Int J Thermophys (2008) 29:787–789
DOI 10.1007/s10765-008-0380-6

BOOK REVIEW

Zhuomin M. Zhang: Nano/Microscale Heat Transfer, McGraw-Hill, 2007, 479 pp

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Published online: 14 February 2008

I would like to recommend a recent book on Nano/Microscale Heat Transfer to researchers and students interested in thermal physics and thermophysical properties of small systems and micro/nanostructures. The author should be complimented for putting forth such a comprehensive text within a reasonable length, covering the essential physics of thermal transport with numerous examples, illustrations, references, and end-of-chapter problems. The first chapter gives some historic perspective about microelectronics, microelectromechanical systems, and nanoscience, as well as contemporary trends in nanotechnologies. Emphasis is placed on the thermal aspects and thermophysical problems in nano- and microdevices.

Chapter 2 provides an overview of classical thermodynamic laws and heat transfer equations, with an introduction of the definitions of thermodynamic, transport, and radiative properties from the macroscopic standpoint. Chapter 3 delivers the microscopic theory with an outline of statistical distribution functions and quantum mechanics. It also discusses the energy storage modes of molecules and explains the specific heat behavior of ideal gases. Chapter 4 first uses kinetic theory to derive the transport properties, such as thermal conductivity, viscosity, and mass diffusion coefficient, from a microscopic viewpoint. Furthermore, a detailed presentation of the Boltzmann transport equation (BTE) is given and its relationship with the macroscopic conservation equations is formulated. The last part of Chapter 4 describes microscale flow, involving slip flow and free-molecule flow. Examples are given on how the heat transfer coefficient is modified by slip flow and how the thermal conductivity changes from the diffusion regime to the free-molecule (i.e., ballistic) regime.

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Chapter 5 is the central chapter of this book, covering the specific heat and thermal conductivity of solids, as well as how micro/nanostructures can affect their values, a phenomenon known as the size effect. After an introduction of the concept of phonons, the Einstein model, and the Debye model of specific heat, attention is paid to the quantum size effect on the specific heat. The physical mechanisms and trends of how size and temperature affect the specific heat of solids are explained clearly with analytical formulations. It is noted that there exist two quantum size effects on the specific heat. Furthermore, illustrative examples of the size effect on specific heat are given pertaining to graphene sheets, carbon nanotubes, and nanocrystals, with extensive references. The Drude free-electron model is then employed to describe the electrical and thermal conductivities of metals, taking into account the electron-phonon and electron-defect interactions. The BTE is then used to depict the lattice or phonon thermal conductivity. The classical size effect on thermal conductivity due to a reduction of the mean free path by boundary scattering is elegantly elaborated. Furthermore, the quantum conductances in nanostructures are presented according to the Landauer formulation, by considering the reduced density of states in quantum structures. These materials are extremely important for understanding thermal transport and thermophysical properties of materials used in microelectronics and nanodevices. Another aspect of Chapter 5 deals with thermoelectricity within the extent of irreversible thermodynamics. The analyses of thermoelectric generators and refrigerators are also presented using practical examples. This section ends with a summary of the emerging research on nanostructured materials for use to improve the performance of thermoelectric coolers.

Chapter 6 is an in-depth treatment of solid-state physics, focusing on crystalline structures, interatomic forces, electron band structures, phonon branches, and dispersion, as well as electron and phonon scattering. The Hall effect, the quantum Hall effect, photoelectric effect, and electron tunneling are also discussed. Several semiconductor devices are introduced, such as thermionic emission, field emission, p–n junctions, transistors, photoconductors, and photovoltaics. Chapter 7 concentrates on transient and nonequilibrium heat conduction in micro/nanostructures. The advantages and drawbacks of modified Fourier heat conduction equations are addressed. The equation of phonon radiative transfer (EPRT) is derived, along with discussions on the boundary thermal resistance and heat conduction through superlattice structures. This chapter completes the conduction part by developing a regime map to guide readers on what models should be applied under prescribed time and length scales.

The last three chapters provide a thorough treatment of thermal radiation, especially in micro/nanostructures. While excellent textbooks are available on electromagnetic waves and physical optics, the focus of this book is on the energy transport and radiative properties of micro/nanostructures. Chapter 8 begins with the Maxwell equations to derive the wave equation and the reflection and transmission coefficients for a plane wave incident from one medium to another. The blackbody distribution function is obtained from statistical mechanics, with a detailed discussion on the radiation entropy and a brief coverage of measurements of thermal radiation and radiation temperature. The emissivity, absorptivity, and reflectivity are defined and formulated for ideal surfaces. Furthermore, the dielectric and magnetic properties of real materials are presented with various models for metals, semiconductors, and superconductors, as well as the recently emerged class of materials called metamaterials.

Chapter 9 focuses on the radiative properties of thin films and multilayer structures. It also discusses the effect of surface roughness and partial coherence. Furthermore, the propagation and interaction of light with periodic structures such as photonic crystals and gratings are depicted. The author's group has developed a software tool, Rad-Pro, to facilitate calculation of radiative properties of multilayer structures, especially semiconductors. Chapter 10 covers the most advanced topic of thermal radiation: radiative transfer in the near-field limit, where the distances are much less than the wavelength of interest. The concept of optical fiber and waveguide is first introduced to stress the coupling of evanescent waves. Photon tunneling through a rarer medium is explained next, based on the interaction of forward and backward evanescent waves. Surface electromagnetic waves or surface polaritons, including surface plasmon polariton and surface phonon polaritons, are also introduced. Some other microstructures, such as microcavities and periodic hole arrays, and their effect on the radiative properties are presented. The energy streamline method is depicted and, finally, extensive discussion of the nanoscale heat transfer between heavily doped silicon is provided. The fluctuational electrodynamics based on the fluctuation-dissipation theorem is summarized. The last two chapters form a strong foundation of nanoscale thermal radiation.

In summary, this book is timely and may be used as a textbook for a graduate course, as well as for self-study by engineers who are interested in understanding the physical principles and/or wish to solve thermal science problems involving multiple time and length scales. The book is well written and the chapters are carefully organized. The materials are covered in sufficient detail suitable for engineering students.