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Thermal cooling of high-power electronics using SiO_2 nanoparticle packings

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Introduction

Nanoparticles have generated significant interests recently due to their unique plasmonic behavior under the illumination of light or when used for near-field thermal heat transport. Indeed, when nanoparticles dispersed in solvents, they exhibit very strong localized surface plasmon resonance (SPR) peaks induced by the collective free electron oscillations in a metal. We have demonstrated that at the nanoscale, the van der Waals forces dominate the interaction between the nanoparticles, resulting in nanoparticle agglomeration to create nanoparticle clustering [1]. Hence the nanoparticle packings can be designed and synthesized to yield useful and tunable properties in order to develop optimized nanostructures with novel optical, thermal and electrical properties. In this study, we first demonstrate the theory and computational method of surface plasmon resonance in nanoparticle packing. Then we proceed to analyze the optical-thermal properties of SiO_2 nanoaparticle packings using Fourier transform infrared attenuated total reflection (FTIR-ATR) measurements (ESI) on 10-20 nm and 60-70 nm diameter packed SiO_2 nanoparticle beds, and a bulk SiO_2 film. We find that the reflectivity of the nanoparticle packing exhibits a resonant-like minimum at a certain wavelength and the surface plasmon resonance frequency depends on the type and size of the nanoparticle and the interparticle spacing as well as the heat transport direction. The results show that SiO_2 nanoparticle packing exhibit a unique optical-thermal behavior and can be optimized for the next generation thermal cooling applications such as high heat dissipation electronics, or other high heat flux applications

COMPUTATIONAL METHOD

Finite difference frequency domain has been applied to observe the reflection spectrum of the 10-20 nm and 60-70 nm diameter packed SiO_2 nanoparticle beds, and a bulk SiO_2 film by solving Maxwell's equations. Moreover, the SiO_2 nanoparticles were surrounded with air which the refractive index is taken as n=1 and dielectric function of the SiO2 nanoparticle based on Lorentz model[7], $\varepsilon(\omega) = \varepsilon_\infty[1 + \frac{(\omega_{LO}^2 - \omega_{TO}^2)}{(\omega_{TO}^2 - \omega^2 - i\omega\Gamma)}]$, where ε_∞ is relative permittivity at infinite frequency, ω_{TO} and ω_{LO} are the resonance frequencies of transverse optical and longitudinal optical phonons, respectively, and Γ is the scattering rate. These properties for SiO2 are also obtained from experimental data[7] ($\varepsilon_\infty = 2$, second resonance Γ =8.92 Trads-1, ω_{TO}=207 Trads-1, and ω_{LO}=234 Trads-1). We also analyze the scattering efficiency vs frequency of the SiO_2 nanoparticle bed by calculating the surface integration of the scattered Poynting vector.

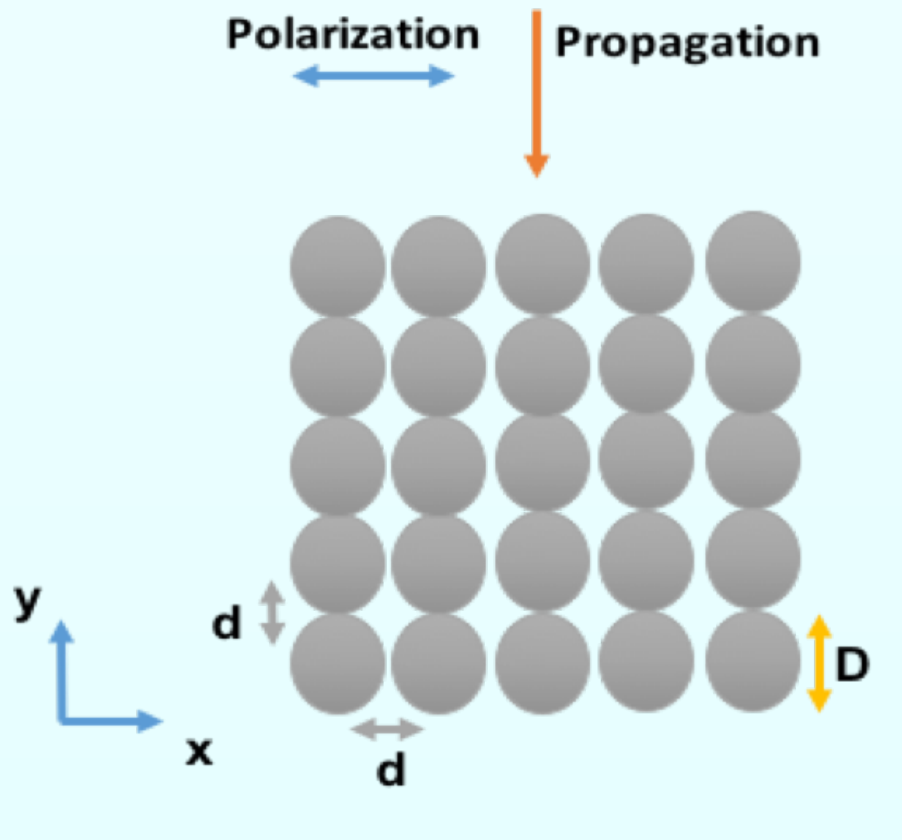

Fig 2. Particle configuration (Front view)

FTIR MEASUREMENT

FTIR-ATR measurements on 10-20 nm and 60-70 nm diameter packed SiO_2 nanoparticle beds have been performed to observe the SPhPs resonance. It has been seen that SPhP resonance frequency, ω_{SPhP}, in the frequency range between the transverse optical (TO) and longitudinal optical (LO) phonon frequencies. The FTIR-ATR spectroscopy analysis of the nanoparticle bed shows minimas in the spectrum which agrees with the expected [2-4] values of the second resonance ω_{TO} for SiO_2. Moreover, SPhPs resonance is consistent with Fröhlich resonance frequency[5] and recent experiments[6].

