# Near-Field Thermophotovoltaic Conversion with High Electrical Power Density and Cell Efficiency above 14%

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that near-field thermophotovoltaic converters are now competing with other thermal-to-electrical conversion devices and also pave the way for efficient photoelectric detection of near-field thermal photons.

**KEYWORDS:** Thermal radiation, nanoscale, thermophotovoltaics, conversion efficiency

significant number of experimental demonstrations of the enhancement of thermal radiation heat transfer between hot and cold bodies<sup>1-5</sup> have established a firm basis for new nanoengineered devices based on thermal photons in the near field, involving, for instance, thermal rectification<sup>6</sup> and photonic cooling.<sup>7</sup> In particular, it was predicted 20 years ago that approaching a hot emitter and a photovoltaic cell at nanoscale distances would drastically increase the thermal radiation exchange and, in turn, the electrical power generation by the cell.<sup>8-10</sup> Many theoretical publications have further elaborated on this idea.<sup>11-16</sup> An early experiment<sup>17</sup> qualitatively showed enhancement of the photogeneration of electrical charges at microscale gaps between the emitter and the cell. More recently, three experimental works<sup>18–20</sup> reported on an enhancement of the electrical power in the near field, with estimations of power conversion efficiency hardly reaching 1% and a maximal power density of 0.75 mW cm<sup>-2</sup>. These modest performances indicate that a clear proof of efficient photovoltaic conversion of near-field thermal radiation is still lacking. This is puzzling since ultra-efficient thermophotovoltaics, based on the conversion of radiative heat emitted in the far field, has recently been demonstrated.<sup>21,22</sup> Nevertheless, the electrical power density measured for these far-field devices remains moderate, approaching the W  $\rm cm^{-2}$  level<sup>21-23</sup> only for high-temperature emitters above 1000 °C. The interest for near-field thermophotovoltaic

converters, where the transferred radiative power is much higher, comes from their potential to lead to both significant output power and power conversion efficiency.<sup>24</sup> They could also work with heat sources of lower temperatures.

In the present work, we designed and implemented an experiment to maximize near-field radiative heat-to-electricity conversion from a medium-grade heat source (temperatures in the range 250–650 °C), demonstrating improvements in the three directions (efficiency, power, temperature) and therefore resolving some obstacles to high performance. First, we used a configuration improving the view factor between the emitter and the photovoltaic cell. In the present case, it involves a spherical emitter exchanging radiation with a planar receiver.<sup>1,2,25–28</sup> Our setup allows us to scan a large emitter–cell distance range, from millimeters down to nanometers, and thus to directly compare far-field and near-field configurations. Second, we used photovoltaic cells with specific architectures for efficiently collecting near-field photons. They are made of indium antimonide (InSb), having

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**Figure 1.** Device and simulated radiative heat transfer for near-field thermophotovoltaic conversion. (a) Schematic of the spherical emitter—planar photovoltaic cell device. (b) Scanning electron micrograph of the emitter seen from below. A graphite sphere is glued on the tip of a SThM-doped Si probe with a ceramic adhesive. (c) Optical microscopy top view of an InSb cell having an active area diameter of 160  $\mu$ m. (d) Simulated thermal radiation heat transfer spectrum in the case of an emitter at 732 K and a cell at 77 K for far-field (blue curve) and near-field (red curve) configurations.

a very low bandgap energy (0.23 eV, i.e., 5.3  $\mu$ m, at 77 K) particularly well suited for converting mid-infrared photons typical for thermal radiation. Finally, we identified cell design parameters that allow the maximization of electrical power density and power conversion efficiency.

The experimental setup (see Figure 1) consists of a hot micrometer-sized spherical emitter (Figure 1b) and a micrometer-sized photovoltaic cell (view from top in Figure 1c), separated by a distance that can be varied. It allows for measuring both the radiative power exchanged between them and the electrical power generated by the cell, as a function of the emitter-cell distance. The photovoltaic cell is a p-njunction (Figure 1a) made of InSb, one of the III-V semiconductors with the longest bandgap wavelength. The cell can thus convert thermal radiation with wavelengths in the micrometer range (Figure 1d). The InSb bandgap (bandgap wavelength) depends on temperature and varies from 0.23 eV (5.3  $\mu$ m) at 77 K to 0.17 eV (7.3  $\mu$ m) at room temperature. The photovoltaic cell was specifically designed for harvesting thermal radiation fluxes of medium-grade temperature sources (around 500 °C) in the near field.<sup>29</sup> Its architecture was optimized based on full calculations involving the coupling of electrical charge transport and radiative transfer in a 1D configuration.<sup>29</sup> The p-n junction is located close to the cell top-surface (a few hundreds of nanometers only) to collect a large share of the near-field photons. The size of the cell should match the size of the emitter to avoid nonilluminated zones, which are detrimental to electrical performance. Thus, the active (uncovered, therefore radiation-absorbing) area of the cell (Figures 1a and c) is a few tens of micrometers in diameter in order to optimize the view factor (see Section S1 and Figure S8a). To assess the impact of the view factor, three different active area diameters (160, 80, and 20  $\mu$ m) are considered. Gold layers are used as top and bottom electrical contacts. It is important to note that an InSb *p-n* junction can operate properly only at low temperature.<sup>30</sup> Hence, in this experiment the cell is cooled to 77 K by placing it on the coldfinger of a cryostat located in a vacuum chamber (see Section S1).

