Improving photovoltaic performance through radiative cooling in both terrestrial and extraterrestrial environments

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Abstract: The method of detailed balance, introduced by Shockley and Queisser, is often used to find an upper theoretical limit for the efficiency of semiconductor pn-junction based photovoltaics. Typically the solar cell is assumed to be at an ambient temperature of 300 K. In this paper, we describe and analyze the use of radiative cooling techniques to lower the solar cell temperature below the ambient to surpass the detailed balance limit for a cell in contact with an ideal heat sink. We show that by combining specifically designed radiative cooling structures with solar cells, efficiencies higher than the limiting efficiency achievable at 300 K can be obtained for solar cells in both terrestrial and extraterrestrial environments. We show that our proposed structure yields an efficiency 0.87% higher than a typical PV module at operating temperatures in a terrestrial application. We also demonstrate an efficiency advantage of 0.4-2.6% for solar cells in an extraterrestrial environment in near-earth orbit.

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1. Introduction

The detailed balance method used by Shockley and Queisser to calculate the limiting efficiency of ideal solar cells entails balancing of particles entering and exiting the solar cell [1]. In the detailed balance formalism, all incident photons above the bandgap of the semiconductor are absorbed and lead to photocurrent. At open-circuit conditions, no current is drawn from the device, and the incoming photon flux must be balanced by an outgoing photon flux from radiative carrier recombination, hence the detailed balance. The emission from the solar cell is approximated as blackbody radiation above the semiconductor bandgap resulting in a temperature dependent emission spectrum of the solar cell. As the cell temperature rises, the blackbody radiation increases. However, under illumination there is a quasi-Fermi level splitting within the device, which must be reduced when the cell is at a higher temperature in order to maintain the detailed balance of absorbed and emitted photons. The reduction in the quasi-Fermi level splitting results in a reduced open circuit voltage. Consequently, the efficiency of the cell deteriorates with increasing temperature.

The efficiency limit described by Shockley and Queisser is derived for a solar cell in contact with a heat sink at an ambient temperature of 300 K [1]. This is an idealization of the best case scenario, and in reality the solar cell heats up considerably above the ambient temperature, when at operating conditions, and leads to a significantly lower efficiency. Hence, a mechanism is needed to cool down the solar cell during operation to maintain efficiency.

Many strategies have been adopted to lower the cell temperature such as the use of photovoltaic/thermal hybrid solar technology [2], the use of heat pipes to passively enhance heat conduction [3], active cooling using forced air and water cooling, and natural convection and conduction to heat sinks [4]. Recently, Zhu *et al* presented a scheme using radiative cooling to reduce the temperature of a Si solar cell by 18.3 K below its operating temperature; however, the device would still operate above the ambient, leading to an efficiency decrease compared to the ideal Shockley-Queisser limit [5].

Here we present a method to increase the photovoltaic power conversion efficiency above the Shockley and Queisser limit calculated at 300 K by lowering the solar cell temperature below the ambient using passive radiative cooling. The general approach of passive radiative cooling uses the cold darkness of outer space as a thermodynamic resource to reduce the temperature of terrestrial objects. Nighttime passive cooling below ambient air temperature has been demonstrated using this technique by pointing the device toward the sky to radiate heat to outer space through the atmospheric transparency window from 8 to 13 μm [6–12]. Recently, Raman *et al.* demonstrated daytime radiative cooling using photonic structures that reflect incident solar illumination while thermally emitting into an atmospheric transparency window [13–15]. Unlike traditional cooling strategies, the radiative cooling mechanism requires no input energy, making it a very attractive option for cooling solar cells to improve power conversion efficiency [5].

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In this paper we propose and analyze a structure consisting of a solar cell and radiative cooler to achieve cooling of the solar cell both below the ambient in terrestrial applications and below the nominal operating temperatures in space applications. In our analysis, we show that for solar cell materials with bandgap energy greater than 1.18 eV, our proposed structure is capable of achieving higher efficiencies than a traditional cell at standard operating conditions. For semiconductors with bandgaps above ~1.52 eV, the efficiency even surpasses the Shockley-Queisser limit at 300 K, due to net cooling of the solar cell below the ambient. We also analyze the use of radiative cooling for space applications and show that our proposed device improves the efficiency of solar cells operating under standard conditions in low-earth orbit (temperatures typically between 293 and 358 K) [16].

