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Hybrid thermionic-photovoltaic converter

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A conceptual device for the direct conversion of heat into electricity is presented. This concept hybridizes thermionic (TI) and thermophotovoltaic (TPV) energy conversion in a single thermionic-photovoltaic (TIPV) solid-state device. This device transforms into electricity both the electron and photon fluxes emitted by an incandescent surface. This letter presents an idealized analysis of this device in order to determine its theoretical potential. According to this analysis, the key advantage of this converter, with respect to either TPV or TI, is the higher power density in an extended temperature range. For low temperatures, TIPV performs like TPV due to the negligible electron flux. On the contrary, for high temperatures, TIPV performs like TI due to the great enhancement of the electron flux, which overshadows the photon flux contribution. At the intermediate temperatures, ~ 1650 K in the case of this particular study, I show that the power density potential of TIPV converter is twice as great as that of TPV and TI. The greatest impact concerns applications in which the temperature varies in a relatively wide range, for which averaged power density enhancement above 500% is attainable. © 2016 AIP Publishing LLC.
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There exist two main kinds of high-temperature solid-state heat-to-electric converters, namely: thermophotovoltaics (TPV)^{1,2} and thermionics (TI).^{3,4} Each of them differentiates on the kind of heat carriers, i.e., electrons (TI) and photons (TPV). In TPV (TI), the photons (electrons) emitted by an incandescent emitter (cathode) are absorbed by a photovoltaic cell (anode) and converted into (delivered as) external electrical current. The main fundamental drawback of both the converters is the relatively low output power density, which is ultimately limited by the heat transfer capacity of the heat carriers.

A few concepts have been proposed to enhance the power density, mostly for TPV converters: In micron-gap TPV, the TPV cell is located at micro/nano-metric distances from the emitter, enabling the transmission of the evanescent photonic modes.^{5,6} Other ideas are light-pipe TPV (LTPV)⁷ and thermophotonics (TPX).⁸ LTPV uses a medium with refraction index greater than one in between the emitter and the cell and TPX uses a biased LED as thermo-luminescent emitter. These concepts currently face very challenging practical issues, e.g., a robust spacing arrangement (micron-gap devices), material degradation and conduction losses (LTPV), or too low external electroluminescence efficiency (TPX).

In this paper, I present a conceptual device that hybridizes TI and TPV in a single TI-TPV (TIPV) solid state device for direct heat-to-electricity energy conversion. TIPV uses two kinds of heat carriers simultaneously (electrons and photons), which enables a significant enhancement on the heat transfer and the output power density of the converter.

A TIPV converter comprises three elements: emitter, collector, and TPV cell (Figure 1). The emitter is a refractory material that reaches high temperature upon external heating and subsequently radiates electrons and photons. The electrons are absorbed by the collector, a low work-function and partially transparent material located in between the emitter and the TPV cell. The photons pass

through the collector and reach the TPV cell, where they are converted into electricity.

The collector is a key element of this device, which must be optically transparent and have a low work function simultaneously. This element could be directly stacked onto the TPV cell (monolithic TIPV), or arranged independently as a separate element. Previous works have explored the possibility of fabricating transparent collectors using very thin metallic layers on sapphire.⁹ Other possibilities include using relatively simple elements, such as metallic grids, or some more sophisticated such as low work function transparent conducting oxides (TCO), or negative electron affinity (NEA) semiconductors,^{10,11} such as cesiated GaN and AlN.¹²

Two possible arrangements for the TIPV device are shown in Figure 1: three-terminal and two-terminal. The former uses independent connections for TI and TPV converters, and therefore, they can be biased independently in their respective maximum power points (MPP), at the expense of that current must flow laterally in the collector, which could produce important resistive losses depending on the particular collector implementation. In the two-terminal arrangement, the TI and TPV converters are internally connected in series; thus, the current passing through both the devices must be identical. This arrangement notably simplifies the device design at the expense of hindering the simultaneous MPP operation in both the devices.

Notice that TIPV concept could be further generalized by using a semiconducting emitter or an LED, as it is the case of PETE¹³ or TPX⁸ devices, respectively. For the sake of concreteness, these structures are not analyzed in this letter. It is also worth mentioning that other kinds of combinations of PV and TI have been proposed in the past.^{13–15} However, those devices are conceived for different applications, none of them being aimed at increasing the output power density of a heat-to-electric conversion process, as it is the case of the device described in this letter.

FIG. 1. Bandgap diagram of the hybrid thermionic-photovoltaic (TIPV) converter.

