of thermal radiation using the selective filter is a vital and practical approach. One dimensional-photonic crystals (1D PCs) have the advantage of simple structure that can be fabricated easily. Si/SiO_2 photonic crystals were recently reported for the dielectric–dielectric PCs filters used in TPV applications [4–8]. O'Sullivan et al. [4] suggested and fabricated a ten-layers quarter-wave periodic structure with Si and SiO_2 layers of 170 and 390 nm thick, respectively. They suggested reducing the first layer thickness to one half of its original thickness. Mao et al. [5] designed and fabricated a 1D ten layers (five-units) Si/SiO_2 PC in which the first and fifth units serve as refractive index match units. Celanovic et al. [6] analyzed the optical performance of 1D PCs and presented an optimized dielectric stack design that yields better TPV system efficiency than a simple quarter-wave stack. Liu et al. [7] designed a 4 periods (8 layers) PC by using SiO_2 and Si layers of thicknesses equal to 204 and 194 nm, respectively in the first period and 408 and 176 nm, respectively in the other three periods. Xuan et al. [8] suggested a non-periodic 1D Si/SiO_2 micro-structure filter that was designed by a genetic optimization algorithm. Optical performance of different types of metallic-dielectric photonic crystals (MDPCs) was theoretically and/or experimentally studied [9–12]. Ag/SiO_2 photonic crystals were fabricated and their transmittance and reflectance were measured [13,14]. These studies proved that the

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doi:10.1016/j.renene.2012.03.001

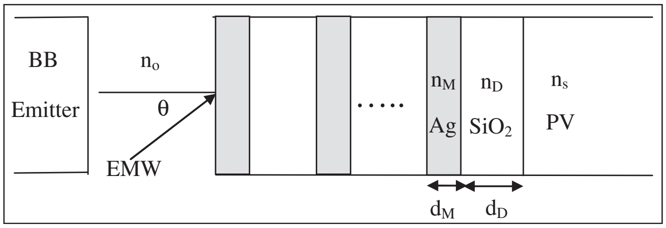

Fig. 1. The TPV system incorporating an ideal blackbody (BB) emitter, a GaSb photovoltaic cell and a front-side 1D Ag/SiO_2 PCs filter.

use of metallic layers in the PCs enlarges the bandgap (the zero-transmittance band) above that would be achieved using dielectric–dielectric layers. In addition, the performance of such PCs can be better adjusted using such metallic layers. However, metals are highly reflective in the visible and infrared regions. Light can actually penetrate a small distance inside the metal known as the skin depth. Hence, the thickness of the metal layers must be less than the skin depth. The Ag skin depth is about 12 nm in the visible range and 13 nm in the near infrared range.

In this work, the use of 1D Ag/SiO_2 MDPCs as a spectral control filter for TPV system having GaSb PV cell is suggested and studied. An $(MD)^N$ filter that consists of a stack of N periods of alternating metal (Ag) and dielectric (SiO_2) is suggested to start with. Then, a modified structure for the filter, namely; $(D/2)(MD)^N(D/2)$ is suggested to enhance the optical response as will be explained in details in Section 3.2. The addition of such half- thickness layer of dielectric in front and at the back of the filter is studied as a way to produce better performance of our Ag/SiO_2 as has been suggested with other PCs in previous work [9].

2. Model and basic equations

The TPV system consists of three devices including a thermal emitter, a filter, and a GaSb photovoltaic cell as shown in Fig. 1. The thermal emitter in this study is assumed to be an ideal blackbody (BB) that is separated from the filter by a thin air gap. All parts of the TPV system are assumed to have the same large cross section area and the emitter and the filter are close. Concentrating on the behavior of the filter, the response of the PV cell (absorbance of photons, emission of photons and so on) is not studied. However, the filter/PV cell interface effect is included in the calculations of transmittance and reflectance. All angles of incidence are included due to the short distance between the BB emitter and the filter. The structure of the Ag/SiO_2 PCs filter is described by $(MD)^N$ as shown in Fig. 1, where N is the number of periods. The thickness of the SiO_2 layer is d_D and the thickness of the Ag layer is d_M. The refractive index of SiO_2 is taken to be $n_D = 1.5$. The frequency-

