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Power dense thermophotovoltaic cells

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Abstract. Class-leading 2-junction (2J) thermophotovoltaic (TPV) cells have been developed with thermophotovoltaic efficiency exceeding 40%. However, these devices have sub-optimal power density because the subcell bandgaps are not matched to the emitter spectrum. Although efficiency is important, power density is also an important metric to gauge TPV cell performance; the greater the power density, the less total area of TPV cells that are needed to satisfy a given power generation target. To quantify the relevance of power density, spectrum-matched 1.04/0.78/0.62/0.48/0.36 eV 5-junction (5J) TPV cells have the potential to be 3.5 times more power dense than state-of-the-art, yet spectrum-mismatched, 1.4/1.2 eV 2J TPV cells when irradiated by a 2400 °C emitter. The proposed 5J TPV cells also have the potential to exceed 40% standard power conversion efficiency.

Keywords: power density / spectrum matching / thermophotovoltaic cell

1 Introduction

Photovoltaic (PV) cells convert absorbed radiation into direct current electricity [1]. A PV cell may generate power from the absorption of sunlight; in this case the device is known as a solar cell. A PV cell may also generate power from the absorption of non-solar thermal radiation; in this case the PV cell is known as a thermophotovoltaic (TPV) cell. Additionally, a PV cell may generate power from the absorption of non-thermal radiation (i.e., cold light) such as luminescence from a light-emitting diode (LED) or laser. In fact, PV cells (including multi-junction designs) that absorb laser light are referred to as Optical Power Converters (OPCs) or more specifically Laser Power Converters (LPCs) [2]. A useful goal with any type of photovoltaic device is to generate maximum power because PV cells are power conversion devices. So, the power conversion efficiency of PV cells, including TPV cells, may be directly correlated with power output as per the expression $\eta = P_{out}/P_{inc}$, where P_{out} is the electric power density output by the cell and P_{inc} is the incident power density (also known as the irradiance).

In 2022, a metamorphic (lattice-mismatched) 2-junction (2J) TPV cell with 1.4 eV GaAs and 1.2 eV GaInAs subcells was reported by LaPotin et al. with class-leading thermophotovoltaic efficiency of 41.1% when irradiated by a tungsten halogen bulb emitter at 2400 °C [3]. LaPotin et al. determined the efficiency of their TPV cell from the formula given by $\eta_{TPV} = P_{out}/(P_{inc} - P_{ref})$, where P_{ref} is the reflected power density due to reflection of unabsorbed photons, including sub-bandgap photons [3]. Quoting LaPotin et al., the reason for including P_{ref} in the equation for TPV cell efficiency is as follows: "By reflecting unconverted photons, the energy of the sub-bandgap light is preserved through reabsorption by the emitter. The reflected and subsequently reabsorbed light helps to keep the emitter hot, thereby minimizing the energy input required to heat the emitter" [3]. See the Appendix and also references [4,5] for more information about thermophotovoltaic efficiency.

Maximum power conversion, instead of majority photon reflection, from the TPV cells may be desired. In other words, one possible goal is to absorb as much of the incident radiation as possible in the TPV cells and then convert the absorbed radiation as efficiently as possible into electricity (i.e., maximize P_{out} for a given P_{inc} within thermodynamic limits). With this in mind, $\eta_{standard} = P_{out}/P_{inc}$ is referred to as the *standard efficiency* whereas $\eta_{TPV} = P_{out}/(P_{inc} - P_{ref})$ is referred to as the *thermophotovoltaic efficiency* in this paper.

2 Analysis and discussion

As shown in Table 1, LaPotin et al. reported $P_{out} = 2.39\ \mathrm{W\,cm^{-2}}$ for the 1.4/1.2 eV TPV cell [3], whereas $P_{inc} = 29.1\ \mathrm{W\,cm^{-2}}$ and $P_{ref} = 23.28\ \mathrm{W\,cm^{-2}}$. While the thermophotovoltaic efficiency is 41.1%, the standard

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Table 1. State-of-the-art 2J TPV cell performance data (2400 °C emitter).