The emission of electrons and photons from a surface is governed by the Richardson-Dushman and the Plank law equations,^{8,9} respectively,

$$J_{el}(\phi, T) = AT^2 \exp(-\phi/kT), \quad (1)$$

$$J_{ph}(\epsilon_1, \epsilon_2, T, \mu) = \frac{2\pi}{h^3 c^2} \int_{\epsilon_1}^{\epsilon_2} \frac{\epsilon(\epsilon) \epsilon^2}{\exp[(\epsilon - \mu)/kT] - 1} d\epsilon. \quad (2)$$

The Richardson-Dushman equation (Eq. (1)) determines the electron flux emitted from a surface with work function ϕ at temperature T , being A a constant that ideally takes the value $A = 120 \text{ A/cm}^2\text{-K}^2$.⁴ The Plank law (Eq. (2)) provides the photon flux (#photons/cm²) within the photon energy interval (ϵ_1, ϵ_2) radiated from an (isotropic) surface with an emissivity $\epsilon(\epsilon)$, electrochemical potential μ (in the case where this surface emits photons due to chemical reaction, such as the electron-hole pair recombination existing in PV devices), and temperature T .¹⁶ In this study, we will make $\epsilon(\epsilon) = 1$ for the sake of simplicity.

Within the TIPV converter (Figure 1), an exchange of photons and electrons exists between the emitter and the collector/TPV cell. This exchange is balanced, so that maximum electrical work is extracted from the device by the external electric current. Assuming ideal behavior for both

TI and TPV converters, the external current density for each kind of device is given by

$$J_{TI} = \begin{cases} J_{el}(\phi_e, T_e) - J_{el}(\phi_e - qV_1, T_c) & \text{if } qV_1 \leq \phi_e - \phi_c \\ J_{el}(\phi_c + qV_1, T_e) - J_{el}(\phi_c, T_c) & \text{if } qV_1 \geq \phi_e - \phi_c, \end{cases} \quad (3)$$

$$J_{TPV} = qJ_{ph}(\epsilon_G, \infty, T_e, 0) - qJ_{ph}(\epsilon_G, \infty, T_c, qV_2). \quad (4)$$

Eq. (3) provides the ideal TI current density as a function of the voltage V_1 . This equation neglects any kind of space charge effects or positive ion emission from the emitter.⁴ Eq. (4) provides the ideal TPV current density as a function of the voltage V_2 and it assumes that 100% of sub-bandgap photons are recycled (turned back to the emitter) by means, for instance, of a reflector in the back side of the TPV cell.¹⁶ It also assumes that 100% of TPV cell recombination is radiative and that external quantum efficiency equals one for photon energies greater than ϵ_G .

The assumptions listed above are acceptable for the aim of this study, which is to introduce the concept and explore its potential. A more thorough analysis will be required though to explore the effect of each parameter in detail, and to evaluate the impact of other kinds of parasitic losses.

The maximum power density is calculated for each independent converter by maximizing the products $J_{TI}V_1$ and $J_{TPV}V_2$ in equations 3 and 4, respectively. In the case of two-terminal device (Figure 1), both TPV and TI devices are series connected and consequently the calculation must take into account that their currents must be equal $J_{TI} = J_{TPV}$. Finally, the conversion efficiency is obtained by dividing the output power by the amount of heat being transferred between the emitter and the converter. Therefore, we can define the following three efficiencies:

$$\eta_{TPV} = P_{TPV}/Q_{ph}, \quad (5)$$

$$\eta_{TI} = P_{TI}/Q_{el}, \quad (6)$$

$$\eta_{TIPV} = P_{TIPV}/(Q_{ph} + Q_{el}), \quad (7)$$

where Q_{el} is the net energy carried by the electron flux between the emitter and the collector⁴

$$Q_{el} = \phi_{max} J_{TI} + \frac{2k}{e} (J_{el}(\phi_e, T_e) T_e - J_{el}(\phi_e - qV_1, T_c) T_c) \quad (8)$$

and Q_{ph} is the net energy carried by the photon flux¹⁶

$$Q_{ph} = \frac{2\pi}{h^3 c^2} \left[\int_{\epsilon_G}^{\infty} \frac{\epsilon^3}{\exp[\epsilon/kT_e] - 1} d\epsilon - \int_{\epsilon_G}^{\infty} \frac{\epsilon^3}{\exp[(\epsilon - qV_2)/kT_c] - 1} d\epsilon \right]. \quad (9)$$

ϕ_{max} in Eq. (8) is the maximum value of the inter-electrode motive, which in this idealize device equals the maximum of either ϕ_e or $\phi_c + qV_1$.

The idealized model of the TIPV device described above has been used to analyze a particular TIPV design case. I have chosen constant values for the emitter and collector work functions: $\phi_e = 2.5 \text{ eV}$ and $\phi_c = 1.5 \text{ eV}$, respectively.

