Graphene-based near-field thermophotovoltaic energy conversion systems

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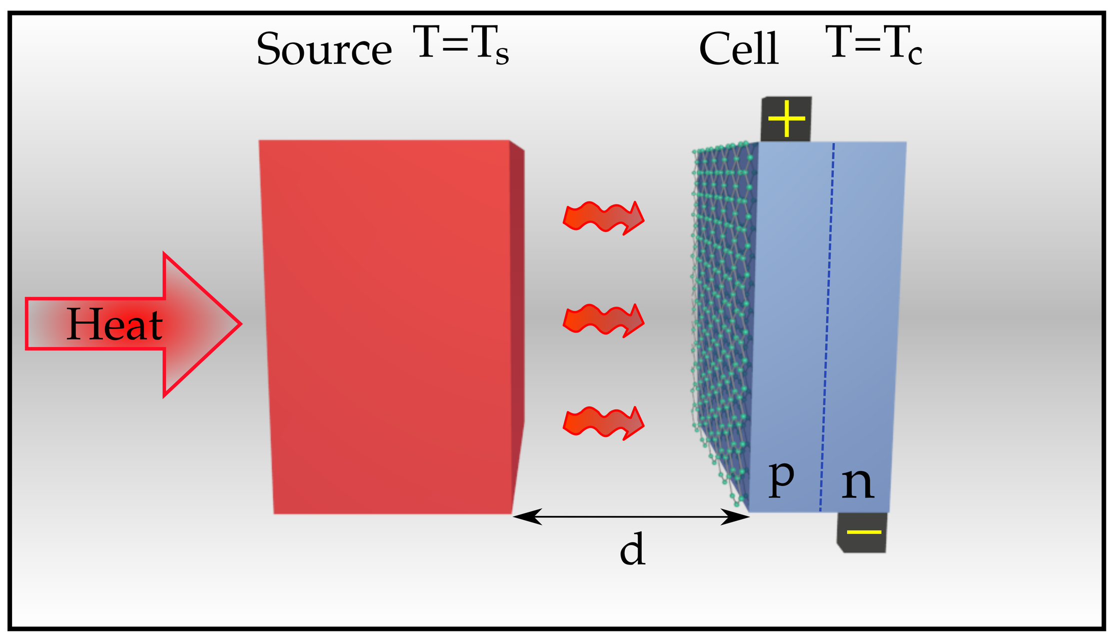
Abstract

Thermophotovoltaic (TPV) devices are energy-conversion systems generating an electric current from the thermal photons radiated by a hot body. While their efficiency is limited in far field by the Schockley-Queisser limit, in near field the heat flux transferred to a photovoltaic cell can be largely enhanced because of the contribution of evanescent photons, in particular for a source supporting a surface mode [1]. This has generated a recent theoretical and experimental interest in near-field TVP devices [2-9]. Unfortunately, in the infrared where these systems operate, the mismatch between the surface-mode frequency and the semiconductor gap reduces the potential of this technology. We propose a modified thermophotovoltaic device in which the cell is covered by a graphene sheet [10]. We show that both the cell efficiency and the produced current can be enhanced, paving the way to promising developments for the production of electricity from waste heat. The results are interpreted in terms of transmission coefficient associated to each field mode.

1. The physical system

Standard thermophotovoltaic cell modified by the presence of a graphene sheet on the interior surface of the cell.



- **Source**: boron nitride (hBN), supporting a surface mode
- **Cell**: indium antimonide (InSb)
- **Graphene** sheet deposed on the cell
- **Temperatures**: $T_s = 450$ K and $T_c = 300$ K

2. Optical description

- **Source**: boron nitride (hBN)

$$\epsilon(\omega) = \varepsilon_\infty \frac{\omega^2 - \omega_L^2 + i\Gamma\omega}{\omega^2 - \omega_R^2 + i\Gamma\omega}$$

with

$$\varepsilon_\infty = 4.48 \qquad \omega_L = 3.032 \times 10^{14}\,\text{rad s}^{-1}$$
$$\omega_R = 2.575 \times 10^{14}\,\text{rad s}^{-1} \qquad \Gamma = 1.001 \times 10^{12}\,\text{rad s}^{-1}$$

$\longrightarrow$ Surface phonon-polariton resonance at frequency $\omega_{\text{spp}} \simeq 2.960 \times 10^{14}\,\text{rad s}^{-1}$