The emitter is a graphite microsphere. It is glued to the apex of the probe of a scanning thermal microscope (SThM, see

Figure 1b), which is an atomic force microscope (AFM) with an electrical resistor located on the cantilever.<sup>31</sup> This resistor acts both as a heater and as a temperature sensor. Its variations with temperature are known thanks to a prior calibration procedure. The microsphere is heated by the resistor and its temperature is assumed to be equal to that of the cantilever apex, determined from measurements of the electrical resistance. Knowing the thermal conductance of the cantilever (determined prior to the experiment) and the input current, it is possible to deduce the radiative heat flux lost by the emitter (see Section S1 and Figure S1 for details). Most of the results presented here were obtained for a microsphere temperature of 732 K (459 °C), which maximizes measurement sensitivity, but the microsphere could be heated up to temperatures larger than 1200 K. Graphite was selected for the emitter as this material maximizes the near-field radiative exchange with InSb and the cell efficiency (Figure S3). Figure 1d indicates that about 40% of the overall power exchanged between a planar emitter and a planar receiver is located in the wavelength range that can be converted to electricity. It also shows that reducing the distance between the emitter and the cell strongly increases radiative exchange. However, for the sake of simplicity in this proof-of-concept experiment, we chose a spherical emitter to eliminate parallelism problems inherent to planar configurations, even though at a given distance a stronger near-field exchange would be obtained with a planar emitter instead of a sphere (Figure S3d). Such a geometry was successful for Casimir force and near-field radiative heat flux experiments,<sup>1,2,25-28,31</sup> and it easily allows us to probe an emittercell distance range down to the sub-100 nm region. In the experiment, a spherical emitter is therefore approached in the vicinity of the cell by moving it vertically with a piezo-actuator. We paid particular attention to designing a setup that can probe a large emitter-cell distance range in order to observe the transition between the far and near fields.

Performance of the cells (maintained at 77 K) is first characterized (Figure 2). I-V curves in the dark indicate a low noise level (mA cm<sup>-2</sup>) in the experiments. Remarkably, radiative emission from the ambient environment (far field) at room temperature already leads to a significant production



**Figure 2.** Current–voltage characteristics of a cell at 77 K having an active area diameter of 20  $\mu$ m. *I*–*V* curves (single realizations) measured in dark conditions (black, inset), under the illuminations of the ambient environment at 300 K (blue), and of the graphite microsphere at 732 K in the far field (orange) and at  $d \sim 2 \mu$ m (red). The dark and light gray rectangles represent respectively the maximum output power and the product  $V_{oc}I_{sc}$  used for computation of the fill factor (FF). The inset shows the current in absolute values according to the applied voltage. The curves were obtained for a 500  $\mu$ m-thick InSb substrate and a 10<sup>17</sup> cm<sup>-3</sup> p-doping level. The observed noise (standard deviation, see, e.g., the dark *I*–*V* curve) is 3.5 × 10<sup>-10</sup> A.

of electrical power by the cell. The open-circuit voltage (inset of Figure 2) is found to depend on the temperature of the emitter and also on the emitter–cell distance. For an emitter at 732 K and the smallest emitter–cell distance in Figure 2 (~2  $\mu$ m), it is equal to 127 mV, leading to a remarkable voltage factor ( $qV_{oc}/E_g$ , where  $E_g$  is the bandgap of InSb at 77 K and qthe elementary charge) of 0.55. In contrast to certain previous works,<sup>19,20</sup> the *I*–*V* curves look like typical photovoltaic cell characteristics with high values of the fill factor (0.74 in Figure 2).

