On maximal near-field radiative heat transfer

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Abstract :

A parametric study of near-field radiative heat flux (NF-RHF) between two plates is presented as a function of Drude and Lorentz models parameters. Identical and different materials plates are considered. The optimal set of parameters is determined and discussed in comparison with existing materials, Silicon carbide (SiC) and Heavily Doped Silicon (HDSi) in this case, and potential metamaterials.

Methods :

Fluctuational electrodynamics expression of NF-RHF [1]

$$\dot{q} = \dot{q}_{prop} + \dot{q}_{evan}$$

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

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

Hypotheses

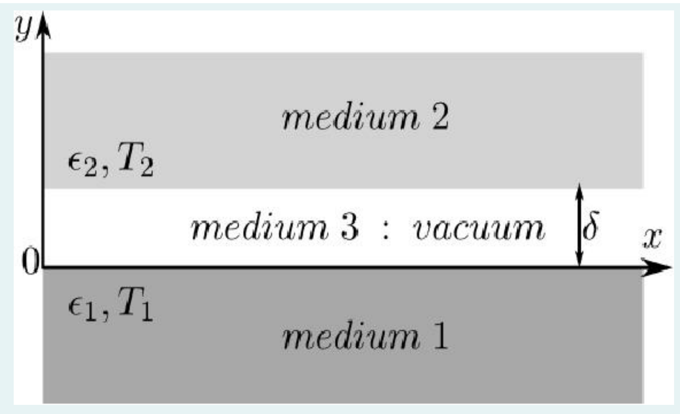
$d = 10 \text{ nm} \ll \lambda_T$

$T_1 = 300\text{K}$

$T_1 = T_2 + 1\text{ K}$

$\dot{q}_{evan}^p \gg \dot{q}_{evan}^s$

System



Landauer-type expression of NF-RHF [2]

$$\dot{q} \simeq \int_0^{\infty} \dot{q}_{evan}(\omega, T_1, T_2, \delta) d\omega$$

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

Definitions

- $\tau_{evan}^i(\omega,q) = 4e^{2i\gamma_3\delta} \frac{Im(r_{31}^i) Im(r_{32}^i)}{|1-r_{31}^i r_{32}^i e^{2i\gamma_3\delta}|^2}$
- $\Theta(\omega,T) = \hbar\omega / [\exp(\hbar\omega/kT) - 1]$
- $r_{jk}^p = \frac{\varepsilon_j\gamma_k - \varepsilon_k\gamma_j}{\varepsilon_j\gamma_k + \varepsilon_k\gamma_j}$
- $\gamma_3 = [(\omega/c)^2 - q^2]^{1/2}$
- $q_0 = \frac{\omega}{c}$

Drude Model

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + \iota\Gamma\omega}$$

Lorentz Model

$$\varepsilon(\omega) = \varepsilon_\infty - \frac{\omega_{LO}^2 - \omega_{TO}^2}{\omega_{TO}^2 + \iota\Gamma\omega - \omega_0^2}$$

Control Parameters

ε_∞ : High frequency limit, $\varepsilon_\infty \in [1, 20]$

ω_p : Plasma frequency, $\omega_p \in [10^{13}, 10^{15}]$

Γ: Damping coefficient, $\frac{\Gamma}{\omega_p} \in [10^{-2}, 10]$ (Drude), $\frac{\Gamma}{\omega_{TO}} \in [10^{-3}, 1]$ (Lorentz)

ω_{LO}, ω_{TO} : Optical phonons circular frequencies, $\omega_{TO} = \omega_{TO,SiC}$, $\frac{\omega_{LO}}{\omega_{TO}} \in [1, 2]$

