Effects of Nano-Scale Heat Transfer

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Abstract –

Through research it is known phonon and electron transport at Nano-scale plays a huge role in heat transfer. Their roles become more significant during heat transfer because of size effect that cause heating issues in the electronic industries. This is because research have shown that heat conduction in nanostructures does not follow the traditional Fourier Law engineers were used to. Actual testing show that size effects leads to higher temperature devices. Size effect comes from the phonon particle and wave properties interaction to interface layer. Size effect can also be exploited to create efficient thermoelectric (TE) materials that are slowly being introduced in development of nanostructured TE materials.

Waves and Particles on Size Effect

Technology has enable fabrication of materials in the Nano-scales such as quantum dots, superlattices, nanowires, and transistors (G. Chen). At this size the fundamental physics of heat transfer for size effect should be reanalyzed. Heat conduction in most semiconductors is dominated by phonons. Phonons are collective excitation of atoms or molecules that can be described as elastically arranged in matter.

The image below shows that only portion of the contact surface of Nano-scale materials are interacting. This means that the energy transfer and small fraction of the atoms are chemically interacting at the surface (Mo and Szlufarska).

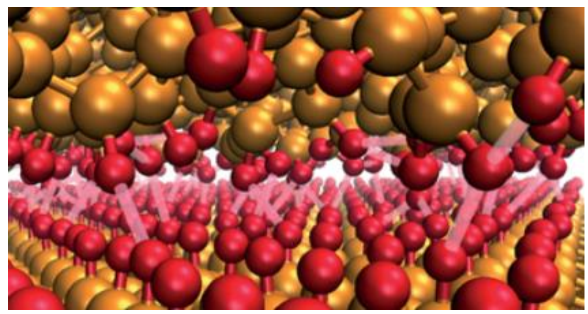

Figure 1: The uneven distributed pressure on a surface.

Size effect start appearing when the structure size is comparable to the phonon characteristic length or size (Chen, Chen and Yang). At this size there are two effect that can exist for phonons. The classical size effect where the phonons are treated as particles. The other scenario is when the phonon wave effect plays an important role. To tell which regime we are in, particles or wave, we have to look at the characteristic lengths of phonon heat conduction (Chen, Chen and Yang).

The characteristics lengths of phonons are determine by wavelength, mean free path, and phase coherence length. Depending on how the phonons are treated we can either get the classical effect of heat transfer or the waves issues. If the phonon is treated as a wave the phase effects must be included in the calculation. Superposition of waves have the following properties, diffraction, interference, and tunneling phenomena.

Chen's article explains that these factors will be needed to analyze the wave effect: interface scattering, carriers' wavelength, and carrier's spectrum. Wave interface scattering can be explain in reflection and refraction of optical waves (Chen, Chen and Yang). In this sense phonons experience the same effect.

The general idea is that when the structure is at Nano-scale, size effect becomes dominant since particle appear discrete (G. Chen). It behave as a particle or has effect that are contributed from wave effects. In the macro scale this was not noticeable because the structure overall large size makes these effect appear continuous as the particles and waves are much smaller than the structure.

Nanostructures Heat Conduction

To better understand heat conduction for Nano-scale structures, heat conduction in thin films, nanowires, and nanotubes shall be explored in greater length. We will see that thermal boundary resistance, nonlocal and fast head conduction affect these structures in various ways.

Resistance in Thermal Boundary Layer

Thermal boundary layer resistance is most prominent in hetero-structures made of multilayers thin films (Chen, Chen and Yang). The many layers act as thermal resistance and traps heat within the layers (G. Chen). This normally causes heating issues for electronic devices. The increased temperature effect comes from phonon rarefaction and non-equilibrium.

Thin Films –

A thin film has two interfaces that have many significant effect on heat transfer. The mean free path and film thickness will determine whether the phonons be scattered more frequently or not. If the film thickness is shorter than the mean free path the phonons scattering will occur more frequently (Chen, Chen and Yang).

Heating in thin film is also caused by interface scattering through diffusion. The thin film act as a wave guidance for the heat transfer so it is crucial to the transfer rate of heat. Heat transfer efficiently only when the interface is specular and experience the classical size effect (Chen, Chen and Yang). In the classical size the thermal conductivity is higher due to free-standing film that are identical to the bulk materials.

Size effects are significantly created because of the existence of interfaces in the material. Wave effect for heat becomes crucial when the film is thinner than the thermal wavelength that it supports.

For thin films there are two main way to transport electrons perpendicular to the thin film interface. The two ways are control the density of electron states with quantum size effect and the other technique is energy filtering through thermionic transport.

