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Comprehensive photonic approach for diurnal photovoltaic and nocturnal radiative cooling

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ABSTRACT

A novel photovoltaic/radiative cooling (PV/RC) hybrid system based on a selective plate is proposed. This system can generate electricity via diurnal PV conversion and obtain cooling energy by radiative cooling. We introduce a comprehensive photonic approach to simultaneously reduce impractical solar radiation absorption of the selective plate and enhance its thermal radiation for the hybrid system. Initially, we design a photonic structure made of 1D multilayer stack and 2D photonic crystal, which can selectively reflect solar radiation and actively radiate heat to the outer space while maintaining its solar transmission in PV conversion band (0.3–1.1 μm). Then, we demonstrate that applying the photonic structure to a monocrystalline silicon solar cell can obtain a diurnal electricity output of 99.2 W m^{-2} and generate a nocturnal RC power by 128.5 W m^{-2}, indicating 6.9% and 30.5% higher than those of a bare cell. In addition, the potential cooling energy obtained is far more in this structure than in existing RC emitters, including daytime RC emitter reported in a recent research. Results indicate that a comprehensive photonic approach can be used to design spectral selective structures for advancing the applications of exploiting solar energy harvesting and radiative cooling utilization.

1. Introduction

The universe, at a temperature of 3 K, represents a significant renewable thermodynamic resource; it is the ultimate heat sink [1]. The atmosphere of the earth exhibits remarkably high transmittance for electromagnetic waves within the atmospheric window band (8–13 μm) that coincides with the peak wavelength of thermal radiation of a blackbody at a typical ambient temperature. Thus, terrestrial objects with high emissivity within the atmospheric window band can obtain cooling energy by radiating heat to outer space when these objects are directly exposed to the sky. This passive radiative cooling mechanism has recently drawn a considerable attention for its potential as an alternative method for thermal management.

Radiative cooling is largely investigated simply because of a single radiative cooling system (RC system) at nighttime to obtain cooling energy in previous studies [2–11]. Spectral selective-independent and spectral selective-dependent emitters are successively developed for utilizing a nocturnal RC process. Daytime RC has been achieved in recent years [12–17]. Specifically, a photonic structure that consists of seven alternating layers of hafnium dioxide (HfO_2) and silicon dioxide (SiO_2) on top of a silver layer and a silicon wafer is reported to cool below the ambient temperature at approximately 5 °C via RC method [13]. This photonic structure can reflect approximately 97% of incident solar irradiance and simultaneously emit remarkably thermal radiation. However, a comparatively low cooling power and high investment are the main challenges for a single RC system in practical applications. By contrast, existing solar energy harvesting systems, including photovoltaic (PV) system (silicon-based cells [18], perovskite-based cells [19] and et al.) and photothermal (PT) system, are also single units working only at daytime. For these applications, the RC method can possibly combine with these systems to simultaneously obtain nocturnal cooling energy and preserve the function of harvesting diurnal solar energy.

In this work, we propose a PV/RC hybrid system based on a selective plate; this system can generate electricity by diurnal PV conversion and obtain cooling energy via nocturnal RC process (Fig. 1). Only solar irradiation with a certain wavelength range (0.3–1.1 μm for monocrystalline silicon solar cell) can be partly converted into electricity for PV conversion technique, and the remaining absorbed solar irradiation is dissipated into heat. However, a 1 K increase in temperature decreases the relative efficiency of the crystalline silicon solar cells by approximately 0.45%. Thus, the selective plate of the PV/RC hybrid system must have a high solar absorption within the PV conversion band to ensure a diurnal PV electricity output and actively reflect the remaining solar irradiation to prevent solar cell from overheating. Moreover, the selective plate should also be powerfully emissive within the mid-infrared band (4–25 μm), thereby allowing the system to

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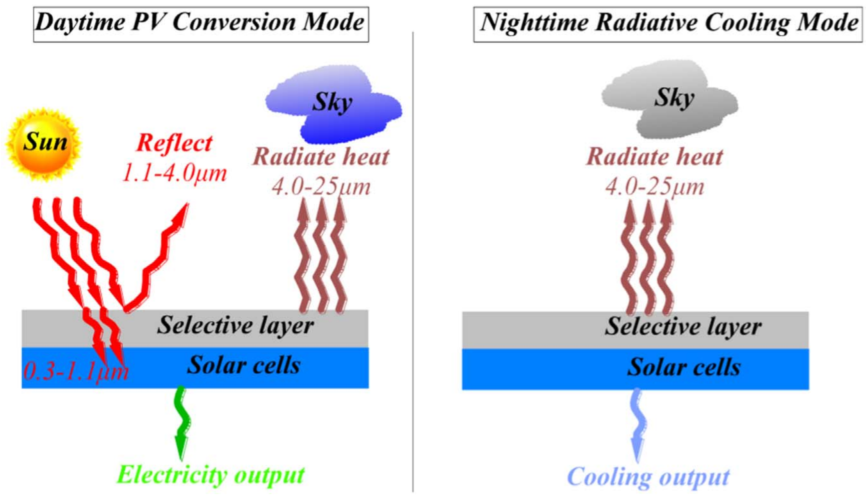

Fig. 1. Schematic of diurnal PV conversion and nocturnal RC process of the selective plate.