FIG. 2. Power density of TIPV, TPV, and TI converters as a function of the emitter temperature.

These values have been chosen taking into account the achievable range of work functions for cesiated metals, typically used in thermionic applications. The semiconductor bandgap (0.687 eV) has been optimized in order to obtain the maximum power density at 1700 K for a two-terminal TIPV device. This bandgap value is provided by typical TPV semiconductor materials such as GaSb or InGaAs. Both the ionic collector and TPV cell are assumed to operate at 300 K.

Figure 2 shows the maximum power density of both three-terminal and two-terminal (Figure 1) TIPV converter superimposed to the power density attainable by using single TPV and TI converters. We see that three-terminal TIPV provides the highest power density in the broadest temperature range. For high temperatures, TIPV approaches the TI performance, while at low temperatures, TIPV approaches that of TPV. At intermediate temperatures (around 1650 K), TIPV provides twice as great power density as that of the independent TPV and TI devices. This is more clearly seen in Figure 3, where power density is shown normalized to that of three-terminal TIPV device. In this figure, we see that there exist a relatively wide range of temperatures for which three-terminal TIPV makes a significant improvement in the power density with respect to independent TPV and TI converters, e.g., an average increment of $\sim 500\%$ if the

FIG. 3. Power density of 2-terminal TIPV, TPV, and TI converters normalized to the power density of three-terminal TIPV device.

temperature oscillates in the range of 1400–2000 K, such as in latent heat thermal energy storage (LHTES) applications.¹⁷

On the other hand, a two-terminal TIPV device could be beneficial or disadvantageous, depending on the temperature range of operation: if $T > 1580$ K ($T < 1780$ K), two-terminal TIPV produces higher power density than independent TPV (TI). Otherwise, independent TPV (if $T < 1580$ K) or TI (if $T > 1780$ K) produces higher power. In particular, at 1700 K, both two-terminal and three-terminal TIPV perform identically due to the current-match achievement at the maximum power points of the independent TPV and TI converters. Thus, two-terminal TIPV converter is well suited for the applications with constant operation temperature, such as waste heat recovery in industry.¹⁸

Figure 4 shows the J-V curve of both TPV and TI independent converters for two emitter temperatures. At 1600 K, a case is shown in which TPV outperforms TI, while at 1750 K, TI outperforms TPV. Precisely, at 1700 K (design case), both TPV and TI converters produce the same current density in the MPP.

Conversion efficiency is shown in Figure 5. As expected, the three-terminal TIPV converter approaches the conversion efficiency of TPV (TI) at low (high) temperatures. This is because the electron (photon) flux becomes negligible at those low (high) temperatures, and consequently the three-terminal TIPV device performs identically than a single TPV (TI) converter. In the case of two-terminal TIPV device, this situation is different because one of the two sub-devices is current limited by the other (except at 1700 K), i.e., at low (high) temperatures, the TPV (TI) device is current limited by the TI (TPV) device. This explains the lower efficiency for temperatures below 1700 K. For higher temperatures, the efficiency of two-terminal TIPV increases above that of the three-terminal TIPV device. This is explained by the higher TI voltage V_1 required to reduce the current of the TI sub-device to equal that of the TPV converter. It is well known that increasing the voltage in ideal TI converters above MPP reduces the electron flux, and consequently, the efficiency increases, at the expenses of vanishingly small heat exchange and output power. From this behavior, we observe another potential advantage of the three-terminal TIPV device, which is the possibility of quickly modulating the

FIG. 4. J-V curves of TPV and TI converters for three different emitter temperatures.

FIG. 5. Conversion efficiency of TIPV, TPV, and TI converters as a function of the emitter temperature. Collector/TPV cell temperature is 300 K.

output power at a constant source temperature, with a minimum impact on the conversion efficiency.

Finally, it is also worth noting that, from a practical point of view, TIPV advantages TI due to the lower amount of heat that must be rejected from the cold side of the device. This should facilitate reaching lower collector temperatures and higher efficiencies for the TI part.

In summary, a conceptual device that hybridizes TI and TPV converters has been presented. Based on the idealistic device performance assumptions, I have shown that this device is able to produce higher power density in a broader temperature range than thermophotovoltaic or thermionic converters operating independently. The proposed TIPV converter takes advantage of both the photon and electron fluxes outgoing from the emitter, which notably enhances the heat flux and the output electrical power of the device. The key element of the device structure is the collector, which must be optically transparent and have a low work function simultaneously. Possible practical implementations of this element include low work function transparent conducting oxides, metallic grids, or wide-bandgap semiconductors with a negative electron affinity, such as cesiated GaN or AlN.

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