Thermoradiative Arrays: a New Technology for Conversion of Heat into Electrical Power

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The thermoradiative cell is a recently developed solid-state device for generating electrical power from heat energy. Thermoradiative arrays could be used as the conversion technology for production of electrical power from thermal sources such as nuclear reactors or radioisotope heat sources in space. The technology has the potential for efficient conversion compared to existing technologies used for space, but as yet is in a low state of development, with considerable work to be done. A roadmap of key research needs is given.

I. INTRODUCTION

The thermoradiative cell is a new technology for generating power from heat energy. The concept of a thermoradiative cell was introduced by Strandberg in 2015 [1, 2], and by Santhanam and Fan in 2016 [3], based on an analysis by Byrnes, Blanchard, and Capasso [4] in 2014 suggesting that infrared radiation to the thermal sink of deep space could be used in the form of an emissive energy harvester.

A thermoradiative cell is, in basic concept, a photovoltaic cell that is run in the thermodynamically reversed direction.

It is based on the concept that an ideal photovoltaic cell is a heat engine, operating on a temperature difference between photons (e.g., from the sun) as a high temperature source, and the external environment as a low temperature sink. Since an ideal heat engine will operate when the high and low temperature sides of the engine were reversed, Strandberg showed that a device identical in structure to a photovoltaic cell would operate with sources reversed. Thus, the thermoradiative cell has heat as the energy input and photons as the waste heat output (figure 1). The cells radiate heat to a lower temperature, which he assumed to be the low temperature of deep space.

A photovoltaic cell absorbs light and produces electrical power. In the process, of course, since thermodynamics demands that no energy converter can be a hundred percent efficient, it also produces waste heat. We can therefore think of a solar cell as a thermodynamic heat engine that converts sunlight (at an effective temperature of 6000 K, the temperature of the sun) into electrical power, and rejecting waste heat on the "cold" side, typically at room temperature, around 300 K. But, thermodynamically, a heat engine is reversable: if you switch the hot side and the cold site, it will still produce power. Thermodynamically, then, it should be possible to heat the photovoltaic device, to make it emit (infrared) light, and in the process produce electrical power. The concept sounds absurd [5]; but nevertheless it is based on sound physical principles.

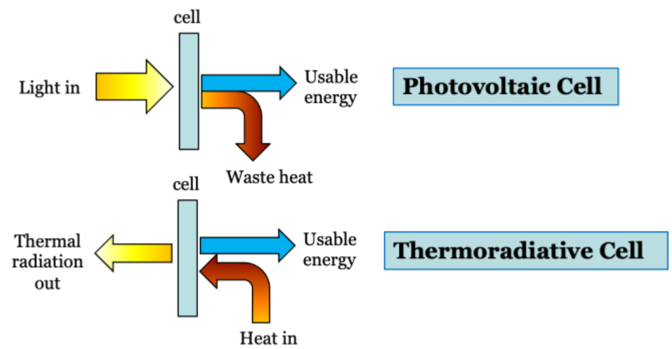

Figure 1: Photovoltaic and thermoradiative cells compared

Thus, the thermoradiative cell is a solid-state device for converting heat energy to electrical power. It is structurally similar to a photovoltaic cell, in that it is a p-n junction semiconductor device, but thermodynamically operates in the reverse direction. Like thermophotovoltaic cells and thermoelectric converters, it is a solid-state heat engine with no moving parts, but the fundamental operating principle is different from either.

Operating in the reverse direction from photovoltaic cells, thermoradiative cells utilize the thermal dark current, and reject the radiation from electron-hole recombination as waste heat in the form of infrared radiation. The waste heat rejection in the form of infrared radiation means that the thermoradiative cell must have an unimpeded view to deep space (or to some other low-temperature heat sink).

