PhD thesis proposal

Heat dissipation at nanoscale and consequences on mechanical stress

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Context: *Hot spots* are one of the main causes of limitations in micro and nanoelectronic devices, since they have impacts on performances (*e.g.* temperature limits the speed at which operations can be performed) and mechanical properties (*e.g.* cracks due to variation of temperature in a device can appear and lead to device destruction). Unfortunately, it is not easy to determine the temperature field below a nanometer-scale heat source. Indeed, heat transfer through conduction is mediated by heat diffusion at macroscopic scale (Fourier's law), but not at nanometer-scale: it is instead mediated by *ballistic* heat conduction, governed by the Boltzmann equation [1]. This regime takes place when energy carriers (air molecules, electrons in metals, collective atomic vibrations called phonons in crystalline solids) move freely between domain boundaries and do not interact between each other through collisions in the volume (the mean free path islarger than the domain size). It is crucial to study the transition between the diffusive and the ballistic regimes, when energy carriers interact weakly with each other (few collisions) and with the domain boundaries. In addition, the impact of thermal boundaries at surfaces is critical in some microsystems since the surface-to-volume ratio becomes larger.

Objective: The goal of the PhD thesis is to analyze how ballistic heat dissipation can lead to a different type of strain than the one usually considered based on the Fourier heat equation, either close to small heat sources or close to interfaces. Establishing novel thermomechanical relations and testing them are planned. First results in previous studies have underlined that the error usually committed by forgetting these effects can be significant, above few dozen of percents. Both numerical, especially multiphysics-based ones [1], and experimental works, based on resistive thermometry and scanning thermal microscopy [2-3], are envisioned.

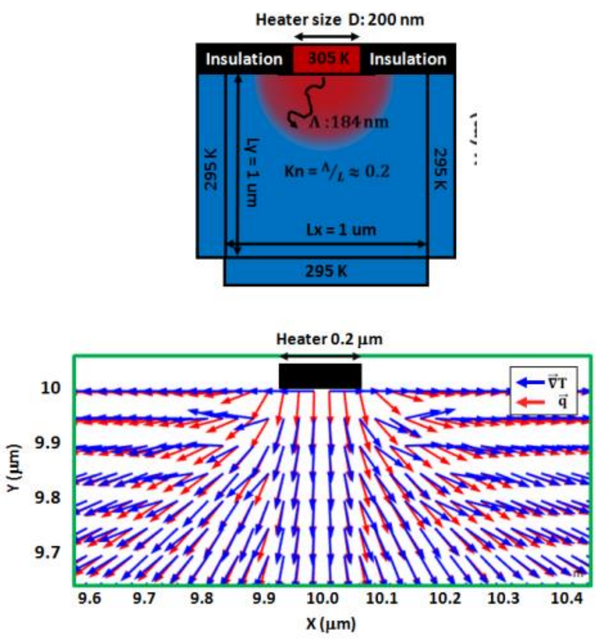

Figure: (a) Heat dissipation below a Joule-heated metallic wire of width close to the heat carrier mean free path (200 nm), i.e. in the ballistic regime. (b) Zoom below the heat source, highlighting an example of phenomenon linked to ballistic heat dissipation: the heat flux and the gradient of temperature are not aligned, in contrast to usual Fourier macroscopic heat diffusion (obtained wirth the tool discussed in [1]).

References:

[1] Coupling mesoscopic Boltzmann transport equation and macroscopic heat diffusion equation for multiscale phonon heat conduction, W. Cheng *et al.*, Nanoscale and Microscale Thermophysical Engineering 24, 150 (2020)

[2] Local heat dissipation and elasticity of suspended silicon nanowires revealed by dual scanning electron and thermal microscopies, J.M.

Sojo-Gordillo *et al.*, Small 20, 2305831 (2024)

[3] Heat dissipation in partially-perforated phononic nano-membranes with periodicities below 100 nm, A. Massoud *et al*., APL Materials 10, 051113 (2022)

Hosting group: Micro and nanoscale heat transfer (MiNT) group at CETHIL - https://cethil.insa-lyon.fr/en/node/52
The group is expert in nanoscale heat transfer and thermal-energy conversion, from atomic scale to macroscopic scale, and addresses topics related to heat conduction, thermal radiation and their applications energy-conversion devices such as thermophotovoltaics and thermoelectrics.

Collaboration: Collaborations with colleagues expert in mechanical stress/strain relationships are envisaged.

Required background: Mechanical or electrical engineering. Numerical simulations. Knowledge of the microscopic mechanisms/physics of heat transfer would be a plus. The student will be able to learn many novel concepts and is not expected to be an expert of the field at the beginning.

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