- **Cell**: indium antimonide (InSb)

$$\varepsilon(\omega) = (n_r(\omega) + ic\alpha(\omega)/2\omega)^2 \qquad \alpha(\omega) = \begin{cases} 0 & \omega < \omega_g \\ \alpha_0\sqrt{\omega/\omega_g - 1} & \omega > \omega_g \end{cases}$$

with [11]

$$\omega_g \simeq 2.583 \times 10^{14}\,\text{rad s}^{-1} \qquad \alpha_0 = 0.7\,\mu\text{m}^{-1}$$

- **Graphene**: conductivity $\sigma(\omega) = \sigma_D(\omega) + \sigma_I(\omega)$

Intraband (Drude) contribution

$$\sigma_D(\omega) = \frac{i}{\omega + \frac{i}{\tau}} \frac{2e^2 k_B T}{\pi\hbar^2} \log\Big(2\cosh\frac{\mu}{2k_B T}\Big)$$

Interband contribution

$$\sigma_I(\omega) = \frac{e^2}{4\hbar}\Big[G\Big(\frac{\hbar\omega}{2}\Big) + i\frac{4\hbar\omega}{\pi}\int_0^{+\infty} \frac{G(\xi) - G(\frac{\hbar\omega}{2})}{(\hbar\omega)^2 - 4\xi^2}\,d\xi\Big]$$

where $G(x) = \sinh(x/k_BT)/[\cosh(\mu/k_BT) + \cosh(x/k_BT)]$ and μ is the chemical potential of graphene. Model [12] already used in calculations of heat transfer [8-9].

3. Energy exchange and efficiency

- **Monochromatic near-field heat flux** as a sum of contributions from each mode $(\omega, \mathbf{k}, p)$

$\omega \rightarrow$ frequency $\qquad \mathbf{k} = (k_x, k_y) \rightarrow$ transverse wavevector $\qquad p = $ TE, TM $\rightarrow$ polarization

$$\phi(\omega, d) = \hbar\omega\, n_{sc}(\omega) \sum_p \int_{ck>\omega} \frac{d^2\mathbf{k}}{(2\pi)^2} \mathcal{T}_p(\omega, \mathbf{k}, d) = \hbar\omega\, n_{sc}(\omega) K(\omega, d)$$

$n_{sc}(\omega) = n(\omega, T_s) - n(\omega, T_c)$ $\rightarrow$ difference of thermal populations $n(\omega, T) = (e^{\hbar\omega/k_BT} - 1)^{-1}$

- **Transmission probability** ($\in [0, 1]$) for each mode

$$\mathcal{T}_p(\omega, \mathbf{k}, d) = \frac{4\,\text{Im}(r_{1p})\text{Im}(r_{2p})e^{2ik_zd}}{|1 - r_{1p}r_{2p}e^{2ik_zd}|^2}$$

  - Wavevector perpendicular to the surface $k_z = \sqrt{\omega^2/c^2 - k^2}$
  - Function of the reflection coefficients of source and cell
  - Describes how efficiently each field mode transfers a quantum of energy $\hbar\omega$

- **Radiative power** exchanged and **electric power** produced [9]

$$P_{\text{rad}}(d) = \int_0^{+\infty} \frac{d\omega}{2\pi}\hbar\omega\, n(\omega, T_s)K(\omega, d) - \int_{\omega_g}^{+\infty} \frac{d\omega}{2\pi}\hbar\omega\, n(\omega - \omega_0, T_c)K(\omega, d)$$
$$P_{\text{PV}}(d) = \int_{\omega_g}^{+\infty} \frac{d\omega}{2\pi}\hbar\omega_0\, n(\omega, T_s)K(\omega, d) - \int_{\omega_g}^{+\infty} \frac{d\omega}{2\pi}\hbar\omega_0\, n(\omega - \omega_0, T_c)K(\omega, d)$$