Results

Drude Model

Identical planes

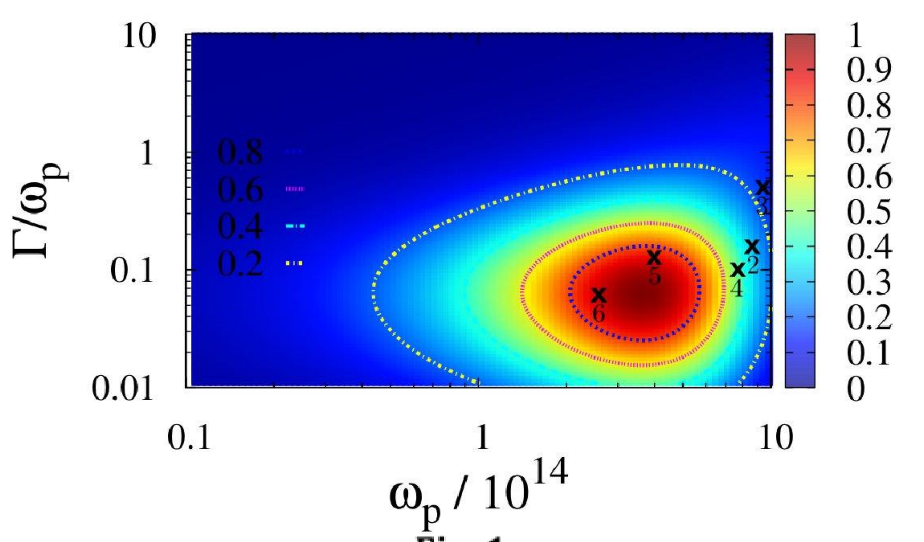


Fig. 1
Normalized NF RHF for identical planes ($\varepsilon_\infty = 11.8$)

$\dot{q}_{max} \simeq 2.2\times10^5$ W.m^{-2} for $\varepsilon_\infty = 1, \omega_p = 1.54\times10^{-14}, \frac{\Gamma}{\omega_p} = 0.17$

$\dot{q}_{max,HDSi-HDSi} \geq 0.9\times\dot{q}_{max,\varepsilon_\infty=\varepsilon_{Si}}$

Sensitivities

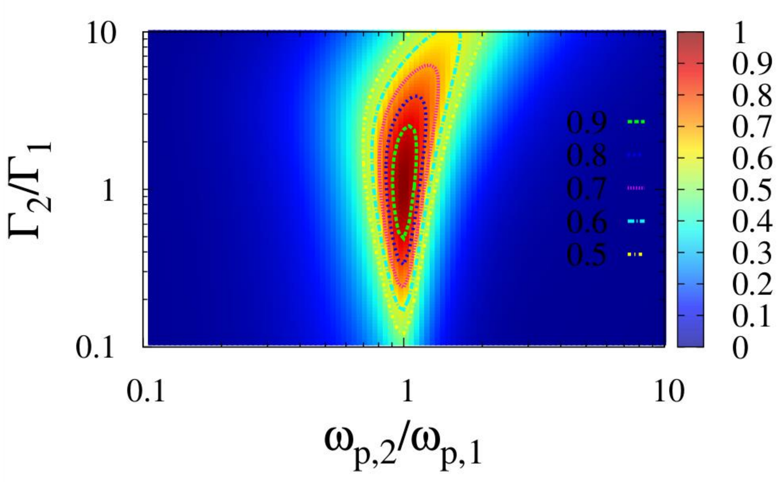


Fig. 2
Normalized NF RHF for planes of different materials (HDSi vs X)

$\frac{\Delta\omega_p}{\omega_{p,HDSi}} \leq [-0.1, 0.1] \Rightarrow \frac{\Delta\dot{q}}{\dot{q}_{HDSi-HDSi}} \leq 10\%$

$\frac{\Delta\Gamma}{\Gamma_1} \in [-0.5, 1.5] \Rightarrow \frac{\Delta\dot{q}}{\dot{q}_{HDSi-HDSi}} \leq 10\%$

