# Near-field radiative heat transfer between a nanoparticle and a rough surface

Svend-Age Biehs

Design de matériaux à propriété radiatives fonctionalisées: de l'angstrom au millimètre





Near-field radiative heat transfer between a nanoparticle and a rough surface

Dipole Model	Roughness	Distance regimes	LDOS	Heat transfer rate	Summary
•	0	0 0 0	0	0	0

# **Dipole model - LDOS**

• for  $\lambda_{\text{th}} \gg R$  and  $d \gg R$ :

$$\boldsymbol{P}^{\mathrm{B}\to\mathrm{P}} = \int_0^\infty \mathrm{d}\omega \, 2\omega \alpha''(\omega) \Theta(\omega, T_\mathrm{B}) \boldsymbol{D}(\omega, \mathbf{r}_\mathrm{P})$$

polarizability

$$\alpha = 4\pi R^3 \frac{\epsilon_{\rm P} - 1}{\epsilon_{\rm P} + 2}$$





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mean energy of oscillator T<sub>B</sub>

$$\Theta(\omega, T_{\rm B}) = \frac{\hbar\omega}{e^{\hbar\omega/(k_{\rm B}T)} + 1}$$





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Local density of states (LDOS)

$$D(\omega, \mathbf{r}_{\mathrm{P}}) = \frac{\omega}{\pi c^2} \mathrm{Im} \, \mathrm{Tr} \, \mathrm{G}(\mathbf{r}_{\mathrm{P}}, \mathbf{r}_{\mathrm{P}})$$





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0	•	0	0	0	0
		0			

Definining a rough surface

### Stochastic surface profile

• gaussian profile  $S(\mathbf{x})$ 

$$egin{aligned} &\langle \hat{S}(\kappa)
angle = 0,\ &\langle ilde{S}(\kappa) ilde{S}(\kappa')
angle = (2\pi)^2\delta(\kappa+\kappa')\delta^2g(\kappa) \end{aligned}$$

power spectrum

$$g(\kappa) = \pi a^2 \mathrm{e}^{-\frac{\kappa^2 a^2}{4}}$$

 root mean square (rms) δ, correlation length a



S(x)

x

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# Mean LDOS above a rough surface

ensemble average

$$\langle D^{(0)-(2)}(\omega,d) \rangle = D^{(0)} + \langle D^{(1)} \rangle + \langle D^{(2)} \rangle$$

reflection coefficient

$$\langle r_{\rm p}^{(0)-(2)} \rangle = r_{\rm p}^{(0)}(\kappa) + r_{\rm p}^{(2)}(\kappa a)$$

- main contribution for  $\kappa \approx d^{-1}$
- ▶ 3 regimes for  $r_p^{(2)}$ :
  - $\kappa a \ll 1$ ,  $(a \ll d)$
  - $\blacktriangleright$   $\kappa a \gg 1$ ,  $(a \gg d)$
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# Mean LDOS above a rough surface

ensemble average (ev. modes)

$$\langle D^{(0)-(2)}(\omega, d) \rangle \approx \int_0^\infty d\kappa \, \frac{\kappa^2 e^{-2\kappa d}}{4} \mathrm{Im}(\langle r_{\mathrm{p}}^{(0)-(2)} \rangle)$$

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main contribution for κ ≈ d<sup>-1</sup>
 3 regimes for r<sub>p</sub><sup>(2)</sup>:
 κa ≪ 1, (a ≪ d)
 κa ≈ 1, (a ≈ d)



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  - κa≈1, (a≈d)



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0	0	• • •	0	0	0

# Large distance approximation (LDA), $d \gg a$





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0	0		0	0	0

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0	0	• • •	0	0	0

# Large distance approximation (LDA), $d \gg a$

• approximating 
$$r_p^{(2)}$$
 for  $1 \gg \kappa a$ 

$$\bullet \ r_{\rm p}^{(2)} \propto \frac{\delta^2}{a}, \, (a \ll d_{\rm s})$$

 $\blacktriangleright \langle D^{(2)} \rangle, \langle P^{(2)} \rangle \propto \frac{\delta^2}{2}$ 

 effective layer (Maradudin and Rahman)





Near-field radiative heat transfer between a nanoparticle and a rough surface

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0	0	• • •	0	0	0

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0	0	0 • 0	0	0	0

# Proximity approximation (PA), $d \ll a$

• approximating  $r_{\rm p}^{(2)}$  for  $1 \ll \kappa a$ 

 $\begin{array}{l} \bullet \ \frac{r_p^{(2)}}{r_p^{(0)}} \approx 2(\kappa\delta)^2 \ \Rightarrow \Delta D = \frac{\langle D^{(2)} \rangle}{D^{(0)}} \approx 6\frac{\delta^2}{d^2} \\ \bullet \ \frac{\langle D^{(2)} \rangle}{D^{(0)}}, \frac{\langle P^{(2)} \rangle}{P^{(0)}} > 0, \text{ do not depend on } a, \epsilon, T \end{array}$ 