E_g	P_{inc}	P_{ref}	P_{out}	η_{TPV}	$\eta_{standard}$
eV	W cm^{-2}	W cm^{-2}	W cm^{-2}	%	%
1.4/1.2	29.1	23.28	2.39	41.1	8.2

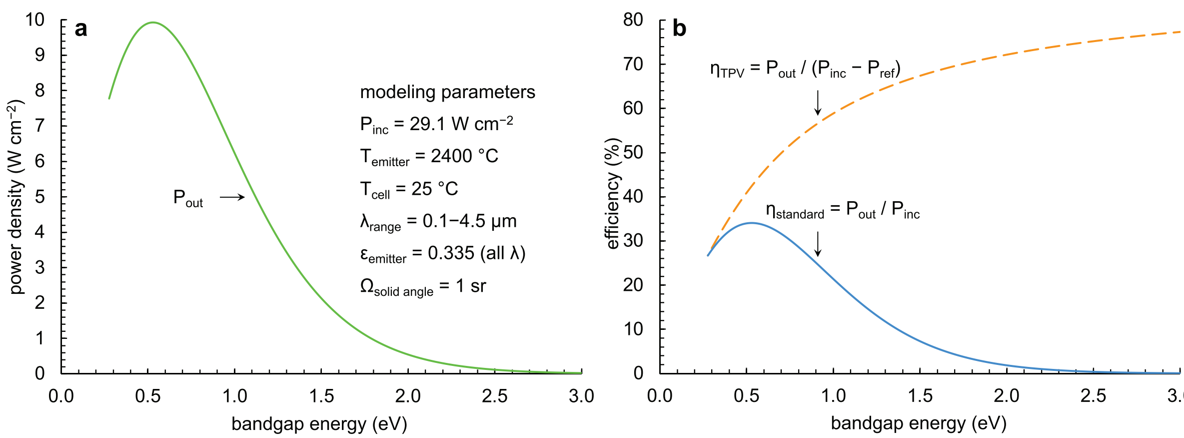

Fig. 1. (a) Detailed balance-limiting power density and (b) efficiency of an ideal 1J TPV cell as a function of bandgap energy.

efficiency is 8.2%. Most of the incident power is reflected rather than absorbed for conversion into electricity. In particular, P_{ref} is 80% of P_{inc}.

It may be helpful to consider the direct correlation between the power output of a TPV cell and its efficiency. Within thermodynamic constraints, maximum power generation is a beneficial goal. As such, power output and efficiency are directly correlated. Designing a TPV system so that 80% of the radiation is emitted and reflected continuously back and forth between a hot emitter and a cool TPV cell may not help in the endeavor to generate maximum power output.

To reinforce this point for illustrative purposes, the detailed balance-limiting [6] output power density and power conversion efficiency of a single-junction (1J) TPV cell are shown in Figure 1. The emitter spectrum wavelength range (λ_{range}), emitter emissivity ($\varepsilon_{emitter}$), and solid angle ($\Omega_{solid\ angle}$) were chosen so as to give $P_{inc} = 29.1$ W cm^{-2} for a 2400 °C gray body emitter. Although LaPotin et al. did not report the spectral emissivity of their specific tungsten emitter, for modeling purposes a fixed emissivity of 0.335 is assumed for tungsten [7], noting that emissivity is a function of temperature, wavelength, surface roughness, oxidation, etc. When a multi-junction TPV cell has minimal grid contact coverage and a high-quality broadband antireflection coating, the majority of P_{ref} may be related to the longer wavelength photons with energy less than the bottom subcell bandgap. For the 1.4/1.2 eV 2J device presented by LaPotin et al., this means sub-bandgap photons with wavelengths ranging from ~ 1–4.5 μm. At 2400 °C, the emissivity of tungsten is < 0.335 for wavelengths between ~ 2 and 4.5 μm [7]. A long wavelength cutoff of 4.5 μm for the emitter spectrum was chosen because LaPotin et al. reported: "The spectral radiance goes to zero > ~ 4500 nm due to the presence of the quartz envelope around the bulb, as quartz is absorbing beyond this wavelength" [3]. Finally, 1 sr is assumed as a representative solid angle subtended by the emitter with relation to the placement of the TPV cell. LaPotin et al. did not report the solid angle. Their experimental setup involved a tungsten halogen bulb emitter located in an ellipsoidal reflector. Emitted radiation was collected in a compound parabolic reflector and then passed through a water-cooled aperture (area of 0.312 cm^2) before irradiating their TPV cell with mesa area of 0.8075 cm^2 and illuminated area, discounting the busbar, of 0.7145 cm^2 [3].