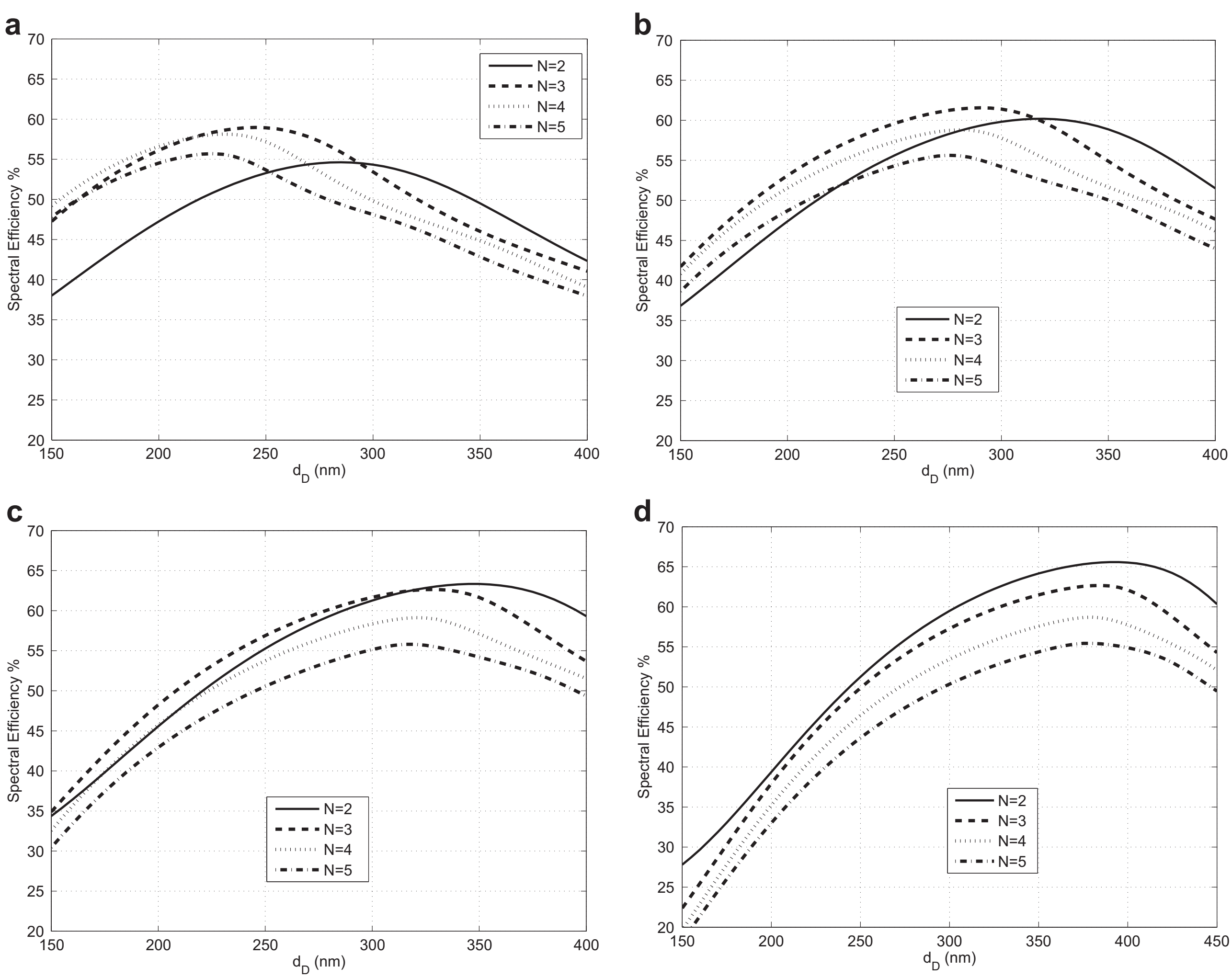

Fig. 2. The spectral efficiency, η_{sp}, vs dielectric thickness, d_D, at different number of periods, N. (a) $d_M = 3$ nm, (b) $d_M = 4$ nm, (c) $d_M = 5$ nm and (d) $d_M = 7$ nm.