Journal of Quantitative Spectroscopy & Radiative Transfer 219 (2018) 304–312

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Near-field thermal radiative transfer in assembled spherical systems composed of core-shell nanoparticles

J. Chen, C.Y. Zhao*, B.X. Wang

Institute of Engineering Thermophysics, Shanghai Jiao Tong University, Shanghai 200240, PR China

ARTICLE INFO

Article history:
Received 17 April 2018
Revised 22 August 2018
Accepted 24 August 2018
Available online 27 August 2018

Keywords:
Near-field thermal radiation
Core-shell structure
Many-body systems
Multibody mutual interaction

ABSTRACT

Thermal radiative transfer can be enhanced significantly when the distance of radiation sources is smaller than the characteristic wavelength of thermal radiation. However, the problem of the near-field thermal radiative transfer (NFTRT) between core-shell nanoparticles has rarely been studied. Moreover, most previous studies investigate the NFTRT between two or three nanoparticles, while few works have been done on real many-body systems where multibody mutual interaction plays a pivotal role. In this study, we choose silicon carbide (SiC) and *n*-type germanium (Ge) as two constituent materials of the core-shell nanoparticle, and describe a complete theoretical investigation of the NFTRT in many body systems composed of core-shell nanoparticles. The results demonstrate that the core-shell nanoparticles inherit both characteristics of SiC and *n*-type Ge: quasimonochromaticity and broad-band. What's more, the spectral features can be tuned by core-shell radius and material composition. Further studies show that multibody mutual interaction has a detrimental effect on the NFTRT between two assembled spherical systems. Still, the enhancement of NFTRTs between a small proportion of nanoparticle dimers inside the systems is observed, which can be attributed to the coherence enhancement of fluctuating thermal fields. And by analyzing the trace of a dyadic Greens functions product, the locations of inherent resonance of nanoparticles and the coherent enhancement due to multibody mutual interaction need to be consistent if we hope strong exaltation effects of NFTRT.

1. Introduction

Near-field thermal radiation is a regime when the size and/or the separation distance of objects is comparable to or smaller than the characteristic wavelength of thermal radiation. In the near filed, Planck's black-body law fails and thermal radiative transfer will be enhanced significantly, which can exceed the far field limit by several orders of magnitude due to the tunneling of evanescent photons [1–4]. When surface plasmon polaritons (SPPs) or surface phonon polaritons (SPhPs) is excited, the near-field thermal radiative transfer (NFTRT) will be further improved [5–8]. Recently, NFTRT has gain much attention due to its high intensity, tunability, and quasimonochromaticity, and leads to plenty of promising applications including radiative refrigeration [9,10], coherent thermal sources [11], near-field thermophotovoltaic [12–17], thermal rectification [18–22], and thermal imaging [23–25].

In recent years, great progress has been made in investigating the NFTRT between nanoparticles which are made up of polaritonic material or metallic material. However, most previous studies focus on the NFTRT between two or three nanoparticles, while few works have been done on real many-body systems where multibody mutual interaction plays a pivotal role. Although it is of prime importance for studying thermal effects due to the presence of evanescent modes in such systems, obtaining the thermal percolation thresholds in random nanocomposite structures, and revealing the underlying heat transport regimes in many-body systems. Narayanaswamy et al. [26] numerically analyse the NFTRT between two adjacent non-overlapping spheres for arbitrary diameters and separation distances. The numerical results show that the dipole approximation is valid for spheres with small diameters and the proximity force approximation fails for spheres with diameters much larger than the separation distances. Ben-Abdallah et al. [27] develop a general theory based on coupled electric dipole method to solve the many-body problem of non-radiative photon heat transport. Then the theory is utilized to analyse the NFTRT in a three-body system, and strong exaltation effect of thermal radiative transfer is observed due to the existence of multibody mutual interaction. Recently, Dong et al. [28] further extend the theory developed by Ben-Abdallah [27]. They consider the coupling between electric dipole moment and magnetic dipole moment. And they further study the NFTRT between various dimers. While the

