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Near-field thermal emission between corrugated surfaces separated by nano-gaps

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ABSTRACT

Near-field thermal radiation with its many potential applications in different fields requires a thorough understanding for the development of new devices. In this paper, we report that near-field thermal emission between two parallel SiC thin films separated by a nano-gap, supporting surface phonon polaritons, as modeled via Finite Difference Time Domain Method (FDTD), can be enhanced when structured nanoparticles of different shapes and sizes are present on the surface of the emitting films. We compare different nano-particle shapes and discuss the configurations, which have the highest impact on the enhancement of near-field thermal emission and on the near-field heat flux. Convolutional Perfectly Matched Layer (CPML) boundary condition is used as the boundary condition of choice as it was determined to give the most accurate results compared against the other methodologies when working with sub-wavelength structures.

1. Introduction

The energy transportation by electromagnetic radiation is generally realized by two types of modes: propagating electromagnetic modes and evanescent modes. The near field evanescent modes could originate from the presence of surface phonon polaritons and surface plasmons. In classical radiative heat transfer, far field propagating modes are the main carrier in energy transport and that is where Planck's blackbody limit is valid. However, when two bodies are in close proximity, it is possible for both modes to be present and tunnel across the gap. It has been shown both theoretically and experimentally that the resulting near-field radiative transfer enhancement can indeed break Planck's blackbody limit [1–17].

With the help of recent advances in nano-manufacturing techniques, devices, which can function at nanoscales, have become possible and started pushing the limits of the traditional applications.

Over the years, different groups have shown interest in near-field thermal radiation and various studies have been performed. Experimental evidence of the existence of radiative heat transfer enhancement in near-field between parallel plates was first shown during 1968–1994 [1–7]. One of the solid applications of these enhancements is in the design and development of new thermophotovoltaic (TPV) devices, which are used to generate electric power directly from terrestrial thermal sources. Traditional TPV technologies are known to suffer from low conversion efficiency and power output due to characteristics of materials used [1]. Yet, with the enhancement of spectral radiative flux due to the plasmonic interactions, this bottle-neck can be avoided. Later, experimental investigations on Nano-TPVs were also conducted [8,9].

Other studies performed on experimental measurements of radiative heat flux enhancement in different

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Nomenclature

d	spacing between the films, m
$\mathbf{D}$	flux density vector, C m^{-1}
$\mathbf{E}$	electric field vector, V m^{-1}
$\mathbb{F}$	Fourier Transform
$\overline{\overline{\mathbf{G}}}$	Green's function tensor, m^{-1}
$\mathbf{H}$	magnetic field vector, A m^{-1}
i	complex constant, $(-1)^{1/2}$
Im	imaginary part
$\mathbf{J}$	current density vector, A m^{-2}
k	wavevector, rad m^{-1}
n	complex refractive index
q	radiative heat flux, W m^{-2}
$\mathbf{r}$	position vector, m
Re	real part
t	time, s or film thickness, m
T	temperature, K
v	speed of light, m s^{-1}
V	volume, m^3
$\mathbf{u}$	energy density
x,y,z	Cartesian coordinates
d_n	distance of nanoparticles, m
h	height of nanoparticles, m
w	width of nanoparticles, m

Greek symbols

ε	electric permittivity, C^2 N^{-1} m
ε_r	dielectric constant $(\varepsilon'_r + i\varepsilon''_r)$
ε_∞	high frequency dielectric constant
Γ	damping factor, rad s^{-1}
λ	wavelength, m
μ	magnetic permeability, N A^{-2}
ρ	local density of state
Θ	mean energy of a Planck oscillator, J
ω	angular frequency, rad s^{-1}
Δ	50 nm above emitting layer where LDOS/Flux is calculated, m

Subscripts/Superscripts

$*$	complex conjucate
$'$	source point
E	electric
H	magnetic
n	time step counter
v	vacuum
ω	monochromatic
LO	longitudinal optical
TO	transverse optical

configurations clearly showed the evidence of ehnhancement of radiative transfer due to near-field effects above the Planck limit [10–17]. An accurate modeling of nano-TPV energy conversion systems through the solution of the coupled near-field thermal radiation, charge and heat transport problem was provided by Francoeur et al. [18]. They reported that resonant modes of thermal emission by a polar crystal can be enhanced and tuned, between the transverse and longitudinal optical phonon frequencies, by simply varying the structure of the system. Their analysis provides the fundamental physical grounds to tune near-field thermal radiation emission via multilayered structures. Various computational studies of radiative heat transfer have also been carried out by other groups as well [19–26].

Recently, we have presented in [27] that the results found for the near-field thermal emission calculations via the FDTD method for perfectly flat, parallel, thin SiC films supporting surface phonon polaritons and separated by a nano-gap show a good agreement with analytical results presented in [18]. Having a computational technique such as FDTD that can model complex electromagnetic geometries, in dispersive, anisotropic mediums where geometry complications may not allow analytical solutions can be promising for both current and future research of near-field radiative transfer. FDTD method belongs to the category of Differential Equation solvers, like Finite Element Method (FEM) and Finite Integration Technique (FIT). Another popular family of solvers is the Integral Equation solvers, e.g., Discrete Dipole Approximation (DDA) and Method of Moments (MOM). FDTD has a number of advantages over Method of Moments and Finite Elements Method: FDTD gives broadband output from a single execution of the program. It has excellent scaling performance as the problem size grows. FDTD is excellent at modeling non-homogeneous media and supports lossy, non-linear and anisotropic media. Boundary conditions are inherently represented and it is robust and easy to implement.

On the other hand, a non-homogeneous medium can be simplified down to a layered homogeneous structure using the Effective Medium Theory (EMT) to avoid computational burden. Different groups have studied the accuracy of EMT for nanoscale geometries in studies of near-field radiative transfer [28–31] to name only a few. However, results have shown misleading results as well as poor accuracy of EMT in several cases.

In this paper, we study corrugated surfaces and the behavior of near-field thermal emission and heat flux through the study of periodicity, shape and size of nanoparticles sitting on the surface of the emitting layer in the aforementioned configuration via the FDTD method. The geometry considered for bench-mark is depicted in Fig. 1a, for two perfectly flat thin SiC films separated by a nano-gap. Fig. 1b–d shows the corrugated emitting layer case where different shape particles, with different sizes and periodicity, are assumed to be imbedded on the high-temperature film.

The study of the enhancement of fields at the vicinity of the particles due to illumination of metallic particles by