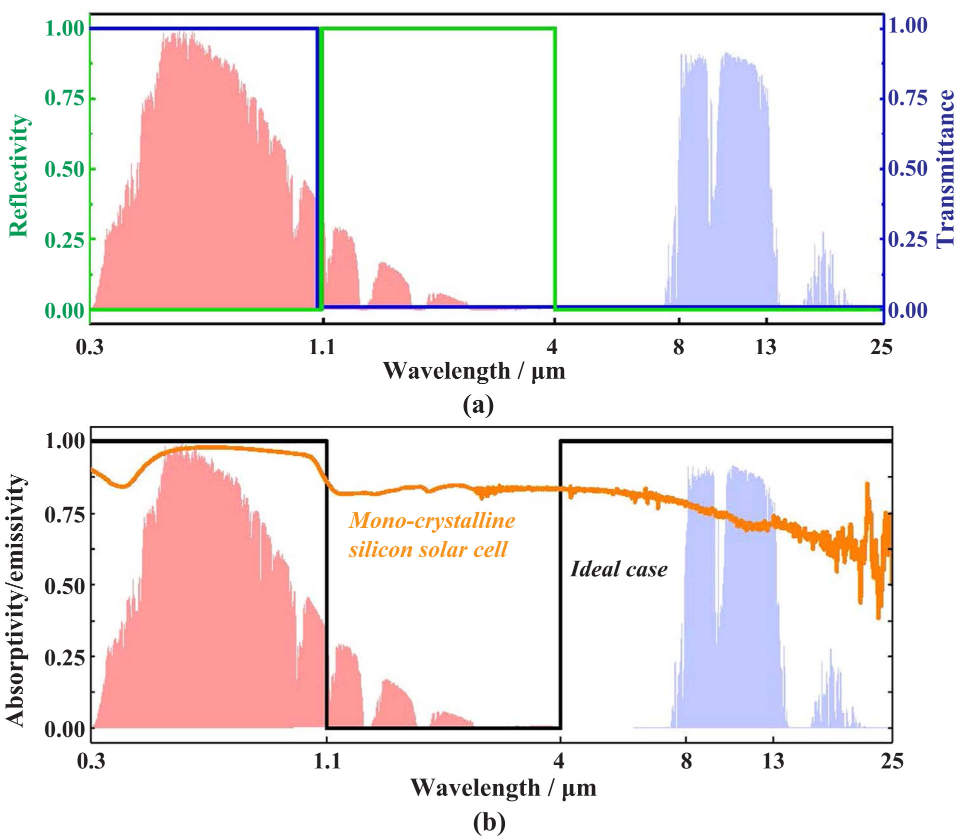

Fig. 2. Idealized spectral selectivity of the selective plate from the ultraviolet to mid-infrared, with the normalized AM 1.5 solar spectrum (red) and typical atmospheric transmittance (blue) plotted for reference. The ideal selective plate demonstrates a high spectral absorptivity (emissivity) in the wavelength range of 0.3–1.1 μm and beyond 4.0 μm, with high reflectivity in the wavelength range of 1.1–4.0 μm. (a) Ideal reflectivity (green curve) and transmittance (blue curve) of the selective layer placed at the top of solar cells. (b) Ideal absorptivity (emissivity) of the selective plate (black curve) comprehensively considering the influence of selective layer and solar cell. The absorptivity (emissivity) of monocrystalline silicon solar cell (orange curve), which was measured by UV–Vis–NIR spectrophotometer (DUV-3700) and Fourier transform infrared spectrophotometer (Nicolet iS10), is plotted for reference. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

produce considerable nocturnal RC power. The high emissivity of a selective plate is better with the mid-infrared band (4–25 μm) than simply within atmospheric window band (8–13 μm) for cooling solar cells in the diurnal PV process [15]. Fig. 2 illustrates an idealized spectral-selective profile of the selective plate, with the spectral absorptivity (emissivity) of the monocrystalline silicon solar cell plotted for reference.

In this work, we develop a comprehensive photonic approach for designing a selective plate for the PV/RC system. This approach aims to place a photonic structure on top of a monocrystalline silicon solar cell. The photonic structure should satisfy multiple spectral characteristics. First, the photonic structure should maximize transmittance in the wavelength range of 0.3–1.1 μm (or *PV band*) to ensure the PV conversion of monocrystalline silicon solar cell. Second, the photonic structure must have high reflectivity in the wavelength range of 1.1–4.0 μm (or *vain band*) to reflect part of solar irradiance that cannot be converted to electricity, thus reducing the temperature of the solar cell. Third, the emissivity of the photonic structure in the wavelength range of 4.0–25 μm (or *RC band*) is designed to be high to maximize the RC process. The diurnal PV conversion and nocturnal RC process, which is a new concept of energy harvesting by exploiting solar energy and radiative cooling applications, can be successfully achieved by placing this photonic structure on a monocrystalline silicon solar cell.

2. Materials and methods

2.1. Design principle and results

In this section, we introduce our design principle for a photonic structure that is placed on a monocrystalline silicon solar cell to satisfy