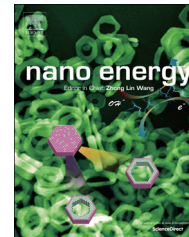




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REVIEW

Heat flow at nanoparticle interfaces



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Abstract

Nanoparticles are expected to significantly enhance future thermal energy generation systems, thermal energy storage materials, thermal interface materials and electronic devices. However, very few of these technologies are able to take full advantage of the unique thermal properties of nanoparticles, primarily due to the unusual transport phenomena that occur at their interfaces. To this end, a wealth of recent research has focused on the characterization and control of heat flow at different types of nanoparticle interfaces. The goal of this review is to provide critical insight into the mechanisms that govern thermal transport at three different types of nanoparticle interfaces, including: nanoparticle-substrate, nanoparticle-matrix and nanoparticle-nanoparticle interfaces. As part of this effort, we quantify the magnitude of heat flow at each type of interface using a collection of data that is available in the literature. This data is used to determine which physical mechanisms govern thermal transport at each different type of interface. Recent progress in the development of state-of-the-art thermal characterization techniques is also examined within the context of each type of nanoparticle interface. Finally, methods to control heat flow at different nanoparticle interfaces are discussed and future research needs are projected.

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Introduction

The physics that occur at sub-micron length scales can be manipulated in order to produce remarkable improvements in the thermal, electrical, optical and mechanical properties of materials, allowing for the development of state-of-the-art thermoelectric devices, solar cells, battery electrodes, capacitors, advanced coatings and composite structures [1-6]. The extraordinarily wide range of thermal properties that have been achieved by nanostructuring materials is primarily due to the reduction in their characteristic dimensions to the point where quantum size effects and energy carrier scattering can be precisely controlled [7-9]. As a result, nanoparticles are beginning to transform future energy technologies [10].

The intrinsic thermal properties of individual nanoparticles have been manipulated and tuned to magnitudes that diverge significantly from the thermal properties of bulk materials [11,12]. For instance, carbon allotropes are typically found to exhibit high thermal conductivities in bulk due to the strong covalent bonds that exist between individual carbon atoms, which allow phonons to traverse through them at very high frequencies. The usual example of a bulk carbon allotrope with a very high thermal conductivity is diamond, whose tetrahedral lattice structure and sp^3 atomic bonds allow for high rates of phonon transport, even in the presence of internal phonon-phonon, phonon-electron and/or phonon-defect scattering. At the nanoscale, the chemical and physical mechanisms that govern heat flow in carbon allotropes are further enhanced. In these structures, sp^2 atomic bonds are formed between neighboring carbon atoms, which allow for even higher rates of phonon transport when compared to their bulk counterparts. Further, when the characteristic dimension of the nanoparticle is less than the mean free path of an energy carrier, its transport is considered to be ballistic (i.e. no internal energy carrier scattering exists). This phenomenon has led to the development of carbon-based nanoparticles having thermal conductivities that are measured to be higher than monocrystalline synthetic diamond [13]. Excellent reviews of the physical mechanisms that control heat flow within carbon nanoparticles are given in Refs. [14 and 15].

Alternatively, some nanoparticles are designed to possess extremely low thermal properties. These are exceptionally promising for use in thermoelectric devices and highly insulating composite materials. Researchers have computationally manipulated the grain boundaries and atomic defects within nanoparticles in order to increase internal boundary and Umklapp phonon scattering, thereby reducing heat flow rates

within the nanoparticle itself [16]. Nanoparticles have also been impregnated within bulk materials in order to disrupt harmonic phonon frequencies, which are shown to decrease thermal transport significantly [17]. An excellent review of heat transfer physics in low-dimensional systems with reduced thermal transport properties can be found in ref. [18].

While nanoparticles offer remarkably high or low intrinsic thermal properties, their integration into devices remains challenging from a thermal perspective. In typical devices, nanoparticles are often placed into contact with a substrate, another nanoparticle or are embedded within a host material (matrix). In this review, the mechanisms that govern heat flow at these junctions are discussed, and state-of-the-art methods to measure and control the phonon and/or electron scattering at nanoparticle interfaces are presented.

Fundamental heat flow physics at interfaces

Heat flow at interfaces remains an important topic in a wide variety of engineering disciplines, despite the abundance of research that has been conducted in this field to date. A thermal resistance (or the degree to which the flow of heat is impeded) is generally used to characterize heat flow at an interface (i.e. interfacial thermal resistance). The interfacial thermal resistance can be classified in two ways: (1) by thermal contact resistance and (2) by thermal boundary resistance (otherwise known as Kapitza resistance). Thermal contact resistance originates from mismatches in the surface conditions of two solid bodies and is an important parameter to quantify in electronics packaging, nuclear reactors, internal combustion engines and hypersonic flight vehicles [19,20]. An excellent review of thermal contact resistance at the nano scale can be found in Ref. [21]. In this review, we replace the term ‘contact resistance’ with ‘constriction resistance’ in order to better elucidate the role of the nano-sized length scales that are associated with nanoparticles.

Thermal boundary resistance is distinctly different from thermal contact resistance in that it still occurs over atomically ‘smooth’ interfaces. This form of interface resistance is dependent on the types of materials that are in contact with one another; here, one material’s pertinent energy carriers (phonons/electrons) are ‘deflected’ at its geometric boundaries due to the differences in the electronic and acoustic properties of the contacting material, much the same way that rock formations ‘scatter’ (or break up)

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