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Refractory material based frequency selective emitters/absorbers for high efficiency and thermal stable thermophotovoltaics

Dongyue Jiang, Wenming Yang*

Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore

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ABSTRACT

Refractory materials based frequency selective emission/absorption is extremely encouraging for various applications, especially the combustion based thermophotovoltaics (TPV) and solar-TPV systems. The frequency selective emitters/absorbers also face the challenges of robust operation at elevated temperatures. Here, we report titanium nitride based thermal stable emitters/absorbers with good selectivity in the near infrared wavelength range. The titanium nitride nanocavitity array provides high emissivity/absorptivity at the desired short wavelength range but suppressed emissivity/absorptivity at the long wavelength range, and this design could be used to obtain high power density of the TPV system. The cut-off wavelength could be adjusted by encapsulating the cavities with different dielectrics. Meanwhile, the encapsulating layer protects the nanocavity structure from deformation at high temperatures. The thermal stability at 1073 K and 1273 K for two hours in Argon was demonstrated for the encapsulated nanocavity structure.

1. Introduction

Frequency selective emitters/absorbers exhibit powerful and flexible effectiveness in regulating the propagation of the electromagnetic waves [1–3]. Various applications have been inspired by such devices including plasmon heating mediated catalysis [4,5], heat-assisted magnetic recording [6,7]. Among these systems, the efficient solid-state energy conversion [8] and harvesting [9,10] systems (combustion based thermphotovoltaic (TPV) and solar-TPV) rely more on the frequency selective emitters and absorbers. Combustion based TPV system is an important solid-state energy conversion device with superior power density (12 kWh/kg) comparing with the chemical batteries (0.2 kWh/kg) and could be a promising alternative to the current chemical batteries [8,11–13]. In the combustion based TPV system which as shown in Fig. 1a, hydrogen or hydrocarbon fuel is burned for generating thermal energy in the combustor/emitter [14–17]. The emitter emits photons towards the PV cells for power generation. The spectral radiance of the blackbody is broadband as shown in Fig. 1c. Due to the existence of the bandgap of the PV cell, much of the broadband radiation energy is wasted. In Fig. 1c, the quantum efficiency of InGaAsSb PV cell [18,19] is shown. It is found when the wavelength exceeds 2350 nm, the quantum efficiency of the PV cell is zero, which indicates that the spectral radiance of the emitter which is above 2350 nm is useless for power generation. As a result, an ideal selective emitter which possesses a close to unity emissivity at the wavelength range above the bandgap of the PV cell, but suppressed emissivity at the wavelength range below the bandgap is strongly desired. The scenario in the solar-TPV system is similar to the combustion based TPV system. As shown in Fig. 1b, a broadband absorber is utilized for collecting the concentrated solar energy. The obtained thermal energy is transferred to an emitter which emits photons towards the surface of the PV cells for power generation. In the solar-TPV system, an ideal absorber which absorbs the whole solar spectrum is needed. As shown in Fig. 1d, the solar radiation spectrum is mainly distributed at the visible to near infrared wavelength range (below 1700 nm). The ideal absorber shows a near to unity absorptivity in this wavelength range. At the same time, after absorbing the solar energy, the temperature of the absorber increases (1000–1500 K). The normalized spectral radiance of the absorber which operates at 1500 K is shown in Fig. 1d, the high value part is mainly distributed at long wavelength range (1200–2700 nm). In this wavelength range, the ideal absorber shows an extremely low emissivity which prevents the radiation heat loss. In the solar-TPV system, the determination of the cut-off wavelength is important and it is related to the effects of the solar concentrating factor as well as area ratio between selective absorber and emitter. These effects have been discussed in very detail in [20–22].

Besides the selective emission and absorption, the selective emitters and absorbers should also possess the feature of robust operation at high temperature. When the combustion based TPV and solar-TPV

* Corresponding author.
E-mail address: mpeywm@nus.edu.sg (W. Yang).

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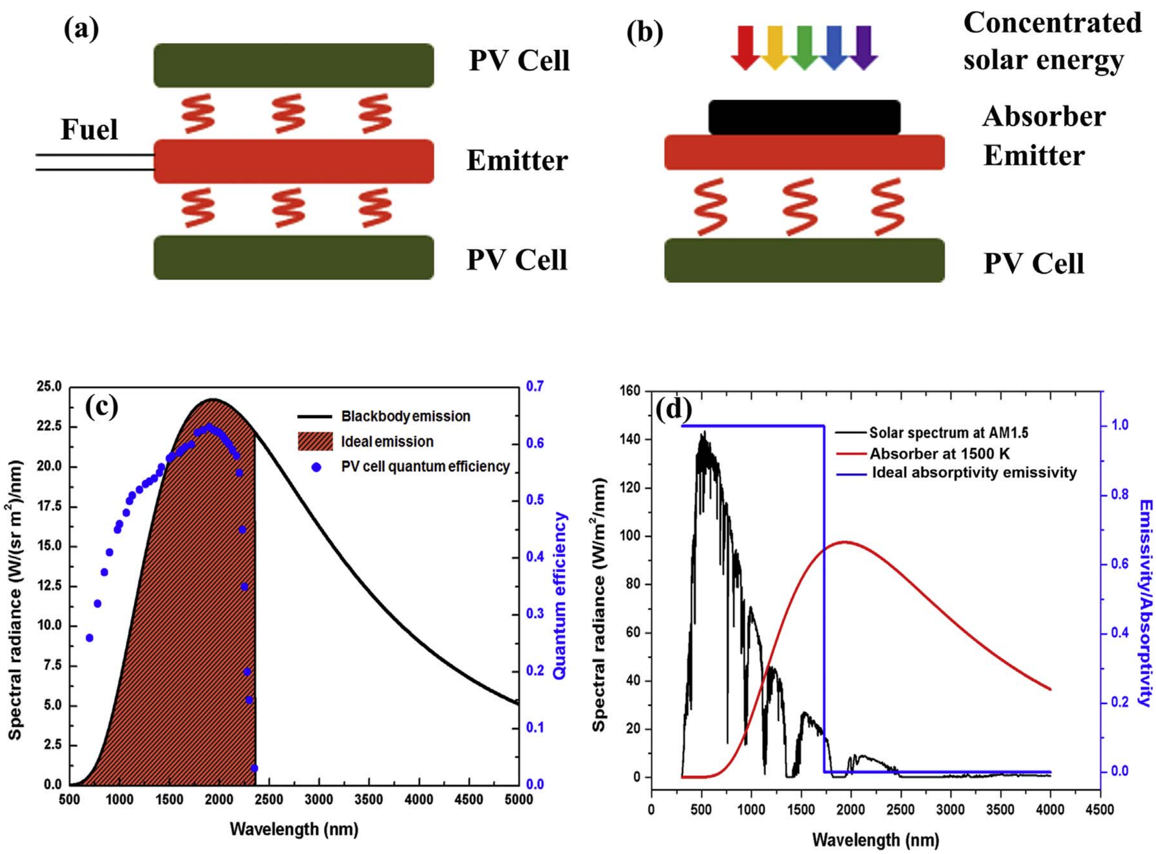

