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Enhanced low-gap thermophotovoltaic cell efficiency for a wide temperature range based on a selective meta-material emitter

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ABSTRACT

The concept of thermophotovoltaic system, based on a compact selective meta-material film structure acting as a selector thermal blackbody radiation emitter, is presented. The meta-material (MTM) film exhibits broad-band thermal radiation absorption with selective narrow-band thermal infrared emission, and can thus be efficiently coupled to a tandem (InAs/GaInAsSb) thermophotovoltaic (TPV) cell, which has based on the experimentally sub-cells data. The TPV tandem cell combined with the selective emitter achieves highest TPV conversion efficiency of 41% for black body radiation temperature (T_{BB}) = 1500 °C, and lowest TPV conversion efficiency of 11.82% for T_{BB} = 300 °C. The TPV combined system thus operates in wide temperature range of 300 °C to 1500 °C, and the combined system shows higher performance when the MTM film is included. It also shows much higher performance than literature values reported for GaSb/GaInAsSb tandem thermophotovoltaic cells having no MTM film.

1. Introduction

Meta-materials (MTMs) exhibit remarkable optical properties such as negative and/or near zero values of reflective indices (Cai and Shalaev, 2010). Nano-structured MTMs have therefore been used in numerous applications. Examples are: small antennas (Zhang et al., 2014), energy harvesting (Wang et al., 2015), invisible cloak (Iwaszczuk et al., 2012), sensor detecting (Meng et al., 2012) and others. Moreover, some MTM absorbers are also tunable (Cheng et al., 2016; Bendelala et al., 2018). Conventional thermophotovoltaic (TPV) converters suffer limitations in the infrared range, and MTM absorber/emitter systems could be an alternative (Giovanni, 2007). The efficiency of a given solar cell is limited by two phenomena which should be carefully considered: Firstly, the probability of photon absorption. This can be understood in terms of quantum efficiency, so-called external quantum efficiency (EQE) based on overall incident radiations. EQE is calculated by including all radiations reflected and transmitted through the cell. Secondly, all heat sources (Blackbody) with low temperature. These are simple forms of heat sources, commonly used in low band gap TPV converters. In such systems, the main loss mechanism is due to broad heat radiations. TPV cells have given energy band-gap values; therefore, the radiations with energy lower than the band-gap are lost as heat without being absorbed (Bauer, 2011). Moreover, photons with higher energy than the band-gap also lose parts of their energy as heat (phonons within the lattice framework). When a given TPV system is considered as a heat machine under blackbody radiation temperature (T_{BB}) and cold side TPV cell T_{TPV}, then the theoretical thermodynamic Carnot efficiency limit is calculated as: $\eta_{Carnot} = (T_{BB} - T_{PV})/T_{BB}$. TPV system efficiencies are commonly limited to ~15% due to mismatch between the EQE of the TPV cell and the blackbody spectrum (Woolf et al., 2014).

Recently, TPV conversion efficiency enhancement is heavily investigated by recycling out of band photons. Tandem cells are being used for this purpose. Lou et al numerically proposed a 0.53 eV GaSb/GaInAsSb tandem cell with conversion efficiency 24.34% (Lou et al., 2017). Modification of the emittance of incident flux from the blackbody is also considered. Alok et al. proposed a Mie-meta-material thermal emitter involving S_iO_2 thin film between tungsten layers (Alok et al., 2016). This showed desired emissive properties, in the wavelength range of 0.4–2 μm, that are suitable for GaSb and InGaAs systems.

To avoid overheating consequences from direct blackbody excitation, and unwanted wave limitation, a novel solution is presented here, for the first time. The strategy is to combine the auto-adjustment of the emittance and tandem low-gap cells simultaneously. Fig. 1 illustrates the concept of an intermediary thermal absorber/emitter based on MTM structures coupled with a tandem low-gap photovoltaic cell (InAs/GaInAsSb) under a heat source (blackbody) radiation. The MTM

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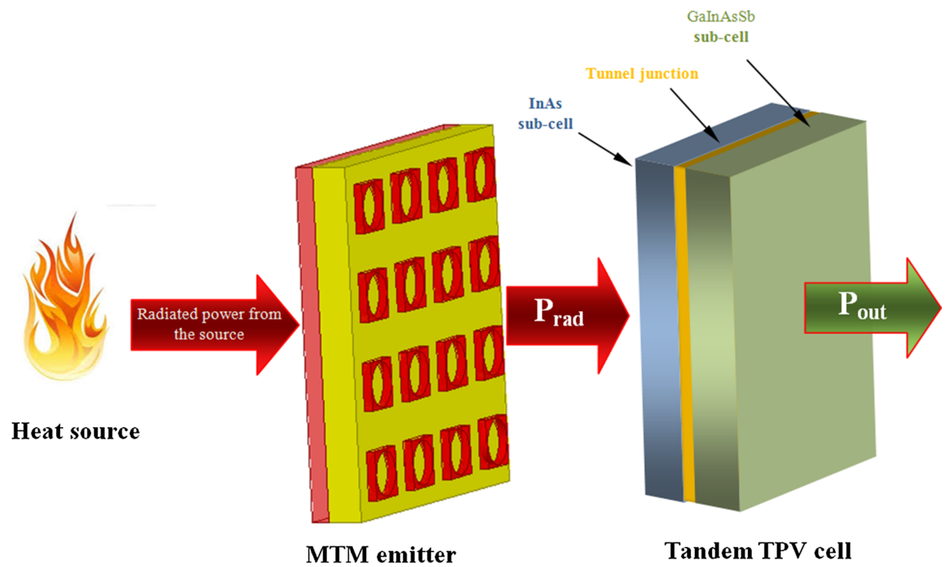