The detailed balance condition represents the ideal radiative limit and does not include losses such as nonradiative recombination. A 1J TPV cell, rather than a 2J TPV cell, is used for simplicity to show the general trends in power output and efficiency. Although a large bandgap TPV cell (e.g., a 1.88 eV GaInP cell) with a backside mirror would have large sub-bandgap reflected power density due to the fact that only a small fraction of the radiation from the 2400 °C emitter would be absorbed, it would also have small output power density and thus small standard efficiency. Or, stated another way, if the goal is to achieve a large η_{TPV}, then a 1.88 eV GaInP 1J cell with a backside mirror would be a simpler option than a 1.4/1.2 eV GaAs/GaInAs 2J TPV cell. In contrast, as an alternative approach, it may be useful to develop TPV cells with large output power density which will also result in large standard efficiency.

Table 2. Detailed balance-limiting power density and standard efficiency of series-connected 2J and 5J TPV cells irradiated by a 2400 °C emitter.

junctions	E_g	J_{sc}	V_{oc}	V_m	J_m	P_{out}	P_{inc}	$\eta_{standard}$	$0.75\eta_{standard}$
TPV cell	eV	A cm^{-2}	V	V	A cm^{-2}	W cm^{-2}	W cm^{-2}	%	%
2J	1.4	2.20	1.249	1.148	2.152				
	1.2	2.22	1.057	0.961	2.162				
				sum V_m	min J_m	$J_m \times V_m$		P_{out} / P_{inc}	
				2.109	2.152	4.54	29.1	15.6	11.7
5J	1.04	6.90	0.935	0.842	6.696				
	0.78	6.90	0.692	0.607	6.620				
	0.62	6.90	0.537	0.458	6.533				
	0.48	6.90	0.415	0.342	6.418				
	0.36	7.10	0.308	0.242	6.419				
				sum V_m	min J_m	$J_m \times V_m$		P_{out} / P_{inc}	
				2.491	6.418	15.99	29.1	54.9	41.2

Modeling parameters: $P_{inc} = 29.1$ W cm^{-2}, $T_{emitter} = 2400$ °C, $T_{cell} = 25$ °C, $\lambda_{range} = 0.1$–4.5 µm, $\varepsilon_{emitter} = 0.335$ (all λ), $\Omega_{solid\ angle} = 1$ sr
E_g is bandgap energy, J_{sc} is short circuit current density, V_{oc} is open circuit voltage, V_m is max power point voltage, J_m is max power point current density.

The following question may arise: is it possible to develop power dense TPV cells with ≥ 40% standard efficiency? To answer this question, the benchmark 1.4/1.2 eV 2J TPV cell design from LaPotin et al. [3] is compared with a 5-junction (5J) TPV cell as shown in Table 2. We focus directly on a 5J architecture in order to bypass 1J − 4J TPV cells, targeting achievable standard efficiencies, after losses, of 40% or greater. For context, note that the highest efficiency (38.8%) 1-Sun solar PV cell with area ≥ 1 cm^2 is a 2.17/1.68/1.40/1.06/0.73 eV 5J III-V cell. A 2.15/1.72/1.41/1.17/0.96/0.70 eV inverted metamorphic 6-junction (6J) III-V concentrator solar PV cell (~ 0.1 cm^2 area) has reached 47.1% efficiency at an intensity of 143 Suns [8]. Therefore, in our view, it is not overly ambitious to focus efforts on developing power dense, efficient, and spectrum-matched 5J (or 6J) III-V TPV cells. The use of five (or six) series-connected junctions will also help to keep current densities manageable, resulting in less loss due to Joule heating (described by the expression I^2R, where I is electric current and R is electrical resistance).