Transfer channels

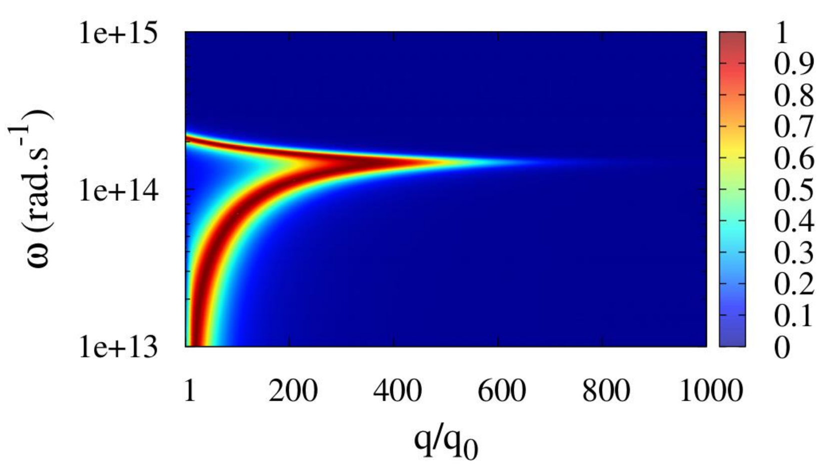


Fig. 3

$\tau_{evan}^p(\omega,q)$

Cutoff wavevector : $q_c \simeq 3/\delta$

- **Large number of occupied channels (modes)**
- **High q-value modes**

Lorentz model

Identical planes

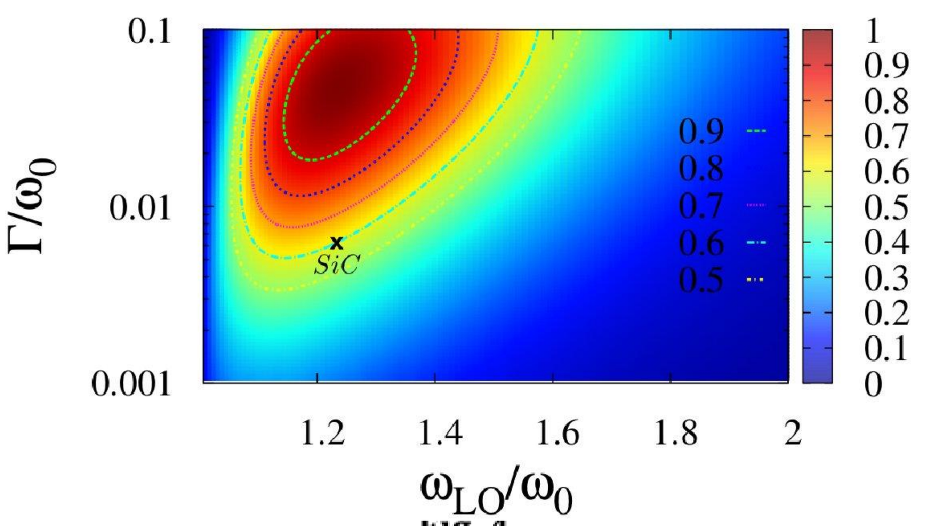


Fig. 4
Normalized NF RHF for identical planes ($\varepsilon_\infty = 6.7$)

$\dot{q}_{max} \simeq 5.4\times10^4$ W.m^{-2}

for $\varepsilon_\infty = 1, \omega_{TO} = \omega_{TO,SiC}, \frac{\omega_{LO}}{\omega_{TO}} = 1.42, \frac{\Gamma}{\omega_{TO}} = 0.19$

$\dot{q}_{max,SiC-SiC} \leq 0.6\times\dot{q}_{max,\varepsilon_\infty=\varepsilon_{SiC}}$

