INTRODUCTION

In thermophotovoltaic (TPV) energy conversion, a heat source is employed to maintain a radiator at a specified temperature, which in turn emits thermal radiation toward a cell generating electricity. In order to potentially improve the power output and conversion efficiency of TPV systems, Whale and Cravalho [1] proposed to separate the radiator and TPV cells by a sub-wavelength vacuum gap. At sub-wavelength distances, radiation heat transfer is in the near-field regime, such that the energy exchanges can exceed the values predicted for blackbodies. For thermal radiation temperatures, the near-field effects become dominant when the bodies are separated by few tens of nanometers. Therefore, a TPV system using the near-field effects of thermal radiation is referred hereafter as a nanoscale-gap TPV (nano-TPV) device. While the literature has clearly shown that the near-field effects of thermal radiation can substantially improve the electrical power output of TPV systems [1-3], some important questions about the feasibility of nano-TPV energy conversion are still unanswered. In this work, we aim to study the energy required for maintaining the TPV cells at room temperature via the analysis of the thermal effects in nano-TPV devices. For purpose of comparison with the literature, we study systems based on In_{0.18}Ga_{0.82}Sb cells [3].

EVALUATION OF NANO-TPV SYSTEM PERFORMANCES

As shown in Fig. 1, a bulk radiator (tungsten W, \(T_0 = 2000\) K) and a TPV cell (In_{0.18}Ga_{0.82}Sb, bandgap \(E_g\) of 0.56 eV at 300 K) are separated by a sub-wavelength vacuum gap of length \(d_c\). The TPV cell consists of a single p-n junction, where the thicknesses of the p-doped and n-doped regions are given by \(t_p = 0.4\) \(\mu\)m and \(t_n = 10\) \(\mu\)m [3]. As the TPV cell is likely to heat up from various sources (absorption by the free carriers and the lattice, non-radiative recombination and thermalization [4]), a thermal management system is used to maintain the p-n junction around room temperature. The cooling system is modeled as a convective boundary with a fixed temperature \(T_\infty = 293\) K and a heat transfer coefficient \(h_\infty\). The performances of the nano-TPV device are evaluated through the solution of the coupled near-field thermal radiation, charge and heat transport problem. The mathematical details as well as the modeling of the optical, electrical and thermophysical properties are given in reference [4].
When the temperature of the cell is varied artificially (i.e., the energy equation is not solved), it can be observed in Fig. 2(a) that thermal radiation absorption increases slightly as the temperature of the cell increases mostly due to the fact that $E_g$ decreases. On the other hand, the electrical power output $P_m$ decreases significantly when $T_{cell}$ increases, regardless of the gap $d_c$. For example, the conversion efficiency $\eta_c$ is 24.8% when $d_c = 20$ nm and $T_{cell} = 300$ K, a value that drops at 3.23% when $T_{cell} = 500$ K.

Figure 2(b) shows that the short-circuit current $J_{sc}$ slightly varies with $T_{cell}$, while the open-circuit voltage $V_{oc}$ significantly decreases with increasing $T_{cell}$ (due to an increasing dark current), thus explaining the low $P_m$ and $\eta_c$ values reported above.

Figure 3(a) shows averaged cell temperature $T_{cell,avg}$ as a function of the heat transfer coefficient $h_\infty$ for various gaps $d_c$. The values of $h_\infty$ needed to maintain the TPV cell around 300 K are quite high. Indeed, for a gap $d_c$ of 5 µm, a $h_\infty$ value of $10^4$ Wm$^{-2}$K$^{-1}$ is required to maintain the p-n junction around room temperature, while a $h_\infty$ of $10^5$ Wm$^{-2}$K$^{-1}$ is needed for gaps $d_c$ of 100 nm, 50 nm and 20 nm. Generally speaking, heat transfer coefficients $h_\infty$ up to $10^3$ Wm$^{-2}$K$^{-1}$ can be achieved via free convection, while $h_\infty$ up to about $2\times10^4$ Wm$^{-2}$K$^{-1}$ can be reached by forced convection; heat transfer coefficients above this threshold is possible via convection involving phase change. The results of Fig. 3(a) should not be surprising, since radiation with energy $E$ exceeding the bandgap $E_g$ largely contributes to heat generation in the p-n junction. The use of a bulk radiator in the near-field provides a broadband enhancement of the flux, which contributes
simultaneously to increase the electrical power output and to increase heat generation within the p-n junction.

The electrical power output is presented in Fig. 3(b) as a function of $d_c$ and the heat transfer coefficient $h_\infty$. As expected, the performances of the nano-TPV devices are significantly affected by the thermal boundary condition imposed at $z = Z_4$. For example, when $d_c = 20$ nm, the conversion efficiency $\eta_c$ is 25.4 % when $h_\infty = 10^6$ Wm$^{-2}$K$^{-1}$ ($T_{\text{cell,avg}} = 294$ K), and this value drops at 6.9 % when $h_\infty = 5 \times 10^3$ Wm$^{-2}$K$^{-1}$ ($T_{\text{cell,avg}} = 466$ K).

CONCLUSIONS

The results presented in this work suggest that the performances of the nano-TPV devices proposed so far in the literature are quite low. A potential way to avoid excessive heating of the cell is to design nanostructures selectively emitting thermal radiation in the near-field. The performances of the nano-TPV device discussed here could be analyzed further as a function of the doping levels, the configuration of the cell, the thicknesses of the p- and n-doped regions and the relative proportion of GaSb and InSb. Finally, the impacts of using radiators made of thin films of W should be investigated in a future research effort.

REFERENCES