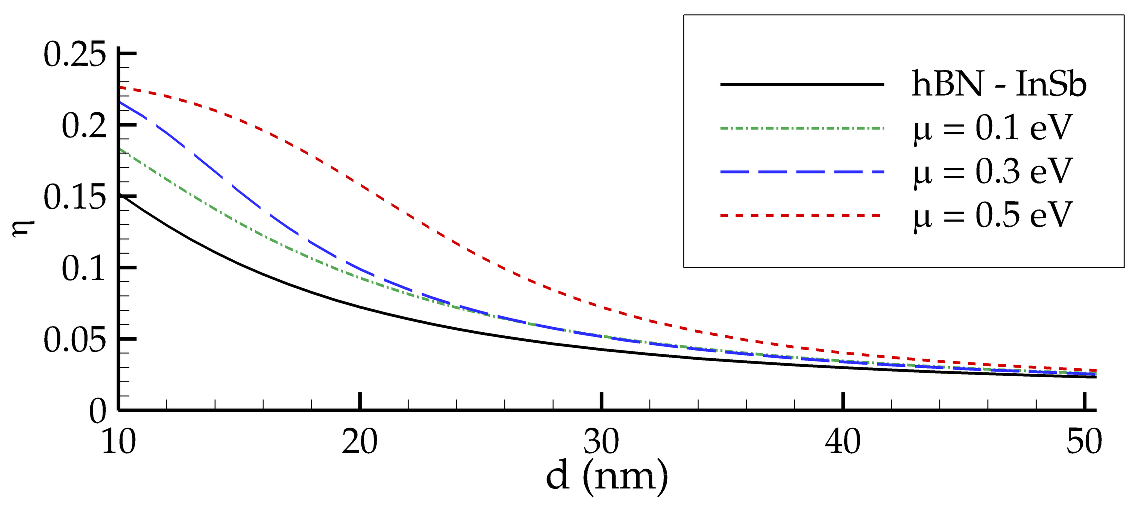
where $\omega_0 = eV_0/\hbar$, $V_0 \simeq \hbar\omega_g(1 - T_c/T_s)/e$ [9]

- **Efficiency** of the cell

$$\eta = \frac{P_{\text{PV}}}{P_{\text{rad}}}$$

4. Results

The efficiency and produced electric power for the graphene-modified cell are compared to the standard cell for different values of the chemical potential μ of graphene.

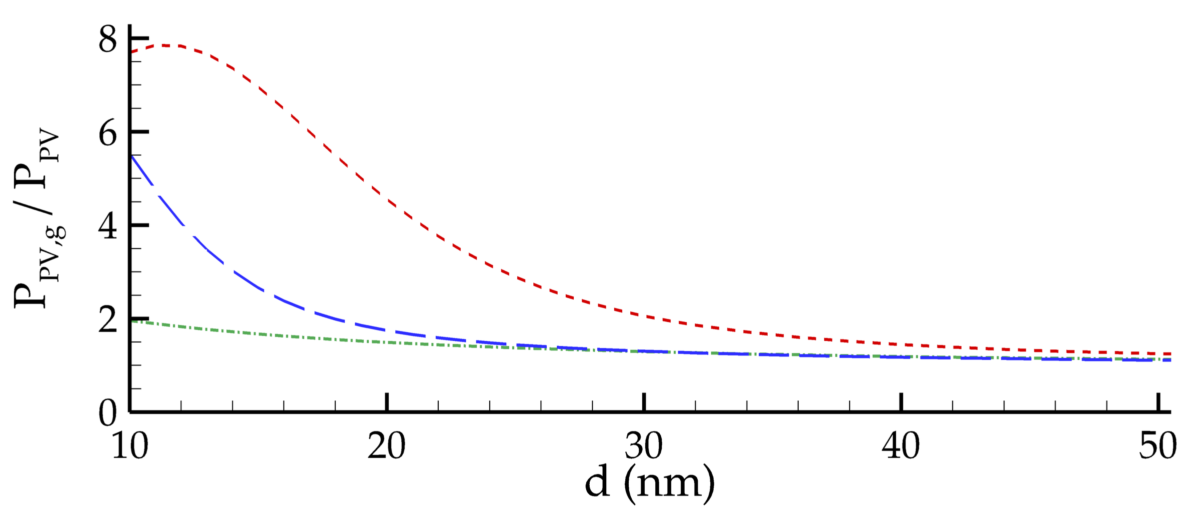


Efficiency

The increase of efficiency with respect to the standard case goes up to 10% for the highest value of the chemical potential. The overall effect decreases with distance.

