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# Biomimetic omnidirectional broadband structured surface for photon management in photovoltaic–thermoelectric hybrid systems

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ABSTRACT

An advanced photon management approach is developed for a photovoltaic–thermoelectric hybrid system to increase the solar energy utilization efficiency. A biomimetic parabolic-shaped structure on the Si film and a thin $SiO_2$ film at the bottom of the Si film as back-antireflection coating improves the absorptance of photons with wavelengths of 0.3–1.1 μm, which can generate electron–hole pairs. Photons with wavelengths of 1.1–2.5 μm transmit through the structured surface and are absorbed by the thermoelectric modules, which improves the conversion efficiency of the entire hybrid system. The structured surface with graded refractive index can effectively harvest photons with wavelengths of 0.3–2.5 μm. The effects of the structural parameters and the incident angle on the spectral features of the structured surface are analyzed. The results indicate that the structured surface provides high omnidirectional absorptance for wavelengths of 0.3–1.1 μm and high transmittance for wavelengths of 1.1–2.5 μm as well as favorable polarization-insensitive features over a good incident angle range as a good candidate for the photovoltaic–thermoelectric hybrid systems.



## 1. Introduction

Solar energy is one of the most promising energy sources for meeting the energy crisis due to its abundant supply and cleanliness compared to fossil fuels which are being rapidly consumed. Recently, a variety of energy conversion devices have been developed to utilize solar energy, such as photovoltaic (PV) solar cells, thermophotovoltaic cells, and photochemical catalysis devices [1–3]. Solar cells are made of semiconductors that directly convert the light into electricity as one of the most important ways to harness solar energy. Many kinds of semiconductor materials have been investigated as candidates for solar cells, such as Si, GaAs, and InP [4–6]. Si is widely used in solar cells because it is very abundant on the Earth. c-Si solar cells can convert light into electricity for wavelengths less than 1.1 μm because the Si band gap is 1.12 eV [7]. For flat Si cells, the large refractive index difference between Si and air causes more than 30% of the incident solar energy to be reflected at the Si/air interface [8]. This energy loss significantly reduces the solar cell conversion efficiency. Therefore, structured surfaces should be investigated to effectively trap the light in the cells. A variety of microstructures have been investigated to reduce the reflectance and enhance the cell performance, including antireflective coatings (ARC) such as $Si_3N_4$, triangular or pyramid gratings, nanoparticles, nanowires, nanoholes, nanocones, photonic crystals, and plasmonic nano-structures [9,10]. Zhang et al. [11] theoretically investigated the reflective properties of c-Si solar cells with a triple-layer anti-reflection coating for wavelengths of 0.3–1.1 μm and found that the average reflectance could be reduced to 0.06. Huang and Chattopadhyay [12] numerically studied the spectral features of taper structured surfaces of solar cells for wavelengths of 0.25–1.1 μm which indicated that the average reflectance could be reduced to below 0.02. However, according to the AM1.5 solar spectrum, the solar energy is mainly concentrated for wavelengths of 0.3–2.5 μm [13]. Most investigations of silicon solar cells have focused on light trapping for wavelengths of 0.3–1.1 μm. Thus, the solar energy carried by photons with wavelengths of 1.1–2.5 μm, which is about 20% of the incident solar energy, cannot be effectively used and is dissipated as waste heat. The waste heat is partly absorbed by the solar cell and increases the cell temperature, which can exert a deleterious effect on the conversion efficiency of the solar cell. For the antireflective structured surfaces mentioned above, the ARC is easily processed. However, the spectral features of the anti-reflective coatings are angle-dependent [14]. In addition, the addition of the antireflective coating creates another interface which reflects more of the light arriving at the solar cell. Therefore, a micro-structure

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should be developed that is applied directly on the Si solar cell to improve the light trapping.

Since the location of the sun is constantly changing, an auto-solar tracker may be used to follow the sun. However, complicated auto-solar trackers are expensive and delicate due to the existence of moving components. Hence, omnidirectional structured surfaces that provide light trapping in solar cells are very attractive. For example, the sub-wavelength Mie resonators reduced the reflectance over a broad range of wavelengths and incident angle [15]. Most micro/nano-structured surfaces for enhancing light trapping in Si solar cells have been for wavelengths of 0.3–1.1 μm with little attention paid to the solar energy range of 1.1–2.5 μm.

Since the seminal work by Lord Rayleigh in 1880 on the problem of gradual transitions [16], the gradually changing of the refractive index of a film has been of interest as an alternative way to reduce the reflectance at an interface. Furthermore, nature has given some methods to solve engineering problems [17]. By observing the corneal structure of the moth-eye, Stavenga et al. [18] found that a subwavelength parabolic-shaped structure (PSS) could be used to achieve broadband antireflection in GaAs solar cells. A structured surface with a graded refractive index (GRI) layer significantly reduced the reflectance. With the large height to width aspect ratio, the surface possessed angle-independent antireflection feature [19]. The grainy microstructure on the moth corneal led Min et al. [20] to investigate the spectral properties of subwavelength-structured nipple arrays on GaSb cells and found that the reflectance was reduced to 0.02. Micro-processing can be used to fabricate the parabolic-shaped structure on silicon solar cells. Sun et al. [8] developed a templating technique for fabricating broadband PSS anti-reflection coatings on a single-crystal silicon substrate. Such structured surfaces exhibited superior broadband antireflective performance to commercial $SiN_x$ coatings. Rahman et al. [21] fabricated the PSS on silicon solar cells by block copolymer self-assembly and plasma etching with precise control over the lateral feature size of the structured surface. The feature size could be smaller than 50 nm to enhance the broadband anti-reflection performance. However, such microstructures have not been widely used on Si solar cells for omnidirectional broadband light trapping for wavelengths of 0.3–2.5 μm. Therefore, more research is needed to apply such bioinspired microstructures to Si solar cells to realize broadband light trapping for wavelengths of 0.3–2.5 μm and to increase the total solar energy utilization efficiency.