 $\blacktriangleright$  PA for  $\delta \ll d \ll a$ 



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►  $\frac{\langle D^{(2)} \rangle}{D^{(0)}}, \frac{\langle P^{(2)} \rangle}{P^{(0)}} > 0$ , do not depend on  $a, \epsilon, \gamma$   
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► PA for  $\delta \ll d \ll a$ 

$$\langle D(d) 
angle pprox \langle D^{(0)}(d-S(\mathbf{x})) 
angle$$



Dipole Model	Roughness	Distance regimes	LDOS	Heat transfer rate	Summary
0	0	○ ● ○	0	0	0

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• PA for  $\delta \ll d \ll a$ 

$$egin{aligned} &\langle \mathcal{D}(d) 
angle &pprox \langle \mathcal{D}^{(0)}(d-\mathcal{S}(\mathbf{x})) 
angle \ &pprox \mathcal{D}^{(0)}(d) + 6 rac{\delta^2}{d^2} \mathcal{D}^{(0)}(d) + \dots \end{aligned}$$



Dipole Model	Roughness	Distance regimes	LDOS	Heat transfer rate	Summary
0	0	0 0 •	0	0	0

Intermediate distance regime

Intermediate distances  $d \approx a$  ( $\kappa a \approx 1$ )  $\blacktriangleright$  Im( $r_p^{(2)}$ )/Im( $r_p^{(0)}$ ) for SiC and  $\omega_t \le \omega \le \omega_1$  $\blacktriangleright$   $a = 200 \text{ nm}, \delta = 5 \text{ nm} \rightarrow \frac{\delta}{a} = 0.025$ 





Near-field radiative heat transfer between a nanoparticle and a rough surface

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0	0	0 0 •	0	0	0

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Dipole Model o	Roughness o o	Distance regimes o o	LDOS ●	Heat transfer rate	Summary o o
		0			

### Distance dependence of LDOS





Near-field radiative heat transfer between a nanoparticle and a rough surface

Dipole Model	Roughness o o	Distance regimes	LDOS •	Heat transfer rate	Summary o o
		0			

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#### Near-field radiative heat transfer between a nanoparticle and a rough surface

Dipole Model o o	Roughness o o	Distance regimes	LDOS •	Heat transfer rate o	Summary o o
		0			

### Distance dependence of LDOS



Near-field radiative heat transfer between a nanoparticle and a rough surface

LCFIO, Palaiseau

GRADUATE SCHOOL

Dipole Model	Roughness	Distance regimes	LDOS	Heat transfer rate	Summary
0	0	0	•	0	0

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Dipole Model	Roughness	Distance regimes	LDOS	Heat transfer rate	Summary
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### Distance dependence of heat transfer rate



Dipole Model	Roughness	Distance regimes	LDOS	Heat transfer rate	Summary
0	0	0	0	•	0



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Dipole Model o o	Roughness o o	Distance regimes o o	LDOS o	Heat transfer rate o	Summary ● ○
Summary					

•  $\Delta P$  and  $\Delta D$  non-monotonous (ev. modes)

▶ d ≪ a:



- coincides with PA
- independent of  $a, \epsilon, 7$

▶ *d* ≫ *a* (LDA):

$$\Delta D, \Delta P \propto \frac{\delta^2}{a}$$

effective laye



Dipole Model o o	Roughness o o	Distance regimes o o	LDOS o	Heat transfer rate o	Summary ● ○
Summary					

△P and △D non-monotonous (ev. modes)
 d ≪ a:

$$\Delta D, \Delta P \approx 6 \frac{\delta^2}{d^2}$$

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- intermediate:  $\Delta P$ ,  $\Delta D$  negative due to SPhP



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# Merci pour votre attention !!!



Near-field radiative heat transfer between a nanoparticle and a rough surface

Perturbation theory	Prop. modes	Evanescent s-polarized modes	NSThM
•	0	0	0

- plane-wave representation of E<sub>i</sub>, E<sub>r</sub> and E<sub>t</sub>
- bc via extinction theorem (Rayleigh hypothesis)
- expand with respect to S(x)
- determine Green's dyadic up to second order
- calculate LDOS





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- calculate LDOS





Perturbation theory	Prop. modes	Evanescent s-polarized modes	NSThM
•	0	0	0
	0		

- plane-wave representation of E<sub>i</sub>, E<sub>r</sub> and E<sub>t</sub>
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Perturbation theory	Prop. modes	Evanescent s-polarized modes	NSThM
0	•	0	0

s- and p-polarized modes

# Propagating modes



Near-field radiative heat transfer between a nanoparticle and a rough surface

LCFIO, Palaiseau

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Perturbation theory	Prop. modes	Evanescent s-polarized modes	NSThM
0	○ <sup>·</sup>	0	0

coupling of s-polarized modes to SPhP

# Coupling of prop. modes to SPhP

> s-polarized wave with **E** in y-direction and  $\kappa_i$ 



Perturbation theory o	Prop. modes o o	Evanescent s-polarized modes ●	NSThM o

s-polarized modes

### Evanescent modes

• 
$$\text{Im}(r_s^{(2)})/\text{Im}(r_s^{(0)})$$





#### Near-field radiative heat transfer between a nanoparticle and a rough surface

Perturbation	theory
0	

# Prop. modes

Evanescent s-polarized modes

Near-field Scanning Thermal Microscope



Near-field radiative heat transfer between a nanoparticle and a rough surface

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