The high sensitivity of the electrical power output measurement allows us to follow the approach of the hot microsphere toward the cold cell with distances from millimeters down to the contact. The evolution of the shortcircuit current is measured as a function of the emitter-cell distance characterized by the z-piezoactuator displacement (inset in Figure 3b and Figure S9b). It superimposes nicely on the prediction of the far-field view factor theory at large distances. The near-field contribution is expected to appear below a distance approximately defined by Wien's wavelength  $(\lambda_{\rm W} = 2898/T, \text{ in } \mu\text{m})$  for the emitter, i.e., below 4  $\mu\text{m}$ . At small distances, a deviation from the far-field view factor prediction is indeed observed. Note that the difference between the exact emitter-cell distance and that measured by the vertical piezoelectric actuator can reach up to around 80 nm close to the contact (see Section S7 and Figure S7).

Our setup allows the measurement of both the exchanged radiative power (Figure 3a) and the current–voltage curve as a function of the emitter–cell distance at the same time. As expected, a strong enhancement of the exchanged radiative power is observed for small distances, where it reaches 7.4  $\mu$ W (Figure 3a). Almost all of this increase is due to the near-field



Figure 3. Near-field exchanged radiative power, generated electrical power at the maximum power point, and near-field power conversion efficiency (PCE) obtained simultaneously as a function of emittercell distance (z-piezo position), for a cell at 77 K having an active area diameter of 20  $\mu$ m and for a graphite microsphere emitter at 732 K having a diameter of 37.5  $\mu$ m. (a) Near-field radiative power according to distance. Measurements (blue curve) are compared with calculations (dark-dashed curve) performed in the frame of the proximity approximation. (b) Generated electrical power, deduced from the measurement of I-V curves as a function of distance. The total electrical power (red curve) is compared to the power increase due to the far-field contribution estimated from the view factor (dashed-dotted black curve). The region between the two curves provides the near-field electrical power. The inset data, obtained with another cell, show the match between the view factor computation (plain line) and the experimental data in the far field. (c) Near-field power conversion efficiency (PCE) calculated by dividing the nearfield electrical power (b) by the near-field exchanged radiative power (a). The dark-shaded zones around the mean curve correspond to the standard deviation (SD) (17 measurements in the small-distance regime, with a decaying number when distance is increased, leading to a larger SD). The small SD (<1%) in panel (b) is not represented. The light-shaded zones represent the systematic relative uncertainty of 20% induced by the calibration of the emitter.

contribution, since the gain from the far-field contribution is much weaker in the last micrometers. While the far-field contribution background cannot be directly measured, it is computed to be ~3.2  $\mu$ W for the configuration analyzed in Figure 3 (Section S5).

The generated electrical power at the maximum power point (Figure 3b, red curve) is derived from I-V curves for each emitter-cell distance (Figure S12). It reaches almost 1.3  $\mu$ W at the smallest distance in the selected configuration. By matching the view factor computation (dashed-dotted black



**Figure 4.** Influence of the cell diameter, substrate thickness, and p-doping level on the maximum electrical power for the smallest emitter-cell distances. The dark and light parts are respectively the far-field and near-field contributions. (a) Influence of the cell active area diameter. The electrical power decreases with the cell diameter because less illumination is collected, but the electrical power density increases. (b, left) Influence of the substrate thickness. The maximum electrical power density is observed for the device with the thinnest substrate. (b, right) Influence of the p-doping level. The maximum power density increases with the doping level. The standard deviations are small (less than 1%) and therefore are not represented.

curve in Figure 3b) to the experimental curve at the largest distances, an increase of the electrical power stronger than what standard far-field theory predicts is clearly visible in the sub-3  $\mu$ m region (in yellow). An electrical power 4.6 times larger than the far-field prediction is found, highlighting the power increase due to the near-field radiation transfer.

Power conversion efficiency (PCE) is a common figure of merit to evaluate the performance of TPV cells,  $^{21-23}$  which is different from the device overall efficiency that includes heat source losses and the power required for cooling the cell. The PCE is defined by the ratio of the electrical power to the net radiation heat flux absorbed by the cell. The total PCE, obtained by considering both near- and far-field contributions, is estimated to be about 12% in the experimental configuration of Figure 3. This is one order of magnitude higher than the best value in previous experiments.<sup>18</sup> By dividing the electrical power by the near-field exchanged radiative power at the same distance, a near-field PCE can be determined (Figure 3c). It is found to be in the range of 14–19% close to contact.

