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► **To cite this version:**

E. Nefzaoui, Younes Ezzahri, Jérémie Drevillon, Karl Joulain. On maximal near-field radiative transfer between two plates. *Nanoenergy* 2013, Jul 2013, Pérouse, Italy. hal-01579470

HAL Id: hal-01579470

<https://hal.science/hal-01579470>

Submitted on 31 Aug 2017

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NANOENERGY LETTERS

On maximal near-field radiative transfer between two plates

Elyes Nefzaoui, Younès Ezzahri, Jérémie Drevillon and Karl Joulain

Institut Pprime, CNRS-Université de Poitiers-ENSMA, Département Fluides, Thermique, Combustion, ENSIP-Bâtiment de mécanique, 2, Rue Pierre Brousse, F86022 Poitiers, Cedex, France

Abstract— Thanks to its partial coherence and to the high exchanged flux densities, near-field radiative transfer is a promising way to significantly and simultaneously enhance both TPV devices efficiencies and power densities. A parametric study of Drude and Lorentz models performances in maximizing near-field radiative heat transfer between two semi-infinite planes separated by nanometric distances at room temperature is presented in this paper. Optimal parameters of these models that provide optical properties maximizing the radiative heat flux are reported and compared to real materials usually considered in similar studies, silicon carbide and heavily doped silicon in this case. Finally, the frequently assumed hypothesis which states a maximal radiative heat transfer when the two semi-infinite planes are of identical materials is numerically confirmed. Its subsequent practical constraints are then discussed. Presented results enlighten relevant paths to follow in order to choose or design materials maximizing nano-TPV devices performances.

I. INTRODUCTION

It has been shown in the late 1960[1, 2] that the radiative heat flux (RHF) exchanged by two media in the near-field (NF), i.e. when these media are separated by very small distances (smaller than the thermal radiation characteristic wavelength ($\lambda_T = hc/k_bT$) could exceed by several orders of magnitude the black body limit. This topic has then received an increasing attention until its recent experimental verifications [3, 4]. In addition, the particular plane-plane configuration, potentially useful for various applications such as the cooling of high flux density electronic devices[5] or thermo-photovoltaic (TPV) conversion of radiative energy[6], has been thoroughly investigated from a theoretical point of view by several groups[7-9]. These works mainly addressed dielectrics, usually silicon carbide (SiC)[8, 10] which surface phonon-polaritons highly contribute to the NF RHF increase. They also considered materials which support plasmon-polaritons in the wavelength range of thermal radiation at room temperature such as tungsten[7, 11] or heavily doped silicon (HD-Si)[9, 12].

In the present numerical work, hypothetical materials modeled by local Drude and Lorentz models are considered. The aim of this work is to find the sets of parameters of these models that possibly maximize the RHF between two semi-infinite planes of identical materials separated by a nanometric gap at room temperature. For this purpose, we calculate the exchanged RHF between the two media while varying the different parameters in a wide range. Exact calculations of the NF RHF expression derived from the fluctuating electrodynamics theory are performed. The optimal hypothetical material performances are compared to those of

usually considered materials, SiC and HD-Si for instance. Finally, the influence of small discrepancies between the two planes optical properties RHF is discussed. Results are discussed from a Landauer-type mesoscopic description of radiative heat transfer which enlightens relevant paths to follow for the design of metamaterials maximizing NF RHF.

II. METHODS

Consider two semi-infinite planes 1 and 2 separated by a vacuum gap of thickness δ and characterized by their dielectric functions and temperatures (ε_1, T_1) and (ε_2, T_2) respectively. The total RHF density exchanged by the two media is given by[13]

$$\dot{q} = \dot{q}_{prop} + \dot{q}_{evan} \text{ where :}$$

$$\dot{q}_{prop} = \sum_{i=s,p} \int_0^\infty \frac{d\omega}{2\pi} [\Theta(\omega, T_1) - \Theta(\omega, T_2)] \int_0^{\frac{\omega}{c}} \frac{d^2q}{(2\pi)^2} \frac{(1 - |r_{31}^i|^2)(1 - |r_{32}^i|^2)}{|1 - r_{31}^i r_{32}^i e^{2i\gamma_3 \delta}|^2}$$