2. Temperature effects on the method of detailed balance

The temperature dependence of an ideal solar cell can be determined using the principle of detailed balance. Here we neglect temperature effects resulting in bandgap shifts or increased non-radiative recombination, which will be specific to the chosen material. Detailed balance calculations are performed by balancing the number of absorbed photons with the number of photons emitted from the solar cell plus the number of carriers exiting the cell to provide power to a load. An absorptivity of 1 is assumed for all photons with energy above the bandgap energy of the solar cell material. The incident photon flux is converted to a net current by assuming one electron-hole pair per absorbed photon, which is then used to determine the current-voltage relationship of the solar cell as well as its maximum efficiency. Using this method, we calculate the temperature-dependent Shockley-Queisser limit under AM 0 [Fig. 1(a)] and AM 1.5G [Fig. 1(b)] illumination [1]. The maximum efficiency is found for bandgaps between 1.1 and 1.4 eV, and the efficiency decreases with increasing cell temperature. For a blackbody, as the temperature is increased, thermal emission increases. However, the principle of detailed balance requires that the emission and absorption fluxes equal at open-circuit conditions. Thus, the quasi-Fermi level of the device must be reduced to decrease the flux out of the cell under illumination. It is this decrease in the quasi-Fermi level that leads to a reduced voltage response and hence reduced efficiency at higher temperatures.

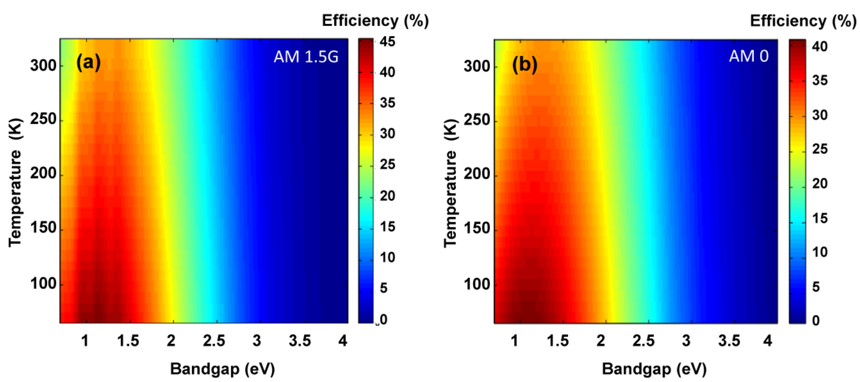

Fig. 1. Contour plot of efficiency as a function of solar cell temperature and bandgap energy for the (a) AM0 (extraterrestrial) spectrum and (b) the AM1.5G (terrestrial) spectrum using the principle of detailed balance. Lower temperatures result in higher maximum power conversion efficiencies.

3. Passive radiative coolers

In order to passively cool a solar cell below the ambient temperature, we consider the use of radiative coolers. These structures transmit heat from a hot body to cold body through thermal radiation. The vast, cold and dark outer space environment can be used as a heat sink to dissipate heat from a hot body. In the case of an object in the extraterrestrial environment, the

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object can directly radiate heat out to space. Whereas, for an object in the terrestrial environment, the earth's atmospheric absorbance has to be bypassed to access this heat sink, which requires careful consideration.

Terrestrial radiative coolers must emit strongly in the atmospheric transparency windows and reflect any incoming thermal radiation from the sun and the earth's atmosphere to achieve cooling. The difference between the absorbed power and the radiated power results in heating or cooling of the structure. Radiative coolers capable of daytime cooling have been constructed to reflect 97% of the solar radiation to achieve cooling [15]. Consequently, radiative coolers reflect strongly in the 280 nm to 4 μm range, where the solar spectrum is present and emit strongly in the infrared region, 8 to 30 μm, where the atmosphere has two transparency windows 8-13 μm and 16-26 μm. Emission from radiative coolers in the extraterrestrial environment does not have this atmospheric constraint and can be modeled as a blackbody emitting thermal radiation at all wavelengths.