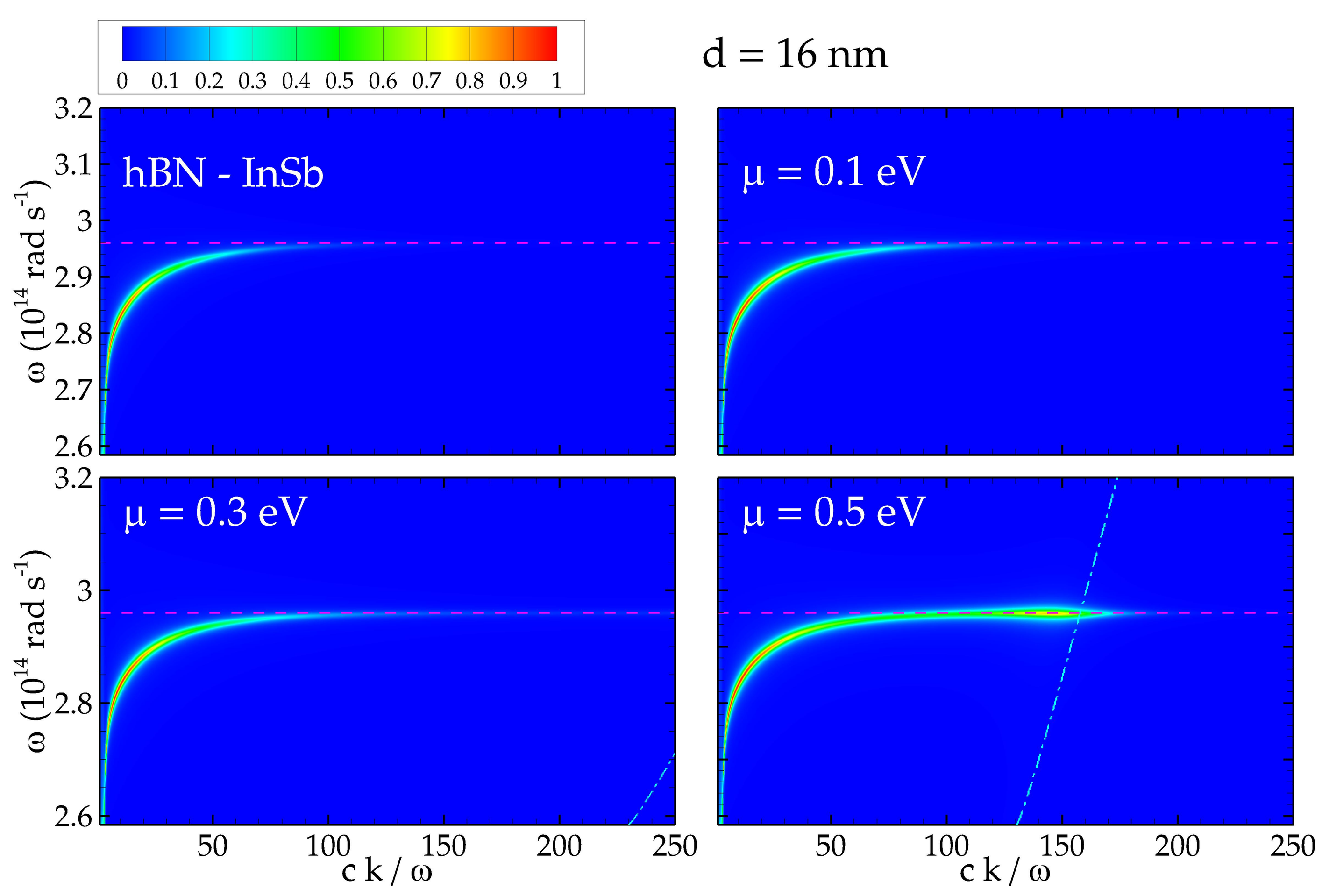
Electric power

Both the efficiency and the produced electric power, the two main parameters characterizing a TPV cell, are enhanced by the presence of graphene.



5. Participation of fields modes

Transmission coefficient in the (ω, k) plane for different values of the chemical potential



- **Violet**: phonon-polariton of hBN, giving the main contribution to heat transfer
- **Light blue**: surface plasmon of graphene

The **modulation of the chemical potential** produces a **coupling** between the surface modes of source and cell, represented by the region of increased transmission probability. This corresponds to an **increase of the number of modes** participating to the energy exchange.

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