Parameters that can improve radiative heat-to-electricity conversion are now analyzed. We underline that the near-field contribution in the sphere-plane geometry is mostly related to optical modes that are evanescent in the gap but propagate in the substrate (frustrated modes, see Figures S5 and S6). First, the effect of the active area diameter of the cell is reported in Figure 4a. A larger share of the exchanged power comes from the near field for the smallest cell (highlighted by the dark orange region) because remote parts of the sphere radiate on the gold coating surrounding the active area, which does not absorb radiation useful for the photovoltaic effect. As a result, the smallest cell performs the best. The generated electrical power is about 2 kW m<sup>-2</sup> (0.2 W cm<sup>-2</sup>), which is three orders of magnitude higher than that of previous reports.<sup>18-20</sup> This highlights the importance of matching the cell and emitter sizes. The influence of two other cell parameters predicted to be critical is analyzed in Figure 4b, namely, the substrate thickness and the p-region doping concentration.<sup>29</sup> When the substrate thickness is decreased from 500 to 200  $\mu$ m (Figure 4b, left), a clear enhancement of the power output is observed in the experiment. By thinning down the substrate of the cell, the near-field efficiency is more than doubled and reaches 14% (see Table S2 and Section S12). Anterior theoretical 1D

analyses predicted that this effect would occur because of lower absorption below the bandgap<sup>29,32</sup> and higher absorption above the bandgap.<sup>29</sup> Measurements show that the efficiency enhancement is the result of a rise in electrical power without any substantial change in the net radiative flux exchanged. 2D effects on radiative transfer and electrical charges transport and the impact of the emitter on external luminescence of the cell<sup>33</sup> can be invoked as possible other explanations. The effect of the doping concentration in the p-region of the junction is finally analyzed. By increasing the dopant concentration from  $10^{17}$  to  $10^{18}$  cm<sup>-3</sup>, an impressive 4-fold enhancement of the electrical power is observed (Figure 4b, right), leading to a record 7.5 kW m<sup>-2</sup> (0.75 W cm<sup>-2</sup>) value for the tested micrometer-sized cells despite the moderate temperature of the emitter (459 °C).

In summary, we have measured photovoltaic conversion of thermal photons in the near field with a cell efficiency above 14% and electrical power densities reaching  $0.75 \text{ W cm}^{-2}$ , close to the  $\sim 1 \text{ W cm}^{-2}$  threshold typical for powerful energy harvesting devices<sup>34</sup> and close to the best far-field thermophotovoltaic performances despite much lower emitter temper-atures. $^{21-23}$  The present approach highlights the possibility of using the photocurrent as a signal for characterization purposes, converting the photons directly close to the surface and therefore acquiring the signature of the sample with superior sensitivity. The experimental setup, intended to measure the increase of electrical power in the near field and the corresponding cell efficiency in laboratory conditions, was not designed for optimizing the global conversion efficiency (see Section S13). Hence, for energy harvesting with a device operating in real conditions as in solar thermophotovoltaics,  $3^{3-37}$  it will be required to upscale the sizes, to mitigate the thermal losses, and to avoid cooling the cell. Our architectures are compatible with more industrial-size implementations involving parallel flat surfaces that were undertaken recently.<sup>38</sup> Recent strategies for designing efficient far-field cells with narrow energy bandgap III–V materials operating at room temperature  $^{39,40}$  can also be applied in the near field with frustrated photon modes and will be particularly useful for harnessing energy of medium-grade heat sources. For high-grade heat sources, we have demonstrated the possibility to maintain a temperature difference larger than 1100 K across

a small distance (Figure S11), so higher energy bandgap materials used in cells operating at room temperature could also be considered with a careful design for the near field. Finally, as a reminder, further enhancement of the performances is predicted for materials with polariton resonances above the energy bandgap.<sup>11,12</sup> This work thus opens the door to efficient exploitation of near-field thermal photons.

## ASSOCIATED CONTENT

#### **Supporting Information**

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.0c04847.

(1) Main experimental methods; (2) selection of the emitter material; (3) sphere-plane vs plane-plane configurations; (4) comparison between near-field thermal radiative measurements and the proximity approximation; (5) contribution of the propagating modes with distance; (6) numerical analysis of the near-field modes and radiative absorption as a function of depth; (7) estimation of the sphere-cell distance close to contact; (8) characterization of the photovoltaic cells; (9) validation of the superposition principle; (10) impact of emitter temperature on power output; (11) impact of emitter temperature on power output; (12) *I*-*V* characteristics and efficiency according to distance; (13) power balance analysis of the experimental setup; and (14) summary of the results (PDF)

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#### **Author Contributions**

R.V., P.-O.C., J.-P.P., E.T., and T.T. conceived and supervised the work. J.-P.P. did the MBE growth of the InSb material and D.C. fabricated the photovoltaic cells. C.L. fabricated the emitter and performed the experiments. C.L. and R.V. performed the simulations. The manuscript was written by C.L., P.-O.C., and R.V. with comments and inputs from all authors.

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#### Notes

The authors declare no competing financial interest.

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