Fig. 1. (a) Schematic diagrams of combustion based TPV system, (b) solar-TPV system, (c) spectral radiance of blackbody emission, ideal emission and InGaAsSb quantum efficiency and (d) spectral radiance of solar spectrum at AM1.5 (100 Suns), absorber at 1500 K and ideal emissivity and absorptivity.

systems operate at high temperature conditions [23–25], the selective emitter and absorber face the problems of thermal stress and intense chemical reaction. The thermal stress may bend or even damage the surface of the device, while the chemical reaction will change the property of the constituent material and make the device lose its selective emission/absorption property.

Thus far, extensive investigations on frequency selective emitters/absorbers have been conducted in the selection of the constituent material and the structure of the unit cells. Assorted structures proposed include 1D photonic crystal (PhC) multilayer stacks [26,27], 2D metallic PhC cavities [28–36], 3D PhCs [1,37–39] and metamaterials [13,40–45]. Among these structures, 2D PhC nanocavities are the most promising for their relatively higher efficiency and stability at elevated temperature [3]. Meanwhile, different constituent materials have been adopted such as Yb_2O_3, W, Ta, Pt, Au, Si/SiO_2, CrAlO-based and other multi-layered materials. However, these materials are suffered from the shortage of reserves [10,34,46–48], high temperature instability [26,43] and reduced performance at elevated temperatures [34]. A group of NiO doped MgO matched emitters have been developed with good spectrum selectivity and high temperature stability for GaSb cell (band gap 0.72 eV) [49–52]. Here, we are proposing a titanium nitride based 2D PhC selective emitter with a tunable cut-off wavelength achieved by dielectric encapsulation.

Titanium nitride becomes attractive both for its refractory property and plasmonic response in the visible-NIR wavelength range [2,7,53]. It has a melting point of as high as 3200 K [54,55] and its optical properties change slightly with the operating temperature [56]. Besides, titanium nitride possesses the excellent properties of chemical stability and mechanic persistence, etc. [7,57]. Titanium has a relatively higher world reservation comparing to other metals such as W and Ta [58–60]. Titanium nitride could be synthesized commonly via chemical vapor deposition [61]. These distinguished properties make titanium nitride one of the most encouraging candidates for tailoring the emission/absorption and reflection band in the visible-NIR wavelength range. Here we are proposing a TiN based nanocavity structure for spectral control, the TiN 2D PhC shows good wavelength selectivity and high temperature stability. The cut-off wavelength could be tuned by encapsulating the nanocavity with different dielectric materials. The proposed TiN 2D PhC selective emitter could be used for TPV and Solar-TPV systems.

2. Selective emitter with nanocavity structure

The schematic of the frequency selective emitter/absorber and one unit cell are shown in Fig. 2a and b respectively. It is composed of a titanium nitride nanocavity and filling dielectric. An encapsulating layer made of dielectric with a thickness t=100 nm is utilized for preventing the morphological change, the shift of the emissivity/absorptivity at high temperature annealing [44] and the performance reduction at high incidence angles. The unit cell is designed with the period (p) of 700 nm, height (h) of 1800 nm, cavity depth (d) of 1400 nm and cavity radius (r) of 300 nm. The bottom of the unit cell is 400 nm which ensures zero transmission. The symmetric structure of the unit cell facilitates polarization independent emission and absorption at normal incidence. The filling dielectric and the encapsulating layer can be made of SiO_2, Al_2O_3 and AlN etc. These materials are stable at high temperature and with increasing refractive indexes of 1.44, 1.74 and 2.12 at 2000 nm [62–64]. The features of the increased refractive indexes could be employed for shaping the cut-off wavelength of the emitter/absorber (Fig. S1). Fig. 2c illustrates the fabricated titanium nitride pure nanocavities in which the achieved structure and size of the unit cell is very close to the designed condition. Accumulated TiN particles are found at the edge of the nanocavities which are mainly formed during the dry etching process. The measured