3.1 Radiative cooling in the terrestrial environment

In order to passively cool a solar cell on earth, we consider a structure that consists of a solar cell on top of a wavelength selective radiative cooler [Fig. 2 (inset)]. Ideally, the solar cell absorbs all photons with energy equal to or greater than the bandgap energy of the semiconductor and is otherwise transparent. The radiative cooler on the bottom only emits and absorbs in the 8-26 μm range (total reflection or transmission occurs for other wavelengths). For such a structure, the net cooling power is determined by summing the total power into and out of the cell:

$$P_{net} = P_{rad,cooler} + P_{rad,cell} + P_{electrical} - P_{atm} - P_{absorbed}, \quad (1)$$

where $P_{rad,cooler}$ is the power radiated by the radiative cooler, $P_{rad,cell}$ is the power radiated by the solar cell, $P_{electrical}$ is the electrical power extracted from the solar cell, P_{atm} is the power absorbed from the atmospheric emission, and $P_{absorbed}$ is the absorbed solar power by the solar cell. For terrestrial applications, the power terms can be calculated using the photon flux obtained from the measured AM1.5 global spectrum, the generalized Planck blackbody law for emission, and the absorptivity of the semiconductor, the radiative cooler, and the atmosphere. The generalized Planck equation incorporates the effect of the quasi-Fermi level splitting in solar cells on the emission to calculate the total photon emission flux per unit energy interval, *dE*, given by [17]:

$$n(E,T,V) = \frac{2E^2}{h^3c^2(e^{\frac{E-qV}{kT}} - 1)}, \quad (2)$$

where h is Planck's constant, k is Boltzmann's constant, c is the speed of light, and qV characterizes the quasi-Fermi level splitting when describing emission from the cell.

We consider a radiative cooler with an emissivity, $\varepsilon(E,\theta)$, which is 1 in the atmospheric transparency window range 8-26 μm and zero elsewhere [Fig. 2]. Such structures with broadband transmission in the infrared region and strong reflection in the solar spectrum range have been designed and demonstrated [5, 13–15]. The power per unit area radiated from the radiative cooler is given by:

$$\frac{P_{rad,cooler}}{A} = \int d\Omega \cos\theta \int_0^\infty E\, n(E,T,V=0)\, \varepsilon(E,\theta)\, dE, \quad (3)$$

where $d\Omega = 2\pi d\theta$ for a hemisphere.

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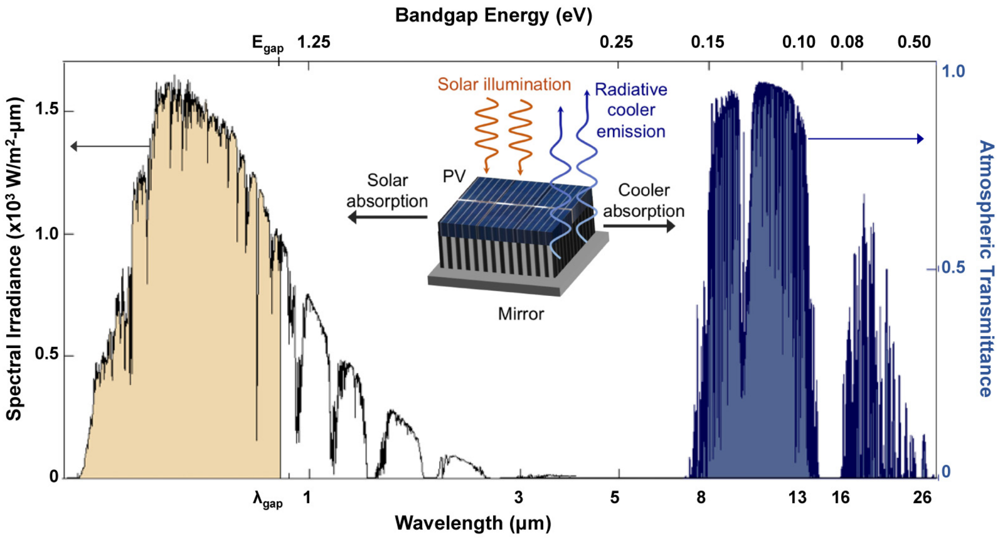

Fig. 2. Schematic of the proposed structure consisting of a solar cell coupled to a selective thermal emitter with back mirror. The solar cell absorbs above-bandgap illumination from the sun (left). The radiative cooler emits (and hence absorbs) strongly in the atmospheric transparency window in the mid-infrared range between 8 and 26 µm (right).

In this work, the cell's absorptivity is represented as a step-function going from 0 (for $E < E_g$) to 1 (for $E \geq E_g$). Further, we assume that the cell is operating at the maximum power point ($V = V_{max}$) and calculate the power radiated out of the solar cell per unit area by:

$$\frac{P_{rad,cell}}{A} = E_g \int d\Omega \cos\theta \int_{E_g}^{\infty} \frac{2E^2}{h^3 c^2 (e^{\frac{E - qV_{\max}}{kT}} - 1)} dE. \tag{4}$$

The final term that corresponds to removing power from the cell is the extracted electrical power, $P_{electrical}$, which is calculated using the method of detailed balance described by Shockley and Queisser [1].