Though electron transport perpendicular to film plane can be exploited this exploited is not as useful as desired. If there is better possibilities or demand for exploiting this electron transport perpendicular to plane there might be more significant research. But currently there are papers signaling the benefits is not worth much right now due to feasibility (G. Chen).

Superlattices –

Superlattices are periodic arrangement of thin film structures which may be stack together (Chen, Chen and Yang). It may be described as layering of two or more materials. These types of structures have been studied mostly due to thin film importance in photonic and thermoelectric devices. For superlattices the experimental results have shown that they have lower thermal conductivities than the value calculated using Fourier law. There is lower thermal conductivities because of possible interface diffusion scattering that could occur.

All these experiments just show that using the wave effects of phonon may be more difficult than expected because of the short phonon wavelength.

The phonons in the superlattices mean free path is usually longer than the thickness of the film. Due to this the scattering effect dominates the heat conduction of the material and will rise the heat. These superlattices are usually used in semiconductor lasers.

Nanowires –

There have been many recent hot topic for nanowires going around. Basically nanowires are nanostructures with diameter of nanometer to tens of nanometers. There are various type of nanowires that may be insulating, semiconducting, and metallic.

Some research on nanowires includes its battery storage properties, strength, and capabilities (Skatssoon) (Stober). Basically nanowires has many usage but the main focus is here is its capabilities to conduct heat. Since nanowires are in the nano-scales the effect of phonon particles and wave properties come into play like before.

The main interest in nanowires heat transfer comes from the axial direction transfer. This is mostly due to the long and thin nanowire structures that makes this a core interest for researchers (Chen, Chen and Yang). If nanowires is specular and trap phonons in its structure the energy transport is say to be ballistic and will be carry along the wire (Chen, Chen and Yang).

Experiment for nanowires at room temperature have shown a lower thermal conductivity (Chen, Chen and Yang). Nanowires is different from nanotubes. Nanotubes has a single wall of carbon atoms align along it. This single wall of carbon nanotube has all the atom along the wall so the phonons can only propagate along the axial direction only (Chen, Chen and Yang).

From research it is suggested that the carbon nanotubes can have a higher thermal conductivity than that of diamond (Chen, Chen and Yang) . Though nanotubes may have higher conductivities the nanotubes thermal conductivities may vary greatly on different conditions (Chen, Chen and Yang). If the nanotubes is tangled and placed in a host material the nanotubes may experience increased interface scattering; therefore, leads to lower thermal conductivity.

<u>Ultrafast and Nonlocal Heat Conduction</u>

Fourier law also fail when the temperature gradient varies significantly within a mean free path (small distance). An example of when Fourier law fail is during metal oxide semiconductor field effect transistor (MOSFET). This fail is because the heat that is generated in a region of 10 by 10 nm is smaller than the phonon mean free path.

<u>ThermoElectrics Energy Conversion</u>

Nano-scale heat transfer phenomena holds significant effect in the productions of data storage technologies, microelectronics, optoelectronics, and energy conversion technologies. These technology are made possible by the thermoelectric effects. The thermoelectric effect is a phenomena where the electric potential create a temperature differences or vice versa where the temperature differences create an electric potential.

These effects that come from thermoelectric materials are called Seebeck effect, Peltier effect, and Thomson effect. Seebeck effect converts temperature to current and Peltier effect does the opposite by converting current to temperature. The Thomson effect is the cooling and heating of current carrying conductor that has a temperature gradient. All materials have some degree of thermoelectric effect but most are too insignificant to be useful in application.

The thermoelectric effect have been a topic of research due to its capabilities of converting waste heat to electricity (Patch). In 2001 thermoelectric efficiency is only at 18%.

The thermoelectric effect is say to be able to convert the waste heat that comes out of power plant to electricity at 18% base on research. Higher efficiency is achieve when there is higher waste heat. This effect is only significant if large amount of heat waste at 200 to 300 degree Celsius is converted. This is especially useful in power plant since they have lots of waste heat that goes directly to the environment (Patch).

<u>Conclusion –</u>

As we found out from experiment that Nano-scale structures experience a significant effect of phonons interface scattering. This scattering is usually created by the specular effect at the interface. This effect is significant since at this Nano-scale size the phonons particle – wave characteristic determine heat transfer rate. At the Nano-scale phonons wave-like properties displays a dominating role over its particle characteristics. This occurs when the superlattices is smaller than the phonon's wavelength. When the phonon wavelength is larger it usually experience scattering at the interface. This is especially true in heterostructures or thin film materials. Either way we learn that at Nano-scale heat transfer properties is very different for bulk materials and continuous research and time will only tell us what we can produce out to it.

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