A multi-technique approach to nanoscale heat transfer

Despite two centuries of investigations on the subject, thermodynamics still poses puzzling questions. In this context heat and mechanical energy transfer at the meso/nanoscale remains one of the greatest intellectual challenges, by far the most relevant under an applicative standpoint. When an object dimension become comparable to the mean free path of its energy carriers (phonons, electrons, etc.), or when the dimensions are scaled to the point where finite-size effects emerge (finite boundary effects, energy level quantization, etc.), the thermal properties deviate from the ones typically found at the macro-scale. On “short” length and time scales the pitfall inherent to Fourier law of heat conduction – infinite velocity of heat propagation upon establishment of a thermal gradient – becomes manifest [1].

The prominent aspect of “nanoscale” energy transfer stands in its characteristic time and length-scales. The thermal dynamics at the nano-scale (a) occurs on an ultrafast time-scale, (b) is severely perturbed by external probes, (c) involves minute energy fluxes. These issues require devising appropriate (a) ultra-fast, (b) low-perturbing non-contact, (c) sensitive techniques, which are (d) applicable on length scales down to the nanometer range.

Unveiling the mechanisms ruling thermal transport at the nano-scale will impact every day life. The acquired knowledge will foster the development of new thermoelectric materials for energy harvesting via dissipated heat recovery and thermal management strategies to enhance heat dissipation in electronic circuits.

The proposal targets heat transfer at the meso/nano-scale on its relevant time scale [2-4]- tens of femtoseconds to nanoseconds - and length-scales - nm to mm - by means all-optical Time-Resolved Microscopy (TRM) [5] and static techniques such as Raman thermometry, Scanning Thermal Microscopy (SThM) and transport measurements (3ω method). TRM fulfils the above-mentioned requirements in terms of non-contact, sensitive probes, granting ultrafast-time resolution on nano-samples, whereas static techniques will allow enlarging the set of materials (semiconductors/insulators) to be investigated and grant higher spatial resolution (SThM and 3ω-method) [6]. The project will focus on the following fundamental issues at the nano-scale: (a) thermal boundary resistance between a metallic nano-object and dielectric environment (b) a multi-technique approach to thermal nanometrology (c) transition from (i) the ballistic to non-ballistic regime (ii) the parabolic to the hyperbolic heat transport regime evidencing coherence effects of temperature fields on ultra-short length and time scales [7, 8].

The experiments will be performed on specifically engineered model systems ranging from semiconductors nanowires [9] to metallic devices nanopatterned on top of insulating/semiconducting materials. Spanning the device dimensions across the relevant phonons mean free paths will allow investigating the transition from the Knudsen to the diffusive regime. Exploiting doped semiconductors [10] and specifically engineered metal-gating strategies [11] will allow selecting the heat transport carriers (phonons vs electrons) via external electric field. Tailoring the compositional grading, interface/surface roughness and material combinations (phonon mismatch) will allow tuning the thermal boundary resistance (for the case of metal-semiconductor nanodevices) and the thermal conductivity (for the case of semiconducting nanowires).

The project will be developed jointly between “Scuola Normale Superiore” and “Université de Lyon”. The candidate will spend two years at both institutions. The successful candidate with earn two PhD degrees, one from each institution.

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