The structure also absorbs power from the ambient (represented by the atmosphere for the sun facing structure in the inset of Fig. 2); however, the majority of radiation from the ambient (at 300 K) lies in the mid- to far-infrared region of the spectrum, which is predominantly absorbed by the radiative cooler and not by the solar cell. Of the 459 Watts/m^2 of integrated blackbody emission power, less than 1 Watt/ m^2 lies in the spectral range from 280 nm to 4 µm. Thus, the absorption of this radiation within the solar cell is neglected. Hence, the only significant absorption of atmospheric radiation is in the radiative cooler, which absorbs in spectral regions with $\lambda > 8$ µm. The power per unit area absorbed by the radiative cooler from the atmosphere is given by:

$$\frac{P_{atm}}{A} = \int d\Omega \cos\theta \int_0^{\infty} E\, n(E, T_{amb}, V = 0)\, \varepsilon(E,\theta)\, \varepsilon_{atm}(E,\theta) dE, \tag{5}$$

where the angle dependent emissivity of the atmosphere, $\varepsilon_{atm}(E,\theta)$, is given by

$$\varepsilon_{atm}(E,\theta) = 1 - t(E)^{\frac{1}{\cos\theta}} \tag{6}$$

and *t(E)* is the atmospheric transmittance in the zenith direction [9,18] and is shown in Fig. 2. Equation (5) results from replacing the absorptivity of the structure by its emissivity according to Kirchhoff's law for thermal radiation.

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The final power input term, $P_{absorbed}$, in Eq. (1) comes from the absorption of all above bandgap photons within the cell:

$$\frac{P_{absorbed}}{A} = \int_{E_g}^{\infty} n_{AM1.5}(E)\,dE, \tag{7}$$

where $n_{AM1.5}(E)$ is the AM1.5G spectral photon flux.

The temperature at which the net power is zero (P_{net} = 0) indicates the steady state temperature of the structure. In our model we assume unity absorption for the radiative cooler from 8 to 26 microns [Fig. 3]. We note that because the thermalization loss decreases with increasing bandgap energy, there is less heat dissipation in the structure for higher bandgap materials; hence, higher bandgap materials result in lower steady state temperatures, as expected. However, with increasing semiconductor bandgap the absorption from sun, $P_{absorbed}$, decreases rapidly due to the fact that fewer high energy photons exist within the solar spectrum, which results in a saturation of the equilibrium temperature at higher bandgaps.

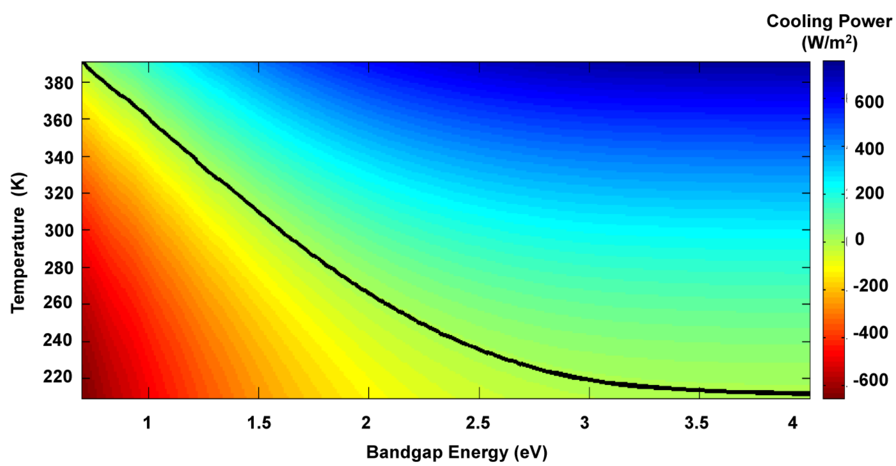

Fig. 3. Contour plot of cooling power for a hybrid structure consisting of a solar cell thermally coupled to a radiative cooler that can emit into 8 to 26 µm infrared region. The black curve indicates the steady state temperature of the structure placed in ambient at 300 K. Positive values of the cooling power result in a reduction of the cell temperature.

