

NANOSCALE HEAT TRANSFER AND INFORMATION TECHNOLOGY

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ABSTRACT

The summary from Goodson's group on their recent work on heat transfer issues in the microelectronics and data storage industries illustrate the critical role of heat transfer for some areas of information technology. In this article, we build on their work and discuss some directions worthy of further research.

INTRODUCTION

The paper from Goodson's group summarized their recent work on heat transfer issues in microelectronics and data storage technologies [1]. Several interesting messages are delivered through their work. One is that heat transfer in nanostructures deviates significantly from that in macrostructures, as exemplified by the hot spots in MOSFET and the excessive temperature rise in interconnects. These nanoscale effects can be detrimental for some devices, as in the temperature overshoots of microelectronic devices, but can also be explored as mechanisms to create new data storage technologies. Another interesting point is that heat transfer issues often involve multi-physical issues and multi-scales. In microelectronics, heat is generated by electron-phonon interactions. The determination of the location of heat generation becomes a nontrivial issue. Heat generated in a chip must be eventually dissipated into the environment, and microtechnology can be used for developing advanced heat rejection systems, as the multiphase microchannel systems being developed in the Goodson group.

In this article, I will build on the paper by Goodson et al. to address some further directions. I will first give more examples of nanoscale heat transfer issues in information technology, followed by some discussion on the fundamental issues that are worthy of further exploration.

MORE EXAMPLES

As the gate length of MOSFET (metal-on-semiconductor

field-effect transistor) continues to decrease, it is also predicted that the operating voltage cannot be correspondingly reduced while maintaining a low leakage current [2]. Cryogenic operation of electronic devices is being seriously considered by the microelectronic industry to improve their performance. The phonon hot spot effect discussed in Goodson et al.'s paper will be even more significant at lower operation temperatures, i.e., the deviations from the predictions of the Fourier law will become larger, because of the increasing phonon mean free path in bulk materials with decreasing temperature. How this effect will impact the scaling of microelectronic devices has not yet been carefully examined.

Another key component of information technology is semiconductor diode lasers which are usually made of multilayer thin films. Two major types of semiconductor diode lasers, edge-emitting lasers and vertical-cavity surface emitting lasers (VCSELs) are currently being commercialized and are used in a wide range of applications including laser printers and high density optical disks, thus playing a central role in today's optical communications. The excessive temperature rise in VCSELs, partly due to the high electrical resistance created by the heterointerfaces and partly due to the low thermal conductivity of the multilayer structures, had been the road block for their commercialization until a few years ago. Studies on the thermal conductivity of superlattices were partly motivated by this issue [3]. Although this problem has partly been solved for some low power applications, heating is still the most important factor limiting the power output and is more severe for near infrared lasers due to their large nonradiative recombination that is eventually converted into heat. Edge emitting devices have less of a heating problem than VCSELs but their facet damage is often associated with heating. The high power outputs required to achieve reliable optical performance, coupled with the low thermal conductivity of multilayer thin-film structures, often result in a short device life. The reduced thermal conductivity occurring in multilayers calls for careful design of the devices to minimize the number

of interfaces and to allow efficient heat removal from the gain region.

While heating in integrated circuit and in semiconductor lasers are undesirable and need to be “managed”, the heating is actually used extensively as a means for writing data onto storage medium, as illustrated in Goodson et al.’s paper. In magnetic hard drives, one of the major factors that determine data storage density is the separation distance between the slider and the magnetic disk known as the flying height. In present-day hard drives the flying height is less than 50 nm while the disk rotates at $\sim 10,000$ rotations per minute (rpm). The airflow between the slider and the disk is crucial in maintaining the height of the disk and is very different from the predictions of continuum fluid mechanics at this small spacing [4]. Another factor to be taken into account is the thermal creep [4], and this effect has also been proposed for novel levitation-based recording systems [5]. Equally important to the storage density is the size of the magnetic domain. It is difficult to increase the storage capacity of current magnetic disks beyond a density of 40 Gb/in² [6] because of the superparamagnetic effect that affects magnetic domain stability. New magnetic materials with larger magnetic anisotropy are being developed [7], and heating has been proposed as a means to assist the writing processes [8,9]. Meanwhile, alternative technologies are being developed, such as the AFM-based local heating for writing into polymers. Many rewritable CDs are based on the phase change caused by laser heating [10-12]. For such applications, it is desirable to limit the heating within a small domain. Nanoscale heat transfer effects including reduced thermal conductivity of thin films and nonlocal heat conduction surrounding nanoscale heating spots can be utilized to confine heat for writing smaller spots.

Fundamental Issues

Heat Conduction. The hot spot issue discussed in Goodson et al.’s paper represents a different class of heat transfer problems compared to heat transfer inside thin films and nanowires. The latter can be considered as internal heat conduction issues, while the former are external heat conduction issues, in analogy to rarefied gas dynamics. Heat conduction around a nanoparticle is one of the simplest examples of the hot spot issue [13]. The work on heat conduction in the vicinity of a nanoparticle was based on several assumptions, including a gray phonon interface between the nanoparticle and the surrounding medium, and considering phonon heat conduction only. While such an assumption may be fine for distinct interfaces, it is not a good one for heat generation on the drain side of a MOSFET. Further modeling from Goodson’s group and our group all shows that such a hot spot effect does exist, even if the heat generation region is of the same material as the host [14,15]. Goodson group’s work further suggests that the distinction of optical phonons from acoustic phonons is important, and also important is the consideration of the electron-phonon scattering mechanisms [16].

