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Photonic nanometer scale metamaterials and nanoporous thermoelectric materials for enhancement of hybrid photovoltaic thermoelectric devices

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ABSTRACT

This paper discusses the design, development and implementation of a plasmonic fishnet meta-structure, synthesis of TE ink and binder, fabrication of conductive ink, and printing technology to improve the overall efficiency of the hybrid PV–TE devices. Embedded fishnet meta-structure in hybrid photovoltaic–thermoelectric (PV–TE) system and, synthesis/characterization of printable nanoporous thermoelectric (TE) ink are proposed. Back passivation layer of the solar cell includes a planar fishnet structure that enhances solar radiation absorption near the infrared band of the solar spectrum. It was observed to improve the efficiency around 11 folds in the hybrid system with fishnet. Nanoporous Bi_2Te_3 and Sb_2Te_3 were used to prepare printing inks to print p–n junctions. Development of fishnet, synthesis/characterization of TE ink, binder and conductive ink are elucidated in this paper.

1. Introduction

Conversion of renewable solar energy into electricity is a widely pursued field of research to reduce the widening demand–supply gap of electricity and its utilization. At the fore front are the photovoltaic (PV) devices, which use ultraviolet and visible light to generate electricity from the solar radiation, which is based on the temperature of the sun that averages around 5800 K. Practically, 3.6×10^4 Tera Watts of power can be collected if the surface of the earth and radiated power are used to its entirety. The sun's radiation constitutes 58% of ultraviolet (UV) and visible light spectrum ranging in the wavelength of 200 nm to 800 nm, and the other 42% is the infrared (IR) spectrum ranging from 800 nm to 3000 nm in wavelength [1,2]. Hybrid systems have been suggested to utilize more solar energy from the available spectrum in sunlight. A hybrid system usually consists of photovoltaic (PV) and thermoelectric (TE) devices to improve the efficiency of electric power generation from solar power.

Thermoelectric generators convert thermal energy into electrical energy, which is very useful for remote locations like rural areas and space applications like rockets that are difficult to connect to a central power distribution network. TE generators are very useful in harnessing the waste heat from cars and power plants, and body heat from human body, high power laser and computer chips. Maximization of power output in TE generators is possible by connecting several TE units electrically in series but thermally in parallel to form a TE module [3]. Fig. 1 (a) [3] that shows a general schematic of TE generator, plugged across a load resistance R_L, is composed of an array of TE units. Each unit is a pair of p-type and n-type semiconductor components exposed at one end to high temperature T_H and the other end to low temperature T_L heat sources. Thermal energy that is absorbed by TE generator is a result of heat flux Q_H and Q_L between TE generator and the two heat sources. Fig. 1 (b) [3] shows basic architecture of a TE generator. Eq. 1 gives the formula for performance (efficiency) of the TE device, which depends on the figure of merit ZT shown in Eq. 2. Eq. 1 relates thermoelectric efficiency η_{TE} to Carnot efficiency η_c, figure of merit ZT, temperature of hot side T_H and temperature of cold side T_C. Eq. 2 relates a figure of merit ZT to Seebeck coefficient S, σ electrical conductivity of semiconductor material, thermal conductivity of semiconductor material κ and temperature difference between hot and cold side T.

$$\eta_{TE} = \eta_c \left(\frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_C}{T_H}} \right) \tag{1}$$

$$ZT = \frac{S^2 \sigma T}{(\kappa_e + \kappa_{ph})} \tag{2}$$

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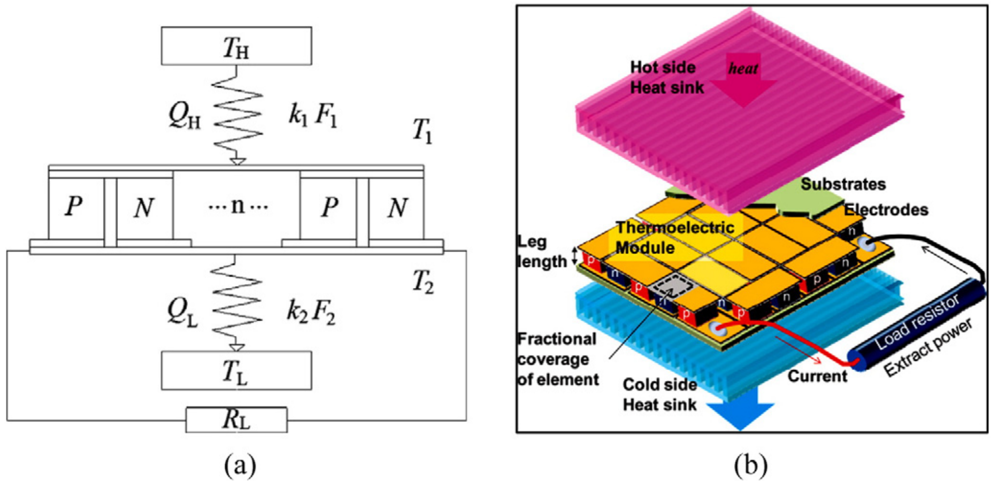

Fig. 1. (a) Schematic diagram of multi-element thermoelectric generator and (b) basic structure of a thermoelectric generator.