Typically, the solar cell temperature increases under operating conditions where its temperature is influenced by solar radiation, the ambient air temperature, and the wind speed. The operating temperature of a PV module can be calculated using the nominal operating cell temperature (NOCT), which is defined as the cell temperature at open-circuit conditions under the standard reference environment, i.e. for an ambient temperature of 293.15 K, an irradiance of 800 W/m^2, a wind speed of 1 m/s, and an open rear surface mounting (the module is tilted at 45°) [19]. A typical crystalline-Silicon photovoltaic module operates at a NOCT of 321 K [20]. The actual operating temperature can be calculated as [21]:

$$T_{cell} = T_{air} + \left(\frac{NOCT - 293.15}{80}\right) S, \tag{8}$$

where T_{air} is the ambient temperature (in K) and S is the solar irradiance (in mW/cm^2).

We compare the efficiency of our structure with the efficiency of a solar cell at room temperature, as assumed in most detailed balance calculations, and a typical solar cell at an elevated operating temperature described by Eq. (8), assuming an ambient temperature of 300 K and solar irradiance of 1 kW/m^2 (i.e. 1-sun illumination). We find that the maximum efficiency of our structure occurs for E_g = 1.38 eV and is 0.87% higher than a typical solar cell at operating temperature [Fig. 4]. We also find that the proposed structure has a higher efficiency than an ideal solar cell operating at 300 K (the typical assumption when calculating the Shockley-Queisser limit) for bandgap energies larger than 1.52 eV. In our calculations, ε_{atm} is taken from Ref [18] with a water vapor column level of 5 mm, which corresponds to a relatively large absorption from the ambient. At a lower water column level, the thermal radiation from the ambient is lowered, resulting in improved efficiency as a result of more effective thermal emission and cooling.

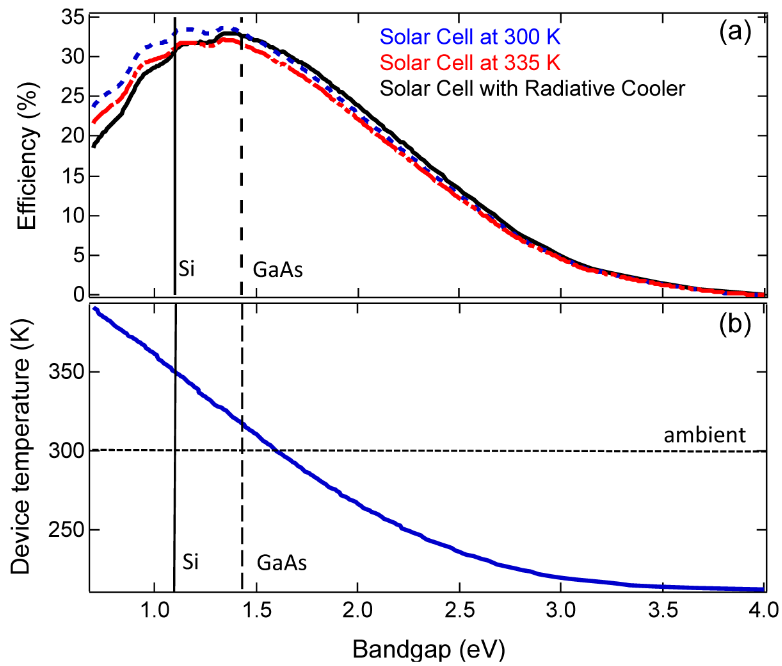

Fig. 4. (a) Efficiency comparison of the proposed structure, solar cells operating at 300 K, and a typical solar cell characterized by a NOCT of 321 K, i.e. a cell operating at 335 K. (b) Steady state temperature as a function of bandgap energy for the structure with a radiative cooler emitting in the 8-26 μm range. Vertical dashed and solid lines indicate the bandgaps of GaAs and Si, respectively.

In this work, we do not include the effects of conductive and/or convective heat exchange, instead assuming that the cells can be packaged in a light vacuum as is done for other mass-produced consumer products like light bulbs or in a higher vacuum as is done for vacuum tubes. Inclusion of such a term will account for additional non-radiative heat dissipation/accumulation depending on the temperature of the structure and the ambient temperature, which will affect the steady state temperature [5]. For example, in a typical operating environment with an ambient temperature of 300K, a wind speed of 3 m/s on the exposed side and 1 m/s on the rear side, assuming uniform temperature distribution throughout the structure, the proposed structure always has better efficiency than the cell at the typical operating temperature (335K).