As a baseline, 75% of the detailed balance-limiting efficiency has been achieved in III-V multi-junction photovoltaic cells, including lattice-mismatched (metamorphic) epitaxial lift-off (ELO) devices [9]. So, 75% of the detailed balance limit is assumed as a reasonable efficiency target. Although a 1.4/1.2 eV 2J TPV cell might be able to achieve standard efficiency of ~ 12% and up to ~ 16% for a perfect cell, a 5J TPV cell might be able to achieve standard efficiency of ~ 41% and up to ~ 55% for a perfect cell. Notice from Table 2 that the detailed balance-limiting standard efficiency of a 1.4/1.2 eV 2J TPV cell, ~ 16%, is less than half that of a 0.5 eV 1J TPV cell, ~ 34%, as shown in Figure 1. This is an indication that if the bandgaps do not match the spectrum, the standard efficiency and power output of a spectrum-mismatched 2J cell can be less than a spectrum-matched 1J cell.

The 5J TPV devices discussed here, and shown schematically in Figure 2, are intended as a case study to emphasize that spectrum matching is important in order to achieve power dense and efficient TPV cells. The maximum output power density (P_{out}) and maximum standard efficiency ($\eta_{standard}$) of the modeled 1.04/0.78/0.62/0.48/0.36 eV 5J cell are 3.5× greater than the modeled 1.4/1.2 eV 2J cell.

Note that the max power point current density (J_m ~ 6.4 A cm^{-2}) of the 5J TPV cell discussed here is less than the max power point current density (J_m ~ 7.5 A cm^{-2}) of commercially available GaInP/GaInAs/Ge 3-junction (3J) concentrator solar photovoltaic cells operating under 500 Suns concentration [10]. Thus, grid metal contact technologies have already been optimized for handling this amount of current density in photovoltaic devices with minimal degradation in fill factor (FF). For context regarding achievable open circuit voltage (V_{oc}) with $Ga_xIn_{1-x}As$ compounds, note that the following V_{oc} values have been achieved in laser power converters (LPCs): 0.8 V for metamorphic 1J GaInAs LPCs designed to absorb 1064 nm laser light [11] and 5.5 V for lattice-matched (to InP) GaInAs 10-junction LPCs designed to absorb 1470 nm laser light (note that all 10 junctions are constructed from the same lattice-matched GaInAs alloy) [12].

The III-V alloy composition values shown in Figure 2 were determined from published semiconductor alloy properties [13]. Subcell "base" layers fabricated from direct bandgap III-V semiconductors are typically ~ 2–3 µm thick. The thickness depends on the absorption coefficient and subcell current density matching (noting that the bottom subcell may be slightly current rich). Subcell

