Power extraction from a thermoradiative operation and its possible applications

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Abstract

Solar power operation has been a significant source of renewable energy; however, it is limited to only day-time production. This talk will focus on a p-n junction device, called the thermoradiative (TR) diode, that is similar to a photovoltaic (PV) cell in basic architecture but works in the reverse in that it generates power from viewing a cold environment such as the night sky. As the 2nd law of thermodynamics indicates that a heat engine can extract power from any temperature difference when heat flows from a hot to a cold surface, this work demonstrates practical evidence that such a TR device can produce quantifiable power by radiating heat as infrared thermal emission. We experimentally show that when an infrared photodiode, maintained at ambient temperature, is exposed to a cold emissive surface, it can yield electric power from positive current and negative voltage (opposite to that of a PV cell) under TR operation when variable passive loads are connected externally. For a maximum of 12.5^{o}C temperature difference below ambient temperature (20.5^{o}C), we could find an extractable power of 2.26mW/m^2.

Concept

A thermoradiative (TR) device has the same p-n architecture as photovoltaic (PV) cells, but unlike a PV device, it is operated at an elevated temperature compared to its surroundings. Hence, instead of being illuminated by a hot photon source, a TR diode radiates to a colder environment. This negative illumination of the diode results in the net emission of above-bandgap thermal photons, causing a depletion of minority carriers by radiative recombination. This indicates a splitting of quasi-Fermi levels and device voltage opposite to a PV cell. Thus, the IV curve for a PV cell occupies the 4th quadrant (bottom right) of an I-V chart (-I, +V), whereas that of a TR cell operates at the 2nd quadrant (top left) of the plain (+I, -V) as shown in Figure 1.

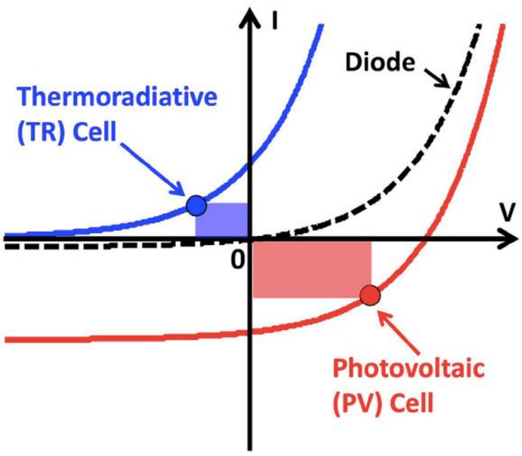

Figure 1. Schematic representation of the Current-Voltage characteristics of photovoltaic and thermoradiative devices

Background

A large amount of work has gone into developing and improving photovoltaic PV cells. In comparison, the concept of a thermoradiative (TR) device is recent. The idea of this kind of device has only been recognized in the last decade when the theoretical possibility of electricity generation from Earth's mid-infrared thermal emissions into outer space was proposed in 2014 [1] with the discussion of emissive energy harvesters (EEH) that can transfer heat from a heat sink to a cold reservoir, i.e., the sky, and convert part of the heat flow into useful work. Based on the EEH concept, a detailed description of the TR working principle was established with the estimation of power conversion efficiency and the output power density. [2] TR performance was evaluated by analyzing the thermodynamic limit of such a device and the impact of non-radiative processes. [3] A recent work measured the negative short circuit current of the TR device experimentally and calculated an output power of 1pW with a 10K temperature difference below the emissive body temperature, [4] but it did not directly measure a photovoltage at a finite current, i.e., power generation. In our work, [5] we explicitly measure the current-voltage characteristic of the TR device and thus demonstrate power generation.

Experimental setup

We used an infrared HgCdTe (MCT) photodiode (VIGO's PVI-5-1x1-TO39-wNone-36) that was facing a temperature-controlled infrared emissive surface through its mounted hyperhemispherical lens (Figure 2). An optical chopper at a rotating frequency of 73Hz was placed between diode and surface to conduct a lock-in measurement of the output voltage. The emissive surface was set at a distance from the diode such that the field of view of the diode is taken up entirely by the emissive surface.