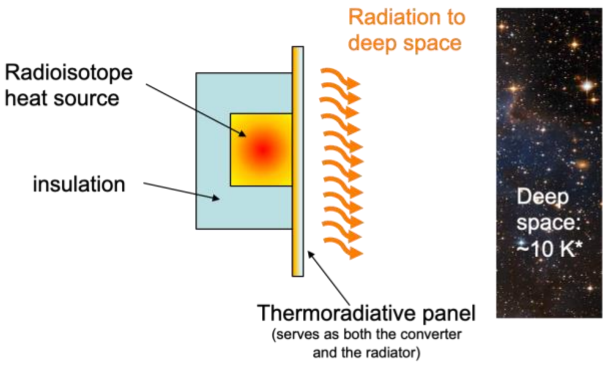

Figure 2: Conceptual diagram of a thermoradiative converter used as a generator for a radioisotope heat source.

II. ANALYSIS

Figure 2 shows a conceptual diagram of how a thermoradiative array would be used to produce power from a radioisotope heat source. The heat source would conduct heat to the thermoradiative array, which in turn radiates infrared waste heat to space, while producing power. The thermoradiative array thus serves both as the energy converter and also the waste heat radiator.

II.A Operation

Analyses of efficiency limits for thermoradiative conversion using various ideal assumptions has subsequently been done by a number of researchers [2-9]. Applications proposed include terrestrial power [1], conversion of waste heat to energy [10], and use as for converting heat from isotope or nuclear power sources to electrical power for spacecraft [11,12].

Thermoradiative cells are typically designed to operate at a heat source temperature that may be as high as 1000 to 1500 K (e.g., for nuclear heat sources), or as low as 300 K (e.g., for recovering energy from waste heat). Since these temperatures are low compared to the equivalent photon temperature of solar energy (~6000 K), the optimum bandgap for thermoradiative cells is correspondingly lower than that for solar cells. Thus, thermoradiative cells are necessarily low-bandgap devices. However, they differ from thermophotovoltaic (TPV) cells in that thermoradiative cells operate at high temperature, while TPV cells operate at lower temperatures.

The power and efficiency can be calculated as a function of bandgap in the detailed-balance case in which all of the thermal emissivity of the cell is due to the recombination of thermally generated electron-hole pairs, and all other recombination losses are ignored. The current produced is directly proportional to the recombination radiation, and thus the more thermally generated pairs, the higher the current. The voltage is proportional to the bandgap. These two constraints set an optimal bandgap that is proportional to the thermal voltage kT.

Since a thermoradiative cell operates by radiating directly to space, the current produced will increase strongly with the temperature. Thus, in contrast to a photovoltaic converter (which operates best at low temperatures), the power increases with operating temperatures. Likewise, in contrast to conventional thermal conversion, high radiator temperature increases, rather than decreases, the power output. Thus, the thermoradiative conversion may fill a power-generation niche in which small radiator size is required.

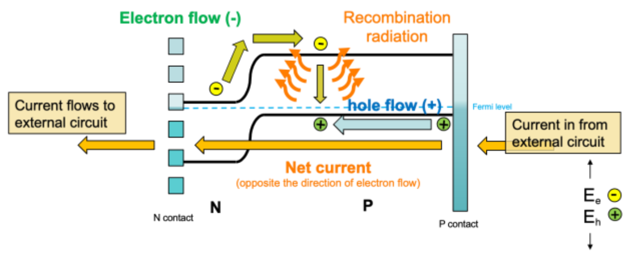

Figure 3: A simplified energy band-diagram schematic of a diode operating as a thermoradiative cell.

II.B Maximum Power Point in the Shockley-Queisser Limit

II.B.1. Operating Point

A thermoradiative device consists of a p-n diode with a surface area that has a view of space (or, generally, any cold-temperature radiative heat sink) to which recombination radiation can be emitted, operating in the case in which the temperature of the diode is higher than the temperature of the heat sink.

Figure 3 shows in simplified schematic the energy band diagram of the operation of a thermoradiative cell, in this case a n-on-p diode. Majority carrier electrons (on the left) are thermally excited across the junction from the emitter (n side of the junction) to the base (p side), where they recombine with holes to complete the circuit.