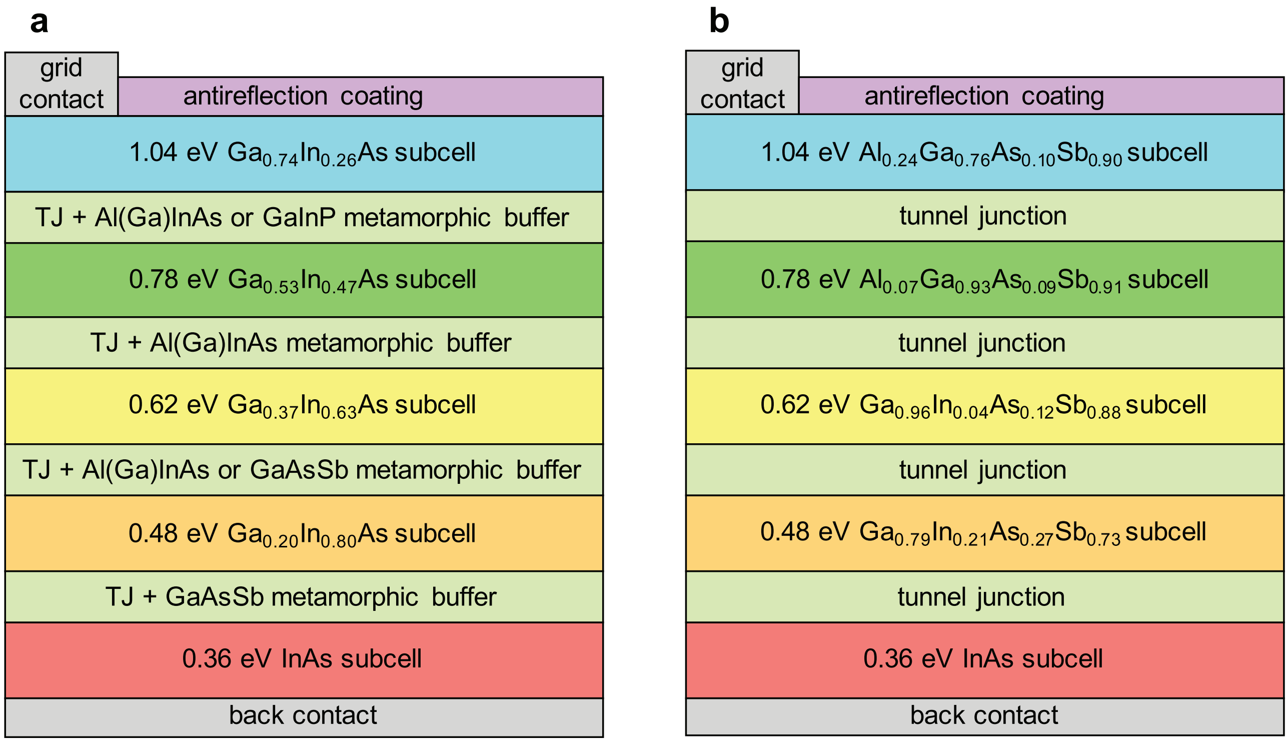

Fig. 2. (a) Metamorphic and (b) lattice-matched series-connected 5J TPV cells (simplified view, not-to-scale, "TJ" is tunnel junction).

"emitter" layers are typically ~50–100 nm thick whereas "window" layers are typically ~20–30 nm thick and "back surface field" layers are typically ~50–100 nm thick. Step-graded metamorphic "buffer" layers are typically ~2–3 μm thick. Tunnel junctions could include AlGaInAs and AlGaAsSb compounds. The 5J cells could be epitaxially grown on commercially available InAs substrates. Note that the $Al_xGa_{1-x}As_ySb_{1-y}$ and $Ga_xIn_{1-x}As_ySb_{1-y}$ quaternary alloy compositions are estimated values [13]. Also note that $Ga_xIn_{1-x}As_ySb_{1-y}$ alloys have an immiscibility range described by $0.24 < x < 0.75$ [13].

Overall, for a given TPV system, the emitter spectrum would need to be known and then this would be used to determine the optimal subcell bandgaps. When compared to solar PV cells which are typically designed for either the terrestrial AM1.5G or AM1.5D spectra or the extraterrestrial AM0 spectrum, the design of TPV cells is more variable due to system-specific emitter temperature and spectral emissivity. More to the point, actual power density and efficiency of a given TPV cell is a function of the temperature and spectral emissivity of the emitter, choice of subcell bandgaps, how close the cell is located to the emitter, temperature of the cell, and quality of the cell which is related to the extent of losses due to nonradiative recombination, parasitic absorption, series resistance, and external reflection from the top grid contact electrodes as well as from the cell when taking into account that antireflection coatings are not perfect.

3 Summary

TPV cells, like solar cells, are power conversion devices. A relevant goal for photovoltaic cells, including TPV cells, is to maximize the power density ($W\,cm^{-2}$) while using the least amount of material to construct the cells. Therefore, power density is an important performance metric for TPV cells. The greater the power density, the smaller the total area of cells and modules that will be required to fulfill a given power generation target. Spectrum matching enables optimal power density. One possible way to achieve large power density is to develop spectrum-matched 5J TPV cells. For example, spectrum-matched 1.04/0.78/0.62/0.48/0.36 eV 5J TPV cells have the potential to be 3.5× more power dense when compared to state-of-the-art 1.4/1.2 eV 2J TPV cells irradiated by a 2400 °C emitter. Furthermore, these 5J TPV cells also have the potential to exceed 40% standard photovoltaic power conversion efficiency.

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Author contribution statement

A.P.K. performed the analysis and wrote the paper.