Sensitivities

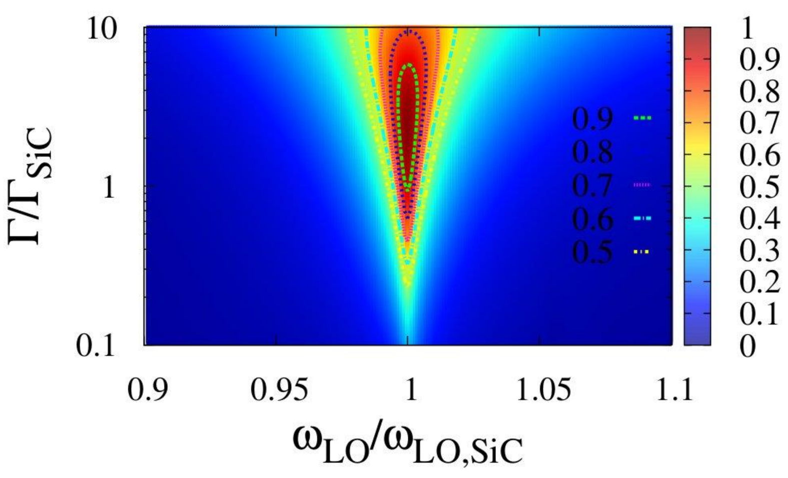


Fig. 5
Normalized NF RHF for planes of different materials (SiC vs X)

$\frac{\Delta\omega_{LO}}{\omega_{LO,SiC}} \simeq 10^{-4} \Rightarrow \frac{\Delta\dot{q}}{\dot{q}_{SiC-SiC}} \simeq 10\%$

$\frac{\Delta\Gamma}{\Gamma_{SiC}} \in [-0.08, 4.8] \Rightarrow \frac{\Delta\dot{q}}{\dot{q}_{SiC-SiC}} \leq 10\%$

Transfer channels

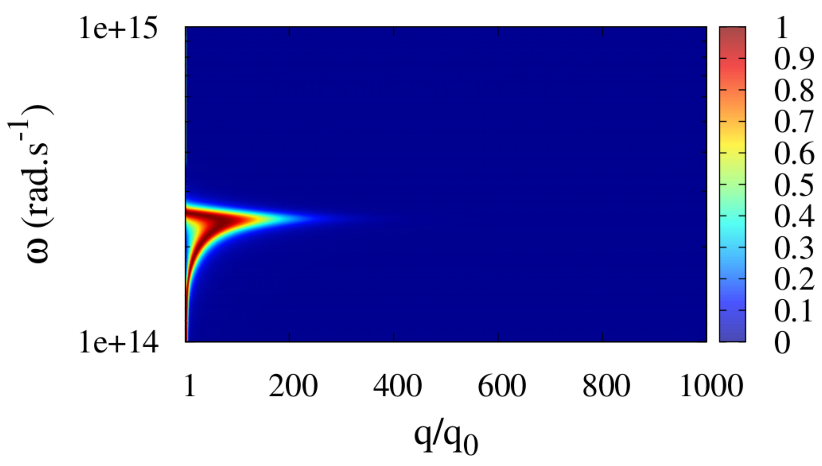


Fig. 6

$\tau_{evan}^p(\omega,q)$

Cutoff wavevector : $q_c \simeq 3/\delta$

- **Small number of occupied channels**
- **High q-value modes**

Conclusions

1. **Drude model allows higher flux values than Lorentz's.**
2. **HDSi is more efficient than SiC to reach these high values.**
3. **Maximal NF RHF values are obtained for identical media.**
4. **Exchanged NF RHF is more sensitive to the planes properties discrepancies for Lorentz model than for Drude's.**
5. **The efficiency of Drude model can be explained by a mesoscopic description of NF RHT : this model allows the use of more transfer channels.**
6. **NF RHF can be further increased by using non-local meta-materials maximizing the number of transfer channels [4].**

References

[1] A.I. Volokitin, B.N.J. Persson, Reviews of Modern Physics, 79 (2007) 1291-1329.

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[3] E.D. Palik, Academic Press Handbook Series, New York: Academic Press, 1985, edited by Palik, Edward D., 1 (1985).

[4] R. Messina, J.-P. Hugonin, J.-J. Greffet, F. Marquier, Y. De Wilde, A. Belarouci, L. Frechette, Y. Cordier, P. Ben-Abdallah, Physical Review B, 87.

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