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Review

Advances in thermal transport properties at nanoscale in China

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ABSTRACT

Thermal transport properties are a significant criterion of performance evaluation for various fascinating nanoscale materials. In this review, we summarize the recent research progresses from China in the field of nanoscale thermal transport properties. Both experimental advances and atomic-level simulation development are reviewed for typical categories of nanoscale materials and structures, *i.e.*, nanotubes and nanowires, nanofilms, nano-interfaces, nano-functional materials and those involving in near field radiation. Some fascinating aspects about the frontier issues in nanoscale heat transfer are also highlighted. In particular, researches have witnessed a remarkable growth in the interface-dominated microscopic thermal transport from both molecular dynamics simulation and experimental methods. In addition, challenges and opportunities will be touched on for the emerging field of near-field radiation. Which is dominated by simulation predictions but with encouraging experimental advances.

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Nomenclature

A	cross-section area, m^2
C	specific heat, J/kg K
d	mean grain diameter, m
K_l	latent thermal conductivity, W/m·K
l	bulk electron MFP or length, m
L	ratio between thermal and electrical conductivities
P	laser irradiation power, W
R	reflection coefficient of the electrons striking the grain boundary
R_c	thermal contact resistance, m^2 K/W
t	time, s
T	temperature, K
u_h	velocity of thermomass gas, m/s
x	heat conduction direction

Greek symbols

α	thermal diffusivity, m^2/s
γ	ratio of specific heat at constant pressure to that at constant volume
θ	temperature rise, K
κ	thermal conductivity, W/m·K
ρ	density, kg/m^3
τ	characteristic time of thermomass motion, s
τ_h	flash time, s

Subscripts

a	axial
b	bulk
f	nanofilm

1. Introduction

Recent advances in nano-synthesis and processing technology have sprouted novel materials with structures on the scale of several nanometers. Generally, representative nanomaterials comprise graphene [1,2], carbon nanotubes (CNT) [3,4], semiconductor or metallic nanowires [5,6], semiconductor or metallic nanofilms [7,8], semiconductor superlattices [9,10] and nanofluids [11]. Some of them have already come into commercial applications, while others remain being developed in the laboratory. An intriguing issue faced by nanostructured materials is how to rapidly dissipate the generated heat for device-scale usage based on these materials. Many attempts have been made to develop novel nanostructures with ultra-high thermal conductivity (κ), such as a suspended single-layer graphene with superb κ up to 5300 W/m·K [2], and a stretched carbon nanotube fiber with κ of around 770 W/m·K [12]. Meanwhile, an extremely low thermal conductivity is also highly expected to attain a high ZT value for nanoscale thermoelectric application [13]. A good example comes from quasi-one-dimensional (1D) core-shell nanowires, which renders phonon thermal conductance $G \approx 0.2 \times 10^{-9}$ W/K by means of strong phonon-boundary scattering and enhanced thermoelectric properties owing to a quantum confinement effect [14]. Undoubtedly, understanding the thermal transport properties, especially their dependence on the nanostructures for these nanomaterials are essential to the potential applications.

In the last decade, China has witnessed a rapid development in the thermal transport properties at nanoscale. Fig. 1 renders the number of academic publications on the thermal transport properties at nanoscale in China during 2008–2017 period. In general, the published papers keep an increasing trend until 2017 with a slight decrease. Both experimental methods and simulation approaches have blossomed into a golden age, when plenty of novel techniques are developed to reveal the intriguing thermal transport phenomenon for nanostructures. Various methodologies are also proposed to supplement or even challenge the classical theory for thermal transport. A good example is the thermomass theory based on Einstein's mass-energy relation, which will be introduced in details in this review. Representative advances in thermal transport characterization will be presented according to typical categories of nanomaterials, *i.e.*, microwire/nanotube/nanowire, nanofilm, interfaces and nano-functional materials. Furthermore, some initial exploration of the near-field radiation issue will also be reviewed here.

2. Microwire, fiber, nanotube and nanowire

1D micro/nanostructures such as microwires, carbon fibers, carbon nanotubes and semiconductor nanowires have recently received a lot of attention. Mesophase carbon fibers and carbon nanotubes have been recognized as promising materials for many applications requiring high heat transfer ability [15–18]. The axial thermal conductivity (κ_a) is the generally referred thermal transport property for evaluating their thermal transport performance. Most researches center on developing novel thermal transport characterization techniques and micro- and mesoscopic simulation methods for an individual microwire, fiber, nanotube and nanowire.

2.1. Experimental techniques overview

In terms of the fine microwire, fiber, nanotube and nanowire, the most representative experimental techniques for thermal transport characterization developed in China include T type probe method, 3ω method, their combination called 3ω-T type method, comprehensive T type method, H type method and laser flash Raman spectroscopy method. T type probe method was first developed by Zhang et al. [19,20], which has proven powerful for measuring κ_a of both metallic and non-metallic fibers. In this technique, a hot wire supported by two heat sinks serves simultaneously as a heater with homogeneous heat generation and a thermometer (Fig. 2a). A direct current I is used to drive the hot wire. By comparing the temperature rise of the hot wire with and without the test wire attached to its center position, κ_a of the individual wire can be accurately extracted [19,20]. Through changing the length of the test wire when an identical junction is maintained, the influence on κ_a of the thermal contact resistance (R_c) at the junction between the test wire and the hot wire can be further [21–23]. 3ω method was originally proposed by Cahill for characterizing the thermal conductivity of solids and films [24]. Wang et al. later applied it to measure κ_a for an individual conductive carbon fiber [25]. The measured fiber acts as both the heater and a thermometer driven by an alternating current in the form of $I\sin(\omega t)$ to generate the Joule heat (Fig. 2b). According to the 3ω test principle, the third harmonic voltage ($U_{3\omega}$) of the fiber contains its thermal transport information, *i.e.* κ_a and the axial thermal diffusivity (α_a). Notice this method cannot be applied to the non-metallic fiber since it relies on the conductive nature of the fiber to be tested. 3ω-T type method was proposed to take the