Compared to the many existing studies of heat conduction in thin films and increasing understanding of nanowires, the understanding of heat conduction surrounding nanostructures is just at the beginning. Many questions remain to be answered

and new applications to be explored. Some are discussed below.

1. The experimental studies carried out by Goodson’s group provide the first quantitative evidence of nonlocal phonon heat conduction effects surrounding nanostructures. The effects are more pronounced at low temperatures, as expected [16]. In their experiment, the heater---also serving as the temperature sensor---is defined by a pn junction. Because the calibration is through measuring the resistance of the heater when the sample temperature is uniformly raised, there are lingering questions on how accurate it is to use such calibration data to infer the heater temperature due to the spatial temperature gradient that may overlap with the space charge region of the pn junction. More experimental studies are needed to provide further experimental data for analysis and to push to even smaller structures.

2. When the heat conduction is nonlocal, the transport is highly nonequilibrium, the temperature used to represent the modeling results is at best a measure of the local energy density, rather than their typical thermodynamic meaning. On the other hand, in microelectronics, the device reliability is often associated with the temperature through the Arrhenius law, which is a manifestation of the Boltzmann distribution and is a result obtained under the assumption of local equilibrium. A valid question is what does this temperature mean for a device. If, for example, the calculated temperature corresponding to the local energy density reaches the melting point, does it mean that local melting occur? The molecular dynamics simulations may shed some light on this question, as is discussed in Goodson et al.’s paper.

3. The simulations so far are based on either Monte Carlo methods or the Boltzmann equation and take the various relaxation times as input parameters. These parameters are subject to a wide range of uncertainties. The phonon relaxation time, for example, were mostly derived from the modeling work in the 1950s and 1960s on the thermal conductivity of bulk materials. The relaxation time in these models is often obtained under various approximations, such as the Debye model for the phonon dispersion. There are many variables in these past models that can lead to different values of the relaxation time. There is a clear need for more accurate information on the relaxation times. Molecular dynamics simulation may be one way to obtain them. Similarly, electron-phonon scattering processes also need further consideration, particularly when electrons have very different temperatures from that of phonons.

4. In addition to the different application problems in microelectronics and in data storage, there are also new fundamental problems associated with nonlocal heat conduction. Past studies have considered phonons only. The concurrent electron and phonon nonlocal transport and nonequilibrium transport is an example. A recent proposal is to use the departure from equilibrium between electrons and phonons at a small contact point as a means to increase the thermoelectric energy conversion efficiency [17]. The transport in this case can well become nonlocal for both electrons and phonons. This possibility was raised, but has never been studied [13].

5. The above examples emphasize the small length scales involved in nano-devices and nanomaterials. Short time scales are also becoming increasingly important. Similar questions

can be raised for transport at short time scales as for the small length scales. Lasers can deliver a pulse as short as a few femtoseconds ($1\text{ fs}=10^{-15}\text{ s}$). Energy transduction mechanisms at such short time scales can differ significantly from that at macroscale. Microelectronic devices are pushing to the tens of gigahertz clock frequency with a much shorter transient time. The device temperature rise in such short time scales can be very different from predictions of the Fourier law.

Radiation. The discussion in Goodson's paper on the immersion lens for sub wavelength imaging also leads to another potentially fruitful research direction: nanoscale radiation heat transfer. This was actually one of the earliest microscale heat transfer problems considered by the late Professor Chang-Lin Tien and others [18], because the relatively long wavelength of photons, particularly at low temperatures, allow the observation of wave effects on photon radiative transport. Recently, there are many exciting developments related to photonics that have potential implications for the heat transfer field.

One example is the photonic crystals, which are three dimensional periodic structures [19]. Similar to the electron band structure formation in a periodic atomic potential, photon energy states in such periodic structures form bands and for appropriate geometries, absolute bandgap can form, such that no radiation can be propagated in any direction. This opens the potential of emissivity control, both spectrally and directionally [19].

A very interesting recent development is the exploration of surface waves, such as surface plasmons and surface phonon-polaritons [20-23]. Surface waves exist only at specific frequencies. The surface modes decay exponentially away from the surface and are normally not useful. However, just as in the case of tunneling, the surface mode can tunnel into a third medium, if it is brought into close proximity to the first interface. These surface modes can also be coupled by grating structures to propagate waves into free space [21]. Because the surface waves have a relatively long mean free path and because they exist only in a narrow wavelength range, the thermal emission from such surface modes can be coherent and nearly monochromatic and can be potentially exploited for improving the efficiency and energy density of thermophotovoltaic energy conversion [24].

The above discussions focus on the photon transport. Another effect of nanostructures is to change the optical constants. For example, the energy spectrum change of electrons and phonons due to quantum size effects will create subsequent change on the optical constants. Another example is the anomalous skin effect that occurs when the electromagnetic field varies strongly over the mean free path of electrons, similar to nonlocal phonon heat conduction effects described above [18]. The impacts of these changes on radiative heat transfer have not been explored, except for the anomalous skin effects.

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