$$\dot{q}_{evan} = \sum_{i=s,p} 4 \int_0^\infty \frac{d\omega}{2\pi} [\Theta(\omega, T_1) - \Theta(\omega, T_2)] \int_{\frac{\omega}{c}}^\infty \frac{d^2q}{(2\pi)^2} e^{2i\gamma_3 \delta} \frac{Im(r_{31}^i) Im(r_{32}^i)}{|1 - r_{31}^i r_{32}^i e^{2i\gamma_3 \delta}|^2}$$

are the contributions of propagative and evanescent waves respectively. $\Theta(\omega, T) = \hbar\omega / [\exp(\hbar\omega/kT) - 1]$ is the mean energy of a Planck oscillator at a temperature T and a circular frequency ω , r_{3j}^i are Fresnel reflection coefficients for an i -polarized wave ($i \in \{s, p\}$) propagating from medium 3

(vacuum) to medium j and $\gamma_3 = \left[(\omega/c)^2 - q^2 \right]^{1/2}$ is the normal wave vector component in vacuum where q is the parallel component.

In the extreme near field regime ($\delta \ll \lambda_T$), the evanescent contribution dominates the transfer. Furthermore, for dielectrics as silicon carbide (SiC) and some doped semi-conductors, heavily doped silicon (HD-Si) for instance, the p -polarized evanescent contribution is dominating. RHF then reduces to:

$$\dot{q} \approx \dot{q}_{evan}^p = \int_0^\infty \dot{q}_{evan}^p(\omega, T_1, T_2, \delta) d\omega \text{ where the monochromatic}$$

flux density can be written in a Landauer form as :

$$\dot{q}_{evan}^p(\omega, T_1, T_2, \delta) = \frac{q_0^2}{4\pi^2} [\Theta(\omega, T_1) - \Theta(\omega, T_2)] \int_{\frac{\omega}{c}}^\infty \frac{q}{q_0} \tau_{evan}^p(\omega, q) dq (*)$$

where $\tau_{evan}^p(\omega, q) = 4e^{2i\gamma_3 \delta} \frac{Im(r_{31}^i) Im(r_{32}^i)}{|1 - r_{31}^i r_{32}^i e^{2i\gamma_3 \delta}|^2}$ can be seen as the average probability that (ω, q) mode contributes to the transfer[14].

III. RESULTS

Medium 1 is considered at $T_1 = 300$ K and medium 2 at $T_2 = 299$ K. With $\delta = 10$ nm, we consider the extreme near-field regime.

Identical media : Drude vs Lorentz models. First, the transfer between identical media was considered. Drude and Lorentz models are considered and their parameters $(\varepsilon_\infty, \omega_p, \Gamma)$ for the first, and $(\varepsilon_\infty, \omega_{LO}, \omega_{TO}, \Gamma)$ for the second, were varied in a large domain of usual values. For both models, the lower ε_∞ the higher the flux density. Values in the range $\varepsilon_\infty \in [1, 20]$ were considered. Drude model provides the highest values ($\approx 2.5 \times 10^5$ W.m⁻²) reached when ω_p is around the circular frequency of Planck oscillator maximal energy at a given T . For $\varepsilon_\infty = 1$ for instance (Fig. 1-a), Drude model maximal NF RHF is 5 times higher than this given by Lorentz model, with $\omega_{TO} = \omega_{TO}(\text{SiC})$ [15]. Finally, HD-Si at doping concentrations around 10^{19} cm⁻³ approaches 90% of optimal Drude model performances while SiC nearly achieves 60% of maximal Lorentz model NF RHF [16].