3.2 Radiative cooling in the extraterrestrial environment

For solar cells in the extraterrestrial environment, we propose a structure with a solar cell separated from the radiative cooler by a perfect reflector [Fig. 5(a), inset]. The device is oriented such that solar cell faces the sun and the radiative cooler is shielded from the sun at all times. The net cooling power of such a structure is obtained from Eq. (1) with P_{atm} = 0:

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$$P_{net} = P_{rad,cooler} + P_{rad,cell} + P_{electrical} - P_{absorbed} \quad . \tag{9}$$

In the extraterrestrial environment there is no constraint on the radiative cooler to emit in a specific wavelength window to radiate thermal energy to outer space; hence, the radiative cooler can be modeled as a blackbody emitting over all wavelengths. $P_{rad,cooler}$ can be calculated from Eq. (3) by setting the emissivity of the radiative cooler, $\varepsilon(E,\theta)$, to be 1 for all photon energies. The terms $P_{rad,cell}$ and $P_{absorbed}$ in Eq. (9) can be calculated from Eq. (4) and Eq. (7); however, the AM 0 spectrum is used in Eq. (7) rather than the AM 1.5G spectrum. Similarly, the electrical power, $P_{electrical}$, can be calculated using the method of detailed balance using the AM 0 spectrum.

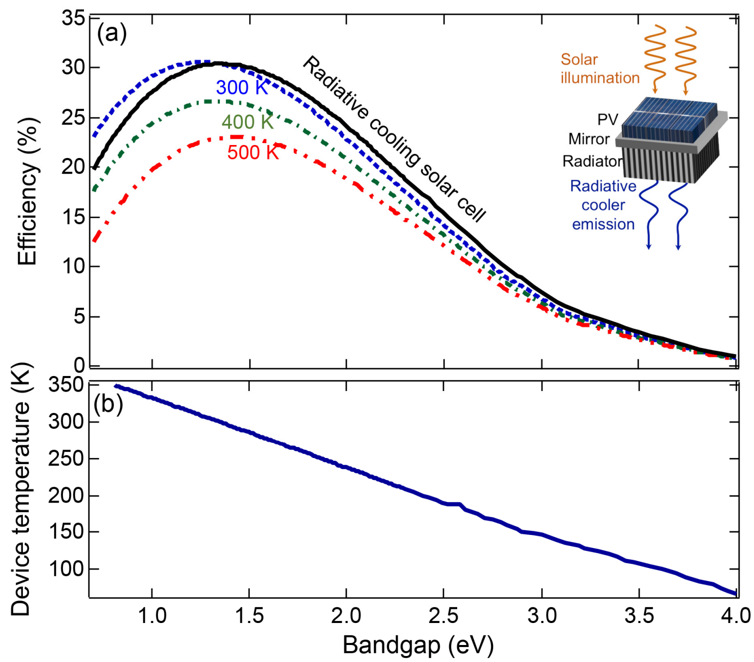

Fig. 5. (a) Efficiency comparison of the radiatively cooled solar cell operating at temperatures between 300 and 500 K under AM 0 illumination. The efficiency of the proposed structure, drawn in black, is greater than that of solar cells with a temperature of 300 K for all E_g > 1.36 eV. (b) The temperature of the proposed structure as a function of material bandgap energy.

We expect the performance of the radiative cooling structure to be better in the extraterrestrial environment than in the terrestrial environment for two reasons. First, the radiator radiates heat over all wavelengths; hence more power is radiated out of the structure. Second, no heat is added to the structure from the atmosphere. Indeed, the proposed structure outperforms solar cells at all temperatures equal to or greater than 300 K for bandgaps above 1.36 eV [Fig. 5]. Typically, the range of temperatures experienced by a solar cell in near-earth orbit is 293-358 K [16]. If we assume that a typical solar cell reaches these temperatures, the proposed structure will have an efficiency advantage of 0.4 to 2.6% over a typical solar cell in low-earth orbit. For near-sun missions where the temperatures can greatly exceed 400 K, more substantial efficiency benefits are obtained [Fig. 5].

4. Conclusion

In conclusion, we have shown that passive radiative cooling has the ability to lower the solar cell temperature below the ambient temperature in terrestrial environments and below the nominal operating temperature in extraterrestrial environments. Cooling of several tens of

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degrees is possible depending on the semiconductor bandgap, resulting in efficiency improvements of several percent. While efficiency improvements are found for both terrestrial and extraterrestrial applications, the largest benefits appear for space applications. Thus, radiative cooling of solar cells offers a new design tool to achieve efficiencies greater than expected for devices that reach an equilibrium temperature with its surroundings, opening new opportunities for next generation photovoltaics.

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