Fig. 1. Schematic of a typical TPV system with a selective MTM emitter/absorber coupled with a tandem cell.

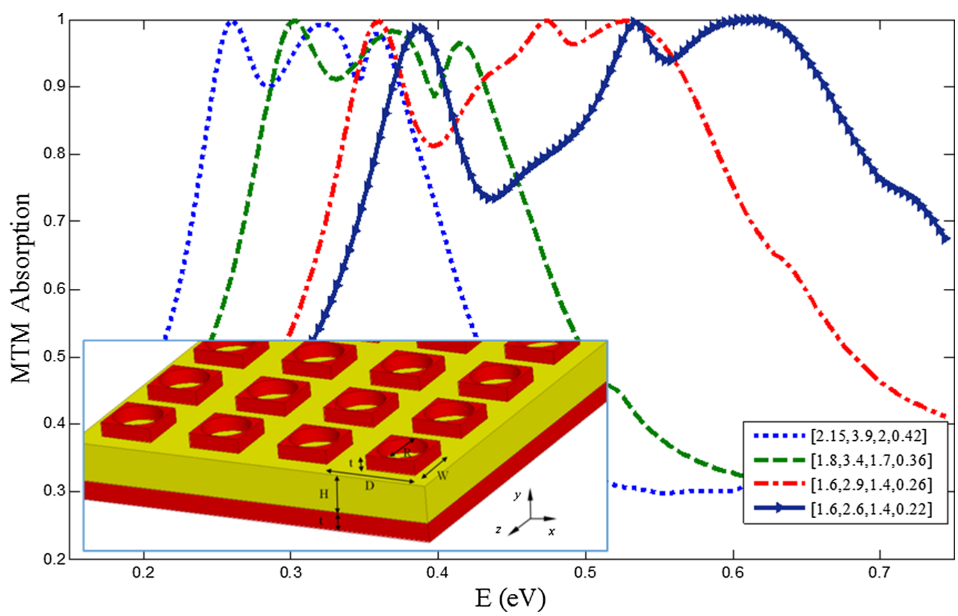

Fig. 2. Calculated absorption spectra of MTM structure for several geometric sizes [W, D, R, H] (in µm) whenever t = 0.2 µm.

absorber/emitter, that involves a dielectric (SiN) deposited on a refractive metal foil, such as tungsten, withstands high temperatures. Infrared energy is emitted by the selective MTM emitter only in the desired band of sub-cells, where the EQE of the sub-cell results from high photon absorbance.

This system involves a wide range of temperatures from 300 °C to 1500 °C, aiming to yield 41% maximal power conversion efficiency at 1500 °C. This can be achieved by the high emitter selectivity for a perfect matching with the sub-cells EQE, in addition this a theoretical improvement of the efficiency based on an experimental data, which are used for the sub-cell parameters. Unlike earlier reports (Lou et al., 2017) on GaSb/GaInAsSb cells, this work aims at maximizing cell performance by inclusion of an MTM layer for the first time.

2. Materials and methods

Power conversion efficiency of a given TPV system is defined in Eq. (1):

$$\eta(\%) = \left(\frac{P_{out}}{P_{rad}}\right).\ 100\% \tag{1}$$

where P_{out} is the output power density, and P_{rad} is the power density radiated by the MTM emitter that reaches the TPV converter as expressed in Eq. (2) (Alok et al., 2016):

$$P_{rad} = \int_0^{\infty} \frac{\omega^2}{4\pi^2c^2}\frac{\hbar\omega}{(e^{\hbar\omega/KT}-1)}e(\omega)d\omega \tag{2}$$

where $\hbar$ is the reduced Planck's constant, K is Boltzmann's constant, T is the emitter temperature, and $e(\omega)$ is the emittance of the MTM emitter. The MTM absorption $A(\omega)$ is utilized for achieving spectrally selective thermal emissivity, by virtue of Kirchhoff's law: $e(\omega) = A(\omega) \times e_{BB}(\omega, T)$, where $e_{BB}(\omega, T)$ is the blackbody emittance spectrum at temperature T.

It should be noted that, the system model based on following simplifications (Giovanni, 2007): Firstly, the surface temperatures of black body emitter, MTM emitter and TPV cells are assumed to be uniform, which means that the spectral properties are constant all over each