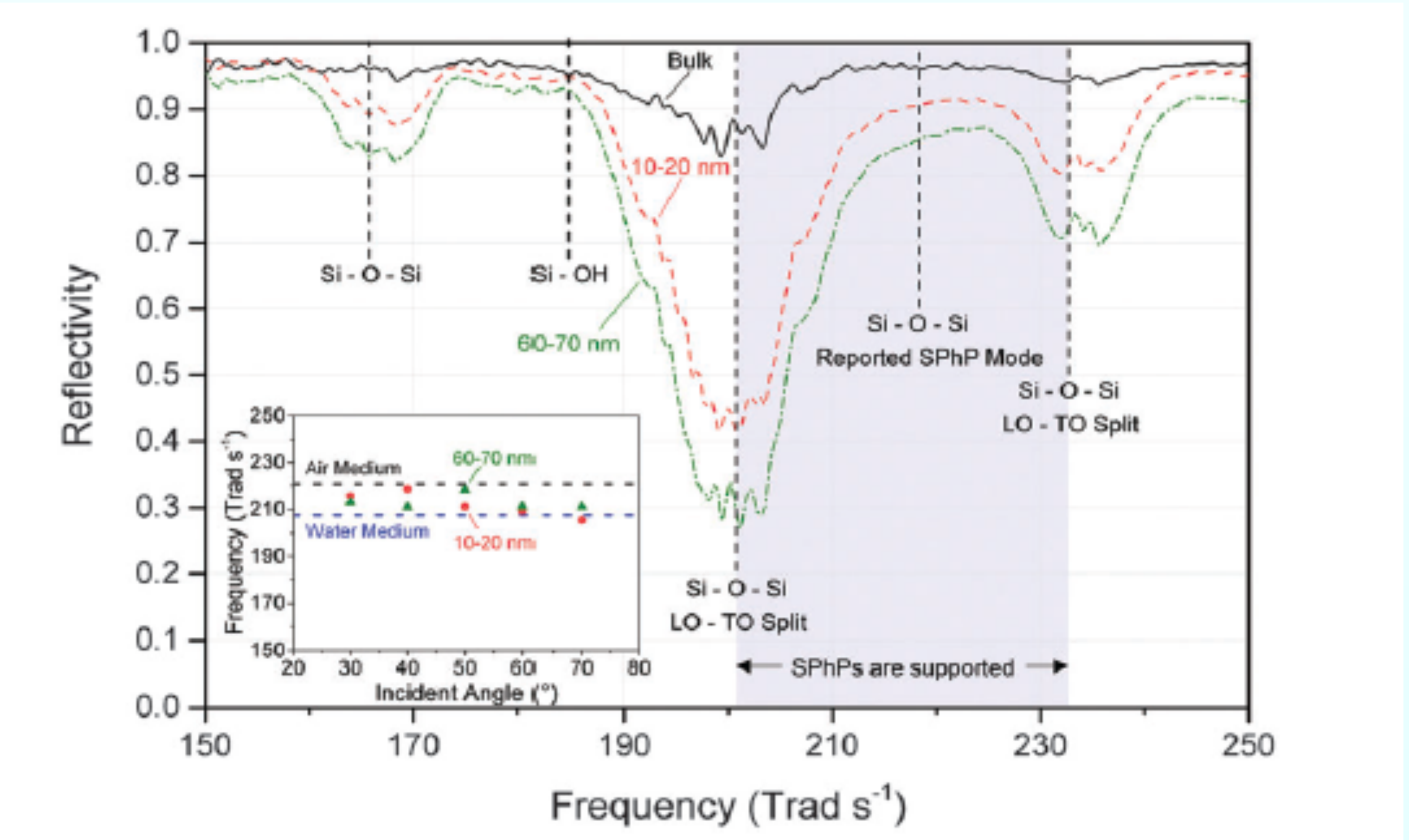

Fig 1. FTIR-ATR reflectivity of packed beds of 10-20 nm and 60-70 nm diameter SiO_2 nanoparticles, and a bulk SiO_2 film, vs frequency at an incident angle 70°

CONCLUSION

Our analysis shows that nanoscale phenomenon affects the bulk material characteristics and exhibit unique optical-thermal behavior which demonstrates the possibility of new class materials useful for better heat dissipation from high-power electronics, LEDs, data centers and other high heat flux applications. As surface phonon polariton (SPhPs) coupling play a key role within the nanoparticle packing and are capable of enhancing thermal transport over macroscopic length scales, tunability of the heat transport could be analyzed with these unique properties of nanoparticle packing in which van der Waals forces are dominant between the nanoparticles. SPhP crystals are also analogous to atomic crystals because, at discrete and ordered locations, both exhibit long-range thermal energy coupling that is defined by a unique dispersion relationship. The dispersion of SPhPs could be activated by thermal self-emission[9] or propagating infrared light[10, 11]. It is also concluded that by discrete resonance frequencies which could enable unique ways to control or enhance the flow of heat, especially in dielectric composites[12].

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