Maximal transfer for identical media. NF RHF between two semi-infinite planes of different material was calculated. Materials dielectric functions of both planes were modeled using the same model but with different parameters values. Normalized NF RHF for Drude model ($\varepsilon_\infty = 1$), where material 1 (ω_{p1}, Γ_1) is the one realizing Fig. 1-a maximum, is plotted in Fig. 1-b as a function of $\omega_{p2} / \omega_{p1}$ and Γ_2 / Γ_1 . The maximum is observed at $(\omega_{p2} / \omega_{p1}, \Gamma_2 / \Gamma_1) = (1, 1)$, i.e. for identical materials. Besides, we observe a 10% drop of RHF value for a 10% relative difference between ω_{p2} and ω_{p1} . The sensitivity of RHF to Γ differences is much lower. On the other hand, for Lorentz model, RHF is far more sensitive to the differences between the two materials optical properties. For instance, in the case of SiC exchanging with another material, a 0,1% difference between ω_{LO} of the two planes leads to a 50% drop of RHF. This high sensitivity is due to the very sharp peak of SiC dielectric permittivity, i.e. to the high SiC damping factor and can be reduced by reducing Γ [16].

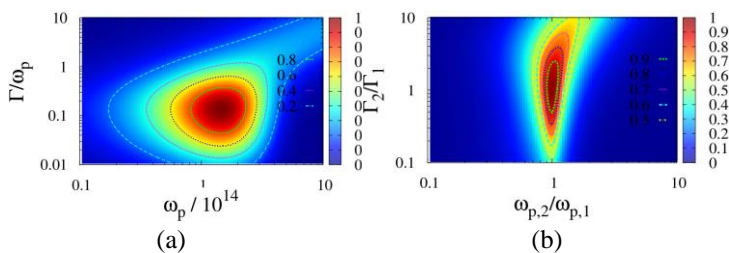


Fig. 1. Normalized RHF for Drude model ($\varepsilon_\infty = 1$) between two planes of identical materials as a function of plasma frequency and damping coefficient (a) and between two planes of different materials (b).

The mesoscopic description contribution : multiplying transfer channels as a key to reach maximal NF RHF

The transmission coefficient $\tau_{evan}^p(\omega, q)$ of (ω, q) evanescent modes ($q/q_0 > 1$) for p polarization is presented in Fig. 2. First, we note that modes contributing to the transfer (hot-colored areas) are significantly more numerous with Drude model. The use of more transfer channels may then explain the higher flux density values.

Now, consider the expression of evanescent contributions to NF RHF (equation (*)). The integrand of the sum over the wave involves $q\tau_{evan}^p(\omega, q)$ and not only $\tau_{evan}^p(\omega, q)$, which means that high q modes have a dominating weight in the total monochromatic flux density. Compared to Lorentz model, Drude model ensures that a higher number of these modes contribute to the transfer.

Thus, in order to maximize NF RHF, used materials dielectric properties should allow the use of the highest number of transfer channel. Then, high wave number value channels should be preferred. The active control of participating modes is possible by meta-materials which present a tunable dielectric function. Materials with non-local dielectric functions, such as graphene for instance [17], allow a finer control of contributing channels which makes them particularly promising candidates.

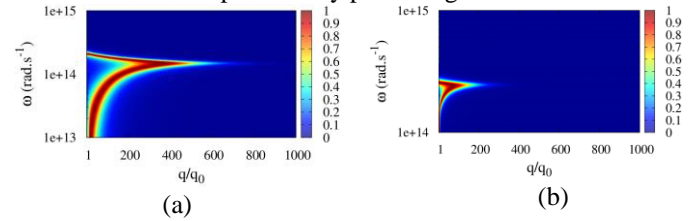


Fig. 2. (ω, q) modes transmission probability in the case of Drude (a) and Lorentz (b) models. In both cases, dielectric function models are used with the sets of parameters maximizin NF RHF for $\varepsilon_\infty = 1$ (and $\omega_{TO} = \omega_{TO}(\text{SiC})$ for Lorentz model).

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