* Corresponding author.
E-mail address: Changying.zhao@sjtu.edu.cn (C.Y. Zhao).

https://doi.org/10.1016/j.jqsrt.2018.08.024
0022-4073/

system they investigate are extremely simple and only contain two or four nanoparticles. Furthermore, some researchers focus on the study of the dynamics of NFTRT in a three-body system [29,30]. The results show that multibody mutual interactions allow us to tailor the temperature field distribution and to drastically change the time scale of thermal relaxation processes. In addition, Dong et al. [31] explore the NFTRT between two clusters of SiC nanoparticles and it is observed that the total thermal conductance is inhibited due to multibody mutual interaction among particles in the clusters. Nikbakht [32] proposes a new representation for radiative heat transfer formalism in fractal structures. By this representation, he investigates the effects of the arrangement of nanoparticles and their material on the thermal properties in many-body systems.

Above mentioned are researches on homogeneous and isotropic nanoparticles. To obtain a large freedom of the tunability of NFTRT, anisotropic nanoparticles have been considered. Incardone et al. [33] derive the closed formulas in terms of anisotropic dipole polarizabilities to investigate the NFTRT between two anisotropic particles in a vacuum. They find thermal radiative transfer depends on the shapes and orientations of the anisotropic nanoparticles, and it allows for a large freedom of tunability. To date, the problem of the NFTRT between inhomogeneous (core-shell) nanoparticles has rarely been investigated. If the nanoparticle consists of two or even more kinds of materials which support SPPs or SPhPs respectively, then the NFTRT between composite nanoparticles may exhibit novel features.

In this study, we describe a theoretical investigation of the NFTRT between two assembled spherical systems composed of core-shell nanoparticles. Silicon carbide (SiC) and *n*-type germanium (Ge) are chosen as two constituent materials. The studied systems consist of many core-shell nanoparticles which are arranged in cubic lattice and densely packed. We study the effects of different core-shell radius and material composition on the NFTRT between two core-shell nanoparticles. The results show that the core-shell nanoparticles inherit both characteristics of SiC and *n*-type Ge, and have some advantages over homogeneous nanoparticles. The features of the spectral NFTRT can be further tailored by tuning the core-shell radius and material composition. Furthermore, we also investigate the effects of multibody mutual interaction on the NFTRT between two assembled spherical systems. And the mechanism underlying the effect of multibody mutual interaction is properly discussed by analysing the spectrum of NFTRT and the trace of a dyadic Greens functions product. In Section 2, we show the geometry of the core-shell nanoparticle and the assembled spherical system. In Section 3, we describe a theoretical investigation of the NFTRT between core-shell nanoparticles. Section 4 shows the results and analyses the effects of material composition, core-shell radius and multibody mutual interaction on the NFTRT between core-shell nanoparticles.

2. Geometry of the nanoparticle and the assembled system

The geometry of the core-shell nanoparticles is shown in Fig. 1a. The materials of the core and the shell can be chosen in any combination. In this study, we choose SiC and *n*-type Ge as two constituent materials and the NFTRT between two core-shell nanoparticles is studied. The inner radius and the outer radius are given by R_i and R_o respectively. To make the dipolar approximation valid, the nanoparticles are separated by an edge-to-edge gap $2R_o$ and the size of nanoparticle is supposed to be much smaller than the characteristic thermal wavelength. In this study, we assume the temperature of the left nanoparticle maintains at $T_1 = 400$ K, while that of the right one is $T_2 = 100$ K.