Researchers [1–4] have pursued improvements in TE materials towards design of solar thermoelectric generator (STEG) to convert solar energy into electricity. In addition to the high ZT value of the thermoelectric materials, significant temperature difference between hot and cold sides of the STEG is an important factor to produce electricity with only solar radiation flux. There are two widely followed approaches. First, a material based wavelength selective solar absorber (SSA) [1,5] can be used to trap and absorb energy from the infrared (IR) region and increase the temperature of the solar field. Generally, a SSA should have high solar absorbance and low thermal emittance, so that it can be coated over the surface of STEG to achieve better efficiency. Second, plasmonic structures are being applied to the applications which involve harvesting solar light. Plasmonics can enhance absorbance of solar radiation by solar energy harvesting systems. By designing the dimensions of unit cell of plasmonic metamaterial (Fig. 2), it can be tuned to absorb solar radiation in specific frequency band and different angles of incidence. Similarly, nano-patterns are more useful in exploiting the thermal energy absorption properties of semi-conductor medium. Even though these approaches increase the efficiency of STEG, the device is restricted to use only 48% (IR spectrum) of the solar energy.

Hybrid systems consisting of PV and TE devices have been investigated to utilize more solar energy from the available spectrum in sunlight. There are several techniques adapted to absorb more solar radiation. In common, the SSA with low reflectance in the wavelength range from 600 nm to 1600 nm can be coated on the hot side of the TE generator of the hybrid system to absorb residual sunlight transmitted through the solar cell [6]. Apart from absorbing more solar radiation, the system can use functionally graded material (FGM) as a heat sink (cold side) of the TE generator to make higher temperature difference between the hot and cold sides of the TE generator [7]. Even though efficiency of the PV–TE hybrid systems can be improved by using SSA to absorb more sunlight or by incorporating TE transport properties with the previously mentioned techniques, the size and cost of the

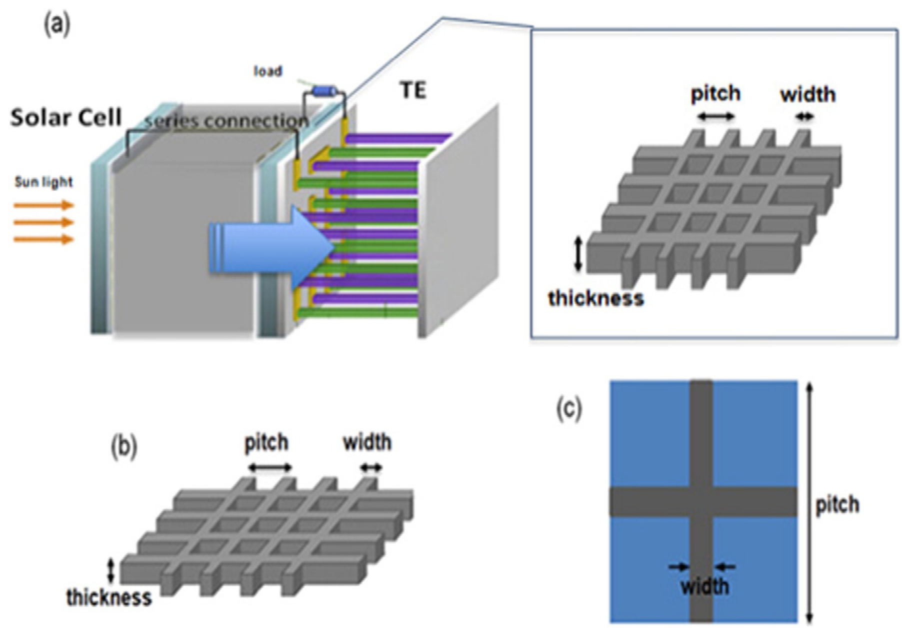

Fig. 2. Schematic of the thin film solar cell of the hybrid system with the fishnet embedded in the back passivation layer. (a) 3D schematic of the solar cell; (b) design parameters of the fishnet structure; (c) top view of the schematic of the unit cell for the full wave numerical simulation.