Optical modeling and characterization of radiative cooling for solar energy applications

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Abstract: Radiative cooling is a method to control the temperature of semiconductor devices used in concentrated photovoltaics (CPV) and solar thermophotovoltaics (TPV). We find that it can increase the operating voltage and efficiency up to 5%.

OCIS Codes: 030.5620 (Radiative transfer); 350.6050 (Solar energy); 350.4238 (Nanophotonics and photonic crystals)

1. Radiative Cooling for Concentrating Solar Power

Radiative cooling is a method that allows one to cool below ambient without any net input energy, by exploiting the sky transparency window; this allows one to send radiation into space at infrared wavelengths from 8 to 13 μm [1–3]. This approach becomes most effective outside on a clear day at higher temperatures, which are the same conditions typically describing many of the geographical sites best-suited for the production of concentrating solar power [4–6]. As such, we have begun to apply this approach to concentrated photovoltaics (CPV) [7] and solar thermophotovoltaics (TPV) [8–10].

2. Constructing a Radiative Cooler

To test the concept of radiative cooling for concentrating solar power, we used our previously-developed energy balance model for radiatively-cooled solar TPV as a starting point [11]. These results indicate that we could design a controlled experiment, depicted in Figure 1, consisting of a GaSb photovoltaic (PV) cell on an aluminum nitride substrate, with or without soda lime glass. It is enclosed by a chamber consisting of high-density polystyrene foam to block conduction heat transfer, sealed on top by a 15 μm low-density polyethylene film that is highly transparent in the visible – mid-IR range, so that convection is restricted within the air pocket. The temperatures of both GaSb PV diodes are measured by a type-K thermocouple (SCASS-020U-12-SHX, Omega) as a function of time.

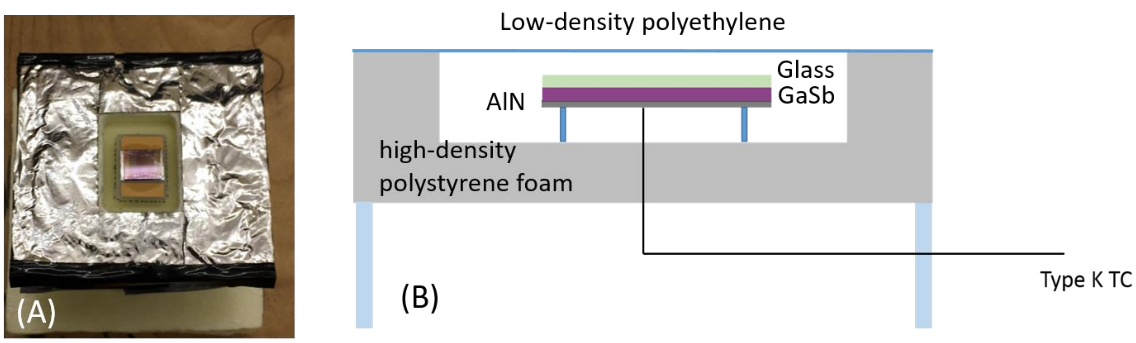

Fig. 1: (A) Radiative cooling test chamber, with 550 μm soda lime glass atop a GaSb PV cell inside. (B) Test chamber schematic: it consists of high-density polystyrene foam, sealed by a low-density, transparent polyethylene film. Two PV diodes (one with soda lime glass and one without) are measured in two nearly-identical chambers at the same time with a type-K thermocouple for comparison.

3. Results and Discussion

First, we measured the mid-infrared emittance of the experimental and control PV cell samples, using a Thermo Fisher Scientific Nexus 670 FTIR spectrometer. We find that for standard low-bandgap PV cells such as gallium antimonide (GaSb), suitable for solar TPV applications, the baseline emissivity (measured at 30° polar angle) in the atmospheric transmission window of 8-13 μm peaks at approximately 74%, as shown in Fig. 2. The spectrum of bare GaSb is then normalized, due to its slight diffuse reflection, to match with the near-IR reflectance measured by a spectrophotometer with integrating sphere (PerkinElmer Lambda950). In contrast, a relatively simple multi-layer stack with front glass and a semiconductor substrate increases the transmission window-averaged emissivity to 81.7%, according to our measurements, again shown in Fig. 2.