For a p-n diode operating outside of thermal equilibrium, if the external temperature is higher than the diode temperature, more carriers are generated from absorption of thermal photons than are injected across the junction, and hence the forward current exceeds the reverse current. This results in thermophotovoltaic operation. On the other hand, if the external environment is lower in temperature than the diode, the reverse current is greater than the forward current, resulting in thermoradiative operation.

Thermoradiative cells thus produce power in reverse bias (*i.e.,* the 2nd quadrant of the IV curve), rather than in forward bias (the 4th quadrant of the IV curve), as photovoltaic cells do. This has the result that the bias voltage at the maximum efficiency point is not the same as the bias voltage for maximum power output.

II.B.2. Shockley-Queisser Analysis

The maximum power operating point can be calculated in the Shockley-Queisser limit, in which only the losses intrinsic to the process are considered. In this limit, all of the thermal emissivity from the cell is due to band-to-band recombination of carriers.

We consider an ideal diode, but remove the assumption of thermal equilibrium of the diode with its surroundings and consider a diode at a higher temperature than the background. In the limit that the background temperature is zero (or negligible compared to the diode temperature), then at a bias voltage V, the thermal dark current is:

$$I(V) = I_o e^{-(qV/kT)} \tag{1}$$

where the applied (bias) voltage is V, k is the Boltzmann constant, I_o the dark saturation current, and T the diode temperature. The power output is then simply the current times the voltage:

$$P(V) = VI_o e^{-(qV/kT)} \tag{2}$$

The maximum power voltage is found by taking the derivative with respect to voltage and setting this to zero, with the result for the maximum power voltage:

$$V_{mp} = kT/q \tag{3}$$

In this ideal case, then, the operating voltage for maximum power will be ~ 25 mV for a thermoradiative cell operating at room temperature, rising to ~ 100 mV for a cell operating at 900°C.

For the case where the external temperature is not negligible, the thermophotovoltaic current must be subtracted from the dark current in equation 1. This shifts the maximum power point to slightly lower voltage.

It should be emphasized that the maximum power point is not the operating point which maximizes efficiency. The maximum efficiency operating point will be at a much higher (negative) bias than the maximum power point. This is because the energy generated per injected carrier is proportional to the voltage, while the power lost to radiation is independent of the voltage.

However, since the current drops off exponentially at bias voltages more negative than the maximum power point, the power produced drops quickly toward zero. The theoretical maximum efficiency occurs at a point where the power output is near zero. A real-world converter would be operated close to the maximum-power bias, and thus the analysis here is for the maximum power, rather than the maximum efficiency, bias.

II.B.3. Bandgap

A similar analysis can be done for the bandgap. In the Schockley-Queisser limit at zero external temperature, an optimum bandgap to maximize the power does not exist. However, the power output drops quickly as the semiconductor bandgap rises above the bias voltage, while the power is only weakly dependent on bandgap for values less than the bias voltage. The result is that even in the ideal limit, practical considerations determine the useable bandgap should be near, or slightly below, the thermal voltage kT. For non-zero external temperature, light-generated current due to the external infrared subtracts from the thermoradiative current at low bandgaps, again driving the optimal bandgap toward E_g = kT.

The net result is that the optimum semiconductors are low bandgap materials, with bandgaps in the range from about 0.025 eV, for cells operating near 300 K, to perhaps 0.1 eV for cells operating near 1200K. This is the range of bandgaps used for long-wave infrared (LWIR) detectors. Since the highest efficiency photovoltaic cells are in the single-crystal III-V family of semiconductor, it is reasonable to look for the optimum efficiency for thermoradiative cells in the III-V family as well. In the III-V family, however, only a small number of materials have bandgaps in this range, with room-temperature bandgaps of InSb at 0.17 eV and InAs at 0.35, with the intermediate ternary compound $InAs_{0.4}Sb_{0.6}$ having at a bandgap of 0.1 eV. Bandgap narrowing with temperature will reduce these values toward the required range, with InSb decreasing by about 0.42 meV/K and InAs decreasing about 0.47 meV/K. The quaternary semiconductor family of composition $Ga_yIn_{(1-y)}As_xSb_{(1-x)}$ is also a possibility. In the II-VI family, mercury-cadmium telluride devices are used for LWIR sensors, and the semiconductor can be produced at bandgaps that can be engineered between 0 and 1.5 eV, covering the range of interest.