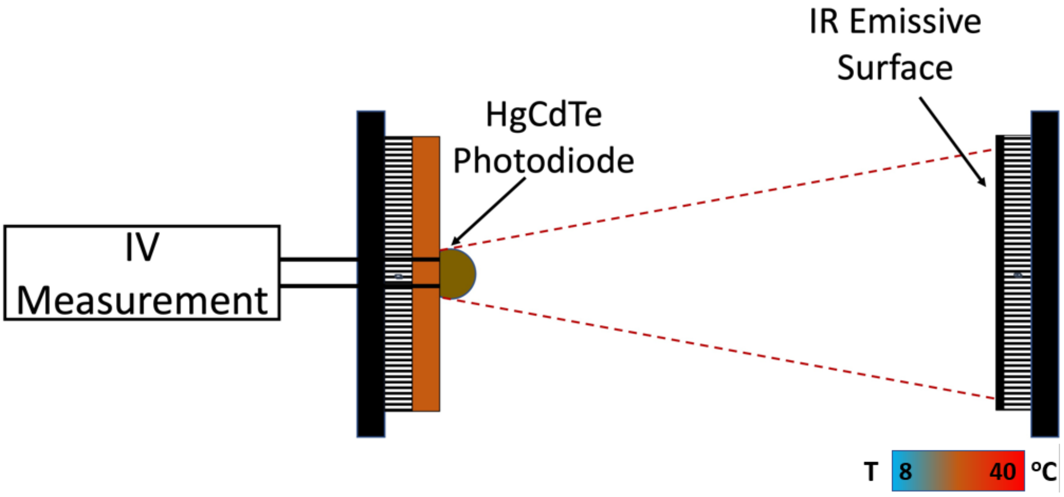

Figure 2. Diagram of the experimental setup

The temperature of the diode was kept at 20°5C whereas the temperature of the surface was controlled between 40°C and 8°C. The diode was connected to a passive variable load, from which the voltage across the load was measured by a lock-in amplifier. The I-V curve was traced with the help of varying resistances acting as loads.

Results and discussion

Figure 3(a) shows the passively measured current-voltage characteristics in both PV and TR mode at varying emissive surface temperatures. In both operations, the IV curves are linear, as expected for a device with a realistic luminescence extraction efficiency [6], and consistent with the dynamic resistance of the diode at room temperature (measured to be 56 Ω).

As in any heat engine, the higher the temperature gradient, the higher the work done as shown by Figure 3(b) where the extracted power density increases with increased temperature difference from room temperature. Our data shows a maximum of 2.26mW/m^2 for a temperature difference of 12.5°C below the room temperature (20.5°C), in accordance with theoretical fitting that take nonradiative recombination in MCT and the external quantum efficiency of the diodes into account.

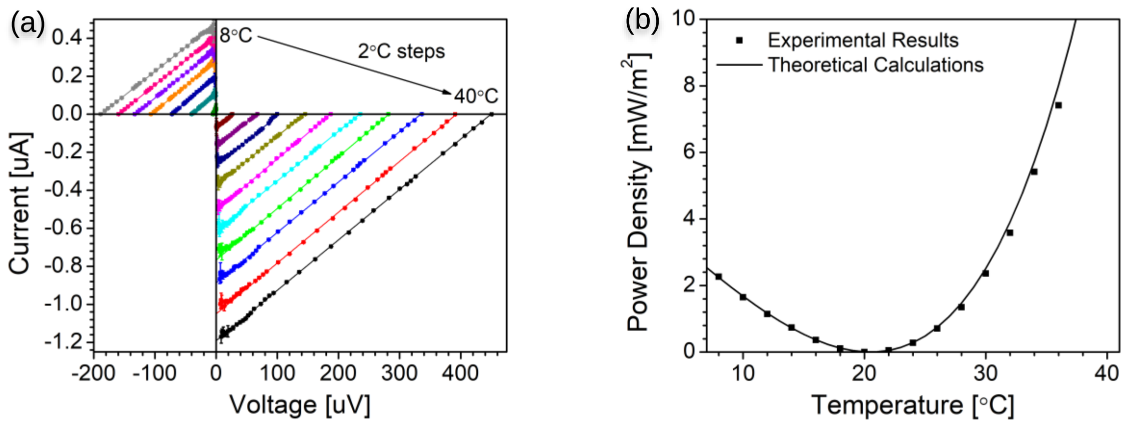

Figure 3. (a) Current-Voltage characteristics of the photodiode both in photovoltaic and thermoradiative mode depicted in the IV plan, (b) Extracted power density as a function of emissive surface temperature

Applications

Thermoradiative diode can have a suitable application for nighttime power generation using the sky as a heat sink option. The high temperature difference between the earth surface (293K) and the sky (~3K) makes the energy harvesting much easier. For the same reason, this technology can be very useful for the deep space exploration as a secondary power source. Alike the thermophovoltaic, thermionic or thermoelectric operation, the TR concept can also be applied for low grade waste heat recovery.

References

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