Solid-state conversion devices using thermoelectric (TE) modules can be used for thermal energy harvesting. They silently and reliably convert heat into electricity due to the temperature difference between the two sides of the module [22]. TE modules have not been widely used due to their low efficiency and expense. However, the rapid development of nanotechnology has led to more efficient TE modules that can be used for a new type of solar energy utilization [22,23]. Photons with wavelengths of 1.1–2.5 μm can be absorbed, converted into heat, and finally converted into electricity by the TE modules.

The PV–TE hybrid system is emerging as a highly-efficient way to maximize broadband solar energy utilization [24–26]. When the solar beam irradiates such a hybrid solar cell, part of the incident solar light is absorbed by the solar cell and part of the incident light is reflected. In addition, photons which transmit through the solar cell are absorbed by the TE module below the solar cell and converted into electric energy. More and more attention is being focused on the structural design of PV–TE hybrid systems to increase the utilization efficiency of the incident solar energy. Van Sark [27] developed a simple model to determine the efficiency of a PV–TE converter. He found an efficiency increase of 8–23% obtained by adding TE modules to the back of PV modules. Liao et al. [28] established a theoretical model to evaluate the performance of PV–TE hybrid systems. They found that a PV–TE hybrid system could provide not only more electric power but also a higher conversion efficiency than a single PV solar cell or a TE generator.

Current designs have a PV solar cell stacked directly on the TE module in a hybrid system without any spectrally optimal utilization procedures for the incident solar energy [27–31]. Investigations of PV–TE hybrid systems are still preliminary. More research is needed for the energy management including the photons and the thermal energy, which challenges the design and application of PV–TE hybrid systems. Proper thermal and photon management is important in such hybrid systems to achieve a high conversion efficiency. In the most efficient PV–TE hybrid systems, the Si solar cell must have a high omnidirectional absorptance for wavelengths of 0.3–1.1 μm and a high transmittance for wavelengths of 1.1–2.5 μm. These spectral features of the structured surface will not only increase the efficiency of the TE modules but also reduce the temperature rise in the solar cell which reduces the cell efficiency. However, most existing investigations [27–32] have paid little attention to the effects of the spectral distribution principle of the incident solar energy inside the hybrid system. Therefore, omnidirectional broadband structured surfaces should be investigated for efficient photon management for wavelengths of 0.3–2.5 μm to increase the efficiency of PV–TE hybrid systems.

Proper photon management is crucial for enhancing the conversion efficiency of hybrid systems. In the near-infrared region, Si is nearly transparent for its negligible extinction coefficient, so the light passes through the Si solar cell and is reflected at the bottom Si/air interface. Therefore, it is intuitive for one to deposit a back antireflection coating (BARC) beneath the Si solar cell to guide the light to transmit it through the solar cell so it can be absorbed by the TE module. The enhanced photon transmission through the solar cell in the wavelength range of 1.1–2.5 um is not only advantageous for the performance of the Si solar cell by suppressing temperature rise of the cell, but is also beneficial by increasing the conversion efficiency of the TE module. Therefore, a back antireflective coating (BARC) is needed so that more photons transmitting through the cells will be absorbed by the TE module.

This paper describes an advanced photon management approach for a PV–TE hybrid system. This study focuses on the feasibility of the photon management and the spectral distribution strategy of the incident solar energy. A bioinspired structured surface is introduced into the hybrid system to achieve omnidirectional broadband light trapping. The Si PSS is directly patterned on a thin Si film to build a GRI layer to reduce the reflectance and absorb photons for wavelengths of 0.3–1.1 μm which can generate electron–hole pairs. The thin $SiO_2$ BARC with a refractive index greater than air and smaller than Si is applied to the bottom of the Si film to guide the photons with wavelengths of 1.1–2.5 μm which are unable to induce electron–hole pairs to transmit through the solar cell. The photons transmitting through the Si solar cell are assumed to be completely absorbed by the TE modules. In this way, the incident solar energy is distributed between the hybrid system components based on their wavelengths for efficient photon and thermal management. The spectral features of the structured surface were calculated using the finite-difference time-domain (FDTD) method. Experimental results in the literature were used to validate the numerical model for examining the feasibility of the proposed photon management approach. The model is used to analyze the effects of the PSS period and height on the spectral features of the bioinspired structured surface. The incident angle-dependence of the antireflection properties for both s- and p-polarizations is analyzed.