The geometry of the assembled spherical systems is shown in Fig. 1b. In this study, we investigate the effect of multibody mutual interaction on the NFTRT between two assembled spherical systems. Both of them contain N core-shell nanoparticles arranged in cubic lattice and densely packed. Without loss of generality, we assume the temperature of the left system maintains at $T_1 = 400$ K, while that of the right one is $T_2 = 100$ K. And the nanoparticles in each system have the same temperature. To make the dipolar approximation valid, the lattice constant is $a = 4R_o$ and the systems are separated by an edge-to-edge gap $2R_o$.

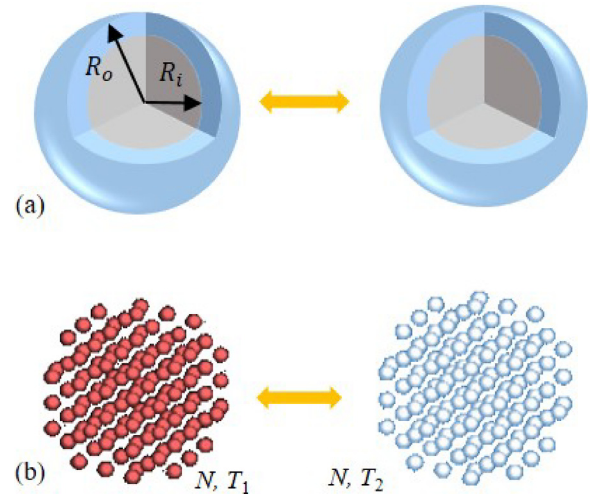

Fig. 1. (a) Geometry of two core-shell nanoparticles. The inner radius and the outer radius are given by R_i and R_o. And the temperatures of two nanoparticles maintain at T_1 and T_2 respectively; (b) Geometry of two assembled spherical systems. Both of them contain N core-shell nanoparticles arranged in cubic lattice and densely packed, and maintain at temperatures T_1 and T_2 respectively.

3. Theoretical modeling

During the past years, a number of methods haven been put forward to solve the problems of near-field thermal radiation: the thermal discrete dipole approximation (T-DDA) [34–36], the finite difference time-domain (FDTD) [37–40], the finite difference frequency-domain method (FDFD) [41], the dyadic Greens function [42], the boundary element method (BEM) [43], etc. Additional information about closed form solutions of the NFTRT derived for special geometries can be found in previous studies [44–46]. In this study, we choose the coupled electric and magnetic dipole (CEMD) approach developed by Dong at el. [28] as the theoretical framework. And each nanoparticle can be modeled to simple radiating electric and magnetic dipoles. To calculate the NFTRT of core-shell nanoparticles, the polarizability is an indispensable parameter. So we implement the *n*-layer Mie Solution provided by Volkov et al. [47] to obtain the dipole polarizability of core-shell nanoparticles. By combing the CEMD approach and the *n*-layer Mie Solution, we describe a complete theoretical investigation of the NFTRT in many body systems composed of core-shell nanoparticles. Here, we assume a set of N core-shell nanoparticles embedded in a non-absorbing environment. The ith nanoparticle locates at position $\mathbf{r}_i$ and maintains at temperature T_i. The multibody mutual interaction between nanoparticles should be taken into account. So the electric $\mathbf{p}_i$ and magnetic $\mathbf{m}_i$ dipole moments of the ith nanoparticle can be divided into two components respectively

$$\begin{pmatrix} \mathbf{p}_i \\ \mathbf{m}_i \end{pmatrix} = \begin{pmatrix} \mathbf{p}_i^{\text{fl}} \\ \mathbf{m}_i^{\text{fl}} \end{pmatrix} + \begin{pmatrix} \mathbf{p}_i^{\text{ind}} \\ \mathbf{m}_i^{\text{ind}} \end{pmatrix} \tag{1}$$

where $\mathbf{p}_i^{\text{fl}}$ and $\mathbf{m}_i^{\text{fl}}$ are the fluctuating electric and magnetic dipole moments, $\mathbf{p}_i^{\text{ind}}$ and $\mathbf{m}_i^{\text{ind}}$ are the induced electric and magnetic dipole moments.