Appendix: Thermophotovoltaic efficiency definition

LaPotin et al. described the efficiency of their TPV cell, $\eta_{TPV} = P_{out}/(P_{inc} - P_{ref})$, as follows: "The efficiency, η_{TPV}, is the metric we use here because it is the conventional and generalizable metric used to describe the performance of a cell–emitter pair independent of other system-level characteristics" [3]. Note that in reference to the definition of η_{TPV}, LaPotin et al. cited a review paper, by Burger et al., that defines TPV "sub-system efficiency" as $\eta_{TPV} = P_{out}/Q_h$ where Q_h is "the heat flow out of the emitter surface" and TPV "pairwise efficiency" as $\eta_{pairwise} = P_{out}/Q_{abs}$ where Q_{abs} is "the heat absorbed by the cell" [14]. Burger et al. state: "We note that $\eta_{pairwise}$ is equivalent to η_{TPV} in the case of an ideal, lossless cavity ($Q_{abs} = Q_h$)" [14].

References

1. A.P. Kirk, *Solar Photovoltaic Cells: Photons to Electricity* (Academic Press, London, 2015)
2. S. Fafard, D.P. Masson, Perspective on photovoltaic optical power converters, J. Appl. Phys. **130**, 160901 (2021)
3. A. LaPotin, K.L. Schulte, M.A. Steiner, K. Buznitsky, C.C. Kelsall, D.J. Friedman, E.J. Tervo, R.M. France, M.R. Young, A. Rohskopf, S. Verma, E.N. Wang, A. Henry, Thermophotovoltaic efficiency of 40%, Nature **604**, 287 (2022)
4. A. Datas, R. Vaillon, Chapter 11-Thermophotovoltaic Energy Conversion, in: A. Datas (ed.), *Ultra-High Temperature Thermal Energy Storage, Transfer and Conversion*, (Woodhead Publishing, Duxford, 2021), pp. 285–308
5. A. Datas, Optimum semiconductor bandgaps in single junction and multijunction thermophotovoltaic converters, Sol. Energy Mater. Sol. Cells **134**, 275 (2015)
6. W. Shockley, H.J. Queisser, Detailed balance limit of efficiency of *p-n* junction solar cells, J. Appl. Phys. **32**, 510 (1961)
7. Y.S. Touloukian, D.P. DeWitt, *Thermophysical Properties of Matter* – The TPRC Data Series Volume 7: Thermal Radiative Properties – Metallic Elements and Alloys (Plenum Publishing Corp., New York, 1970)
8. M.A. Green, E.D. Dunlop, M. Yoshita, N. Kopidakis, K. Bothe, G. Siefer, X. Hao, Solar cell efficiency tables (version 62), Prog. Photovolt. Res. Appl. **31**, 651 (2023)
9. A.P. Kirk, D.W. Cardwell, J.D. Wood, A. Wibowo, K. Forghani, D. Rowell, N. Pan, M. Osowski, Recent progress in epitaxial lift-off solar cells, *Proc. IEEE 7th World Conference on Photovoltaic Energy Conversion, Waikoloa*, 2018, pp. 0032–0035
10. Azur Space Solar Power, GaInP/GaInAs/Ge 3-junction concentrator solar cells under 500 Suns concentration. https://www.azurspace.com/index.php/en/products/products-cpv/cpv-solar-cells
11. Y. Guo, H. Wang, J. Wang, Y. Zhang, R. Niu, X. Chen, B. Wang, Y. Xiao, Z. Zhang, W. Liu, H. Yang, G. Deng, 1064 nm InGaAs metamorphic laser power converts with over 44% efficiency, Opt. Express **30**, 42178 (2022)
12. S. Fafard, D.P. Masson, High-efficiency and high-power multijunction InGaAs/InP photovoltaic laser power converters for 1470 nm, Photonics **9**, 438 (2022)
13. S. Adachi, *Properties of Semiconductor Alloys: Group-IV, III-V and II-VI Semiconductors* (John Wiley & Sons, Chichester, 2009)
14. T. Burger, C. Sempere, B. Roy-Layinde, A. Lenert, Present efficiencies and future opportunities in thermophotovoltaics, Joule **4**, 1660 (2020)

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