II.C Efficiency Losses

II.C.1. Efficiency Losses

Real world devices will not be ideal, but will have additional losses not accounted for in the Shockley-Queisser limit. These will include both operational losses in the diode itself, and efficiency losses due to channels for heat loss other than the flow of dark current across the junction.

In principle, the non-ideal diode losses can be minimized by producing a high-quality crystal with few defects. Efficiency losses due to external channels for heat flow, “parasitic thermal loss”, will have the effect of not changing the output power at a given temperature, but will reduce the efficiency by requiring a higher input power to achieve the same temperature. Since the parasitic thermal losses reduce efficiency, but not power output, adding parasitic thermal losses does not change the optimum bias point.

II.C.2. Efficiency

In the ideal limit, a thermoradiative converter that has an unobstructed view to radiate to deep space with no objects that emit infrared radiation in the field of view can approach the Carnot efficiency limit for a cold side of the thermodynamic cycle at the effective temperature of deep space (typically around 10 K). However, this theoretical efficiency ignores losses, and occurs near zero power output.

Strandberg's 2015 analysis [2], for example, showed a conversion efficiency as high as 68% for a converter operating between a hot temperature of 1000K and a cold temperature of 300K, but for operation far away from the peak-power bias point, at an unrealistic power output of fractions of a milliwatt per square meter. For operation near the peak-power point, calculated conversion efficiency was about 22%. Likewise, Fernández [7] calculated efficiencies at the maximum power point between 20% and 22.5% (depending on assumptions) for similar conditions (in this case for a bandgap slightly above the optimum).

Such efficiency, if achievable, would considerably improve on the performance of existing solid-state conversion, thermoelectric devices, which typically operate at about 6% conversion efficiency in space. However, it remains to be seen whether the diode performance of non-ideal diodes and the parasitic thermal losses can be made low enough to achieve real-world conversion efficiency near these values.

III. APPLICATIONS

Thermoradiative conversion could, in principle, be used for energy conversion for any thermal source.

The original proposals for applications of this technology were for terrestrial applications. Terrestrial applications, however, are far from ideal for this technology, for numerous reasons. Radiative heat rejection on Earth does not have access to the heat sink of deep space, since the atmosphere is not infrared transparent, and thus the effective temperature of the heat sink is at best 200K, for the case of a clear night sky with low humidity, and in most applications much higher. This results in a downward infrared flux which cancels out part of the upward radiation driving the cell current. On the other hand, non-radiative heat rejection is easily achieved on Earth, with either cooling water or simply convective heat transfer to the atmosphere, and there would be little reason to choose a technology that requires a radiative heat sink.

For space applications, however, there is no atmosphere separating the radiator from the heat sink of deep space, while convective heat sinks are in general not available. Thus, in-space applications are ideally suited for this technology. The choices for a heat source would be either a radioisotope (*e.g.*, Pu-238) or a nuclear reactor.

Planetary surface applications may be less well suited. Planetary bodies with atmospheres (Venus, Mars, Titan) will have convective cooling that represents a heat loss (and consequently efficiency loss) that can be large compared to the radiative heat transfer. And the infrared opacity of the atmospheres will mean that the cold side temperature will be the atmospheric temperature, rather than the much lower temperature of deep space.

Surfaces of bodies with no atmosphere (moons, asteroids) may be suitable, with the understanding that the radiating surface must be in the dark, and with no warm objects in the field of view. This would make it difficult to operate a thermoradiative converter on the moon during the lunar day, for example, where the radiating surface must be simultaneously shielded from the sun, the Earth, and the hot lunar surface. Further out in the solar system, for example Ceres, the surface temperature will be low enough that the infrared output may not be significant, and the radiating surface will only need to be shielded from the sun.

