Microscopic Description of Heat Conduction across Dielectric Nanofilms

José Ordóñez Miranda

Laboratoire d'Energétique Moléculaire et Macroscopique, Combustion, UPR CNRS 288, Ecole Centrale Paris, France

The blossoming of nanotechnology involving the miniaturization of devices with enhanced rates of operation requires a profound understanding of their thermal performance. This is particularly critical in nanomaterials, in which the heat transport is not necessarily described by the Fourier's law of heat conduction.

In this work, a nonlocal theory for heat conduction across dielectric nanofilms excited with a laser of modulated intensity is developed and applied to explain the reduction of their thermal conductivity observed in recent experiments. This theory is a novel and analytical solution of the Boltzmann transport equation for phonons in a dielectric film. By considering that the mean free path (MFP) and mean free time (MFT) of phonons are independent of temperature, explicit expressions for the steady state and modulated components of the temperature are derived and analyzed as a function of the film thickness and modulation frequency. It is shown that: 1) For a film thickness much greater than the MFP (diffusive regime) and for frequencies much smaller than the inverse of the MFT, the amplitude and phase of the temperature field exhibit the classical diffusive behavior predicted by the Fourier's law. By contrast, as this thickness becomes comparable to or smaller than the MFP (ballistic regime), these signals display attenuated oscillations, which strengthen as the film thickness reduces to nanoscales or the modulation frequency increases from GHz to THz. This is described as the "dance" of phonons at the rhythm of the "music" of the modulated thermal excitation. 2) The diffusion length is still a meaningful concept in the ballistic regime and its value is given by $\mu = \sqrt{2}\, l / \sqrt{3\omega\tau}$, where l and τ are the MFP and MFP respectively, and ω is the modulation frequency. 3) The cross-plane thermal conductivity k of a dielectric film increases with the ratio λ between the film thickness and the phonon MFP and is given by

$$k = \frac{k_0}{1 + \dfrac{4\beta(\lambda)}{3\lambda}}, \qquad (1)$$

which reaches its bulk value k_0 at the limit $\lambda \to \infty$. The explicit determination of the parameter $\beta(\lambda)$ is provided by our approach, which makes of Eq. (1) an accurate extension of previous formulas reported in the literature.

Our theory facilitates the understanding of heat conduction across dielectric nanofilms excited at high frequencies, and it could be used as the theoretical model to perform the microscopic characterization of nanofilms, through the determination of the MFP and MFT of phonons.

REMEMBER

Microscopic Description of Heat Conduction across Dielectric Nanofilms

October 2, 2014 – 12:00h

Place: ICN2 Seminar Hall, ICN2 Building, UAB

Invited by: Prof. Clivia Sotomayor-Torres

ICN2 Institut Català de Nanociència i Nanotecnologia

Supported by: Institució CERCA Centres de Recerca de Catalunya · Generalitat de Catalunya · CSIC Consejo Superior de Investigaciones Científicas · UAB Universitat Autònoma de Barcelona