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Sebastian Volz (Ed.)

Microscale and Nanoscale Heat Transfer

With 144 Figures and 7 Tables

In Collaboration with Rémi Carminati,
Patrice Chantrenne, Stefan Dilhaire,
Séverine Gomez, Nathalie Trannoy, and
Gilles Tessier

Springer

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Preface

The development of micro- and nanoscale fabrication techniques has triggered a broad scientific and technical revolution. A prime example is provided by microelectronics, which has now become nanoelectronics. Other evolutionary breakthroughs are now clearly established in the fields of optoelectronics, materials, the production and conversion of energy, and techniques for data processing and communications.

A remarkable feature of this trend is the way it has brought together physicists and engineers. On the one hand, the classical laws used to model macroscopic systems are generally unsuitable when system sizes approach characteristic microscopic scales, such as the mean free path or the length of carriers. The physical description of the individual or collective behaviour of the basic elements must then be reassessed. On the other hand, the development and integration of physical ideas exploiting very small structures, such as ultrathin films, superlattices, nanowires, and nanoparticles, in order to improve an industrial system, requires the physicist to understand some of the more technical aspects of engineering.

The international community of thermal scientists, whether in research or engineering, base their approach on the mass, momentum and energy conservation equations associated with the laws of diffusion for conduction (Fourier) and for mass transfer (Fick), and Newton's law for conduction–convection. For radiation, the radiative transfer equation is widely used to treat semitransparent media, grey or otherwise.

But this theoretical framework can no longer describe the conductive and conductive–convective transfer regimes on very small space and time scales, simply because the carriers undergo too few collisions. As the radiated thermal wavelengths are of the order of a few microns, the radiative transfer equation, and even the whole notion of luminance, become quite inappropriate on submicron scales.

One does not even need to approach the limits of macroscopic models to observe that the phenomenology of heat transfer is quite different on the micron and centimeter length scales. Whilst heat transfer is generally felt to be a slow process – the time scale for heat conduction in macroscopic systems (~ 50 cm) is a few minutes – the propagation of heat is an extremely efficient process on the microscale (~ 10 ns). Indeed, the diffusion time is proportional to the square of the length. Moreover the thermal resistances of microscale structures are so small that they become of the same order as the interface resistances between such structures. Microscale heat transfer thus occurs practically without inertia, and is essentially equivalent to interface heat transfer. Naturally, this is even more true for nanoscale heat transfer.

From the experimental standpoint, very weak and highly localised contributions must be detected in order to measure the conductive flux in nanostructures. For example, the methods used must not introduce high contact thermal resistances. Ultrafast optical methods (nano- to picosecond) and near-field microscopy are best suited to satisfy these criteria.

It is therefore clear that the study of heat transfer on micro- and nanoscales requires a quite new approach on the part of the thermal science community. The task here is to integrate the new physical models and also the novel experimental devices now available to treat energy exchanges in micro- and nanostructures.

There are many consequences for industry:

- In housing, superinsulating nanoporous materials can limit heat losses whilst increasing the ground surface, and their conductivity in vacuum is smaller than that of air.
- Nanofluids, i.e., heat-carrying liquids transporting nanoparticles, have conductivities 10–40% higher than those of the base fluid and hence a greatly enhanced transfer efficiency.
- In the nanoelectronics of processors, heating problems have led manufacturers to slow down the miniaturisation trend by switching to multi-unit structures in which several computing units are integrated into the same chip.
- Data storage will for its part be heat-assisted. Heating can activate or inhibit magnetisation reversal. It can also change the phase or the geometry of a storage medium, and this over nanoscale areas.
- Thermoelectric energy conversion is currently undergoing a revolution through manipulation of the thermophysical properties of nanostructured materials. In 2002, certain superlattice alloys were able to produce an intrinsic performance coefficient twice as high as had ever been measured for a bulk solid material. This breakthrough was achieved by improving thermal properties.

In all these fields of application, our understanding of the relevant heat mechanisms and the associated modelling tools remains poor or at best imperfect.

The present book brings together for the first time the physical ideas and formalism as well as the experimental tools making up this new field of thermal science. Although these are usually considered to be the jurisdiction of the physicist, the aim of the book remains quite concrete, since it seeks to solve the problems of heat transfer in micro- and nanostructured materials. The book itself results from a collaborative network in France known as the *Groupement de Recherche Micro et Nanothermique* (GDR), bringing together teams organised by a unit of the *Centre national de la recherche scientifique* (CNRS)[1] and a unit of the department[2] of *Sciences pour l'Ingénieur*. This group combines research centres involved in thermal science, solid state physics, optics and microsystems. Each chapter has been written by one or several authors – sometimes belonging to different research teams – and then edited by experts and non-experts in the GDR.

The first part of the book is theoretical, making the connection between the fundamental approaches to energy transfer and the quantities describing heat transfer. Chapter 1 considers the limits of classical models on small scales. Chapters 2, 3 and 4 then treat the physical models describing heat transfer in gases, conduction, and radiation, respectively, all on these small scales.

The second part of the book covers the numerical tools that can be implemented to solve the previously formulated equations in concrete situations. Chapters 5 and 6 examine solutions of the Boltzmann and Maxwell equations, respectively. Having discussed continuum models, microscopic simulations are tackled in Chap. 7 via the Monte Carlo method and in Chap. 8 via the technique of molecular dynamics simulations. In each chapter, it is shown how to calculate a heat flux or conductivity explicitly through various examples.

The last part of the book deals with experimental approaches. Chapter 9 introduces different forms of near-field microscopy and discusses their applications in thermal science. A thermal microscope is presented in some detail with example applications. Chapter 10 discusses optical techniques as provided by the photothermal microscope and reflectometry, whilst Chap. 11 brings together optical and near-field microscopy in a single hybrid system. This series of chapters on microscopy is followed by two chapters presenting the thermal applications of femtosecond lasers in pump–probe configurations. Chapter 12 deals with the electron–photon interaction on ultrashort time scales and Chap. 13 treats of thermal–acoustic coupling in various types of structure.

The book thus constitutes a particularly complete and original collection of ideas, models, numerical methods and experimental tools that will prove invaluable in the study of micro- and nano-heat transfer. It should be of interest to research scientists and thermal engineers who wish to carry out theoretical research or metrology in this field, but also to physicists concerned with the problems of heat transfer, or teachers requiring a solid foundation for an undergraduate university course in this area.

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Paris, *Sebastian Volz*
November, 2005

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