Thermoradiative converters have also been proposed as a technology to scavenge waste heat from other processes, and convert it to useful power [10]. This is an attractive proposition because the bound to conversion efficiency is the Carnot efficiency, and since for a thermoradiative cell the cold side temperature is deep space, the theoretical efficiency of converting waste heat at low-temperatures (300-400K) is not significantly lower than the efficiency of converting high-temperature heat at 1000K, since even the "low" temperature is well above the cold side temperature of ~10K. However, the actual power density will be much lower at the lower temperatures, since the Stefan-Boltzmann law limits the radiation. However, the simplicity of the device may make this attractive in some circumstances.

Finally, since the thermoradiative arrays are not only energy converters, but simultaneously heat radiators, it is attractive to consider thermoradiative conversion as a "bottoming cycle" for other conversion methods. A thermoradiative array could be used as the radiator for the waste heat from some other converter (for example a Stirling engine or a Brayton converter), and generate additional power from that heat. Here also, the fact that the efficiency does not drop at low temperatures works in our favor; a temperature that would be considered a cold-side temperature for a Stirling engine would still function as a hot-side temperature for a thermoradiative device. However, thermoradiative converters are less efficient than blackbodies as radiators, and hence the radiator area may be larger than a conventional radiator.

Another possibility would be to use thermoradiative converters on the reverse (non-sun-facing) side of a solar array, picking up the waste heat from the array and generating power, essentially acting as a bottoming cycle for the photovoltaic conversion. For this to be done efficiently, the front surface of the array would have to be low emissivity, and hence a new front-surface protection would have to be developed, since conventional silica-based coverglass is emissive in the IR. This would increase the temperature of the array slightly, but assuming that the efficiency of the thermoradiative device is not small compared to that of the photovoltaic device, the loss of power due to the higher photovoltaic operating temperature would be small compared to the energy that could be gained.

IV. ROADMAP OF RESEARCH NEEDS

At the moment, thermoradiative technology is at a low state of development, with devices demonstrating the basic physics, but not yet ready for use.

To bring the state of research toward practical applications, a number of research items need to be addressed:

1. *Demonstrating real-world devices*. To date, proof-of-concept devices have been made at very small areas, but high efficiency has yet to be demonstrated. We need to prove these devices in the real world.
2. *Manufacturing large-area low-bandgap cells*. Existing work on low-bandgap materials is in very small area devices, with little or no research on the large area devices that would be needed for practical applications.
3. *Parasitic thermal losses*. The detailed-balance calculation of conversion efficiency assumes all of the thermal emissivity is due to band-to-band radiative recombination. This is unrealistic: there will be other thermal losses, particularly non-radiative emissivity. We need to understand sources of emissivity and learn how to minimize them.
4. *Operating low-bandgap materials at high temperature*. Power output rises with temperature. We need to learn how to operate low-bandgap devices at high temperatures. To date little or no work has been done on developing materials characteristics and ohmic contacts for high-temperature operation.
5. *Encapsulation*. Like solar cells, thermoradiative devices will need to be protected from the space environment. Since glass is opaque to light in the thermal infrared spectrum, new encapsulation techniques will be required.
6. *Integration into arrays and integrating arrays into systems*. Once thermoradiative devices are developed, a systems-level analysis needs to be done to determine which applications most fit the unique benefits and constraints of the technology, and systems designed to use the arrays.

V. CONCLUSIONS

Thermoradiative conversion represents a new method of converting heat energy to electrical power, using solid state devices with no moving parts. This may have useful applications in space.

The potential efficiency of these devices makes them competitive with (and potentially superior to) the existing solid-state heat-conversion technologies, thermoelectric and thermophotovoltaic conversion. Unlike those conversion approaches, in which separate radiators are required to eject the waste heat, and for which increasing radiator temperature decreases power output, a thermoradiative converter is itself the radiator, and higher radiator temperatures increase the power output.

However, a large number of research questions remain to be addressed before this technology is ready for flight.

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