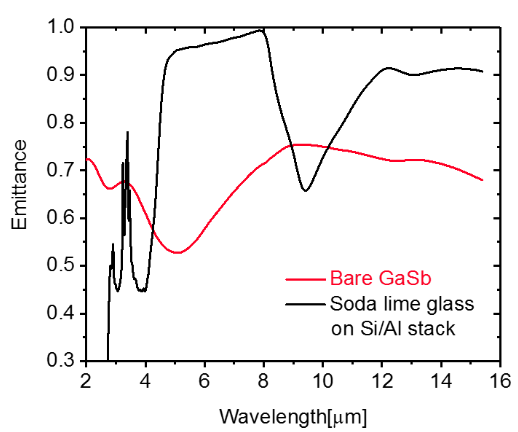

Fig. 2: The mid-IR emittance spectra of bare GaSb (red line) and the soda lime glass (black line). Both are measured by FTIR at a 30° incident angle. The spectrum of soda lime glass is measured when stacked on a Si wafer with aluminum deposited on the back. In the mid-IR, soda lime glass is mostly opaque.

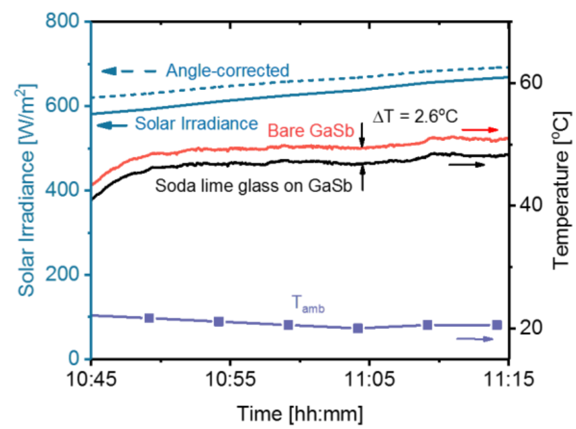

Fig. 3: Daytime radiative cooling measurement on June 7, 2017. Solar irradiance, measured by a pyranometer mounted at 45° facing south (blue solid line) is angle-corrected to quantify the solar irradiance upon a horizontal surface (blue dashed line). Ambient temperature (purple line) is measured by a thermometer sitting below the setup. The stabilized temperature difference between GaSb PV diodes with and without soda lime glass is 2.6 °C.

Using a cooler that has the same size as the PV cell, to simulate low-concentration conditions, we simultaneously measure several key quantities: solar irradiance, angle-corrected solar irradiance, ambient temperature, experimental temperature, and control temperature. The solar irradiance measured on that day by a pyranometer mounted at 45° facing south is angle-corrected to quantify the solar irradiance upon a horizontal surface. The angle-correction assumes ground albedo of 0.5. The ambient temperature is measured by a thermometer sitting in shadow, right next to the setup. Both experimental and control temperatures are measured using a type-K thermocouple, in direct contact with the back of the respective samples, as described previously. Under these circumstances, we find that mounting a single layer of front glass on the standard flat-plate GaSb cell provides a direct decrease in average stabilized temperature of 2.6 °C, under the ambient mostly sunny weather conditions of West Lafayette, Indiana on June 7, 2017, as shown in Figure 3.

This result of 2.6 ºC cooling theoretically corresponds to an increase of approximately 4-5 mV in the open-circuit voltage. Furthermore, we find that a total increase in operating voltage of 15 mV is possible with an augmented design architecture with a higher ratio of the cooler to PV cell area. Implementation of this latter design could potentially increase overall efficiencies of solar TPV systems by up to 5% relative with relatively little increase in cost or overall system complexity. Finally, we project that even larger increases in open-circuit voltage would be possible for multi-junction CPV designs, using the same radiative cooling strategy, since the cooling would individually increase the operating voltage obtained from each junction. In future work, it will be important to test these hypotheses through direct electrical measurements.

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