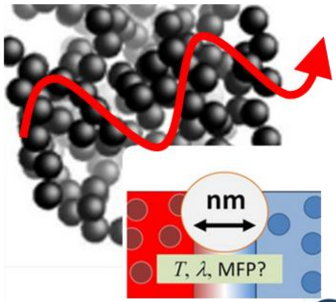

WAVE PHENOMENA AND PHONON THERMAL TRANSPORT

Scientific school

Oléron, Atlantic Coast (France)

September 3-8, 2017

GDRi Thermal Nano

GdR META
Métamatériaux acoustiques pour l'ingénierie

QuantiHeat

PROGRAMME

Sessions	Topics covered by the lectures	Lecturers		
Introduction to Elastic Waves	Acoustic wave equation, Phonon dispersion, phononic crystals, superlattices, etc.	J.F. Robillard	IEMN Lille	France
		B. Djafari-Rouhani	IEMN Lille	France
Introduction to Heat conduction	Phonon dispersion, theory of thermal conductivity, Green-Kubo, Interfaces	S. Merabia	ILM Lyon	France
	Molecular dynamics, superlattices and thermal coherence	S. Volz	LIMMS Tokyo	Japan
Vibrations in disordered materials	Vibration modes in disordered media, relaxation times by spectroscopy	V. Giordano	ILM Lyon	France
Phonon Scattering	Relaxation times	B. Perrin	INSP Paris	France
Design of 2D phononic materials	Thermophononic crystals	M. Nomura	Tokyo University	Japan
Inelastic Light Scattering	Raman and Brillouin scattering for phononic crystals	C. Sotomayor Torres	ICN2 Barcelona	Spain
Metamaterials	Acoustic metamaterials, Transformation wave equation	F. Lemoult	ESPCI Paris	France
Phononic cystals	Local resonances and bandgaps	B. Bonello	INSP Paris	France
Acoustics generated electrically	IDTs and piezoelectricity	B. Dubus	IEMN Lille	France
Heat conduction generated electrically	Electrothermal devices	O. Bourgeois	Institut Néel Grenoble	France
Low temperature and quantum devices	SINIS junctions, quantum of thermal conductance, low-temperature phononics	I. Maasilta	University of Jyvaskyla	Finland
Rectification and reciprocity	Rectification and reciprocity of heat and phonons	B. Li	University of Colorado, Boulder	USA
Numerical methods for Elastic Waves	PWE, FDTD, Green's functions for waves	J.F. Robillard	IEMN Lille	France
Numerical methods for thermal conductivity	Ab initio, Force constants	M. Lazzeri	IMPMC Paris	France
Pump-probe spectroscopy	Pump-probe measurements of acoustical and thermal properties	B. Perrin	INSP Paris	France
Opto-mechanics	Cavity optomechanics in various configurations	R. Braive	C2N Paris	France

Introduction to Elastic Waves

I. Introduction to Elastic Waves

J.F. Robillard, IEMN Lille, France

This lecture will describe basic aspects of elasticity and elastic waves propagation in solids. It is aimed at providing some practical knowledge for people interested in the field of phononic crystals and will serve as an introduction for the lecture on "Numerical Methods for Elastic Waves".

The lecture will span from the description of strain and stress tensors, Hooke's law and establish the elastic waves propagation equation. We will discuss the limitations of linear elasticity at high frequencies and its implications on nanoscale phononic crystals (thermocrystals) calculations. We will end the lecture by presenting experiments on elastic waves propagation in nanostructures.

II. Introduction to phononic crystals and metamaterials

B. Djafari-Rouhani, IEMN Lille, France

Phononic crystals are artificial materials constituted by a periodic repetition of inclusions in a matrix. They have been proposed to achieve the control and manipulation of acoustic/elastic waves. This is a fundamental problem with many potential applications in the field of information and communication technologies, acoustic isolation, imaging, sensing, optomechanics, etc. This presentation gives an introduction to these structures as well as to acoustic metamaterials. The latter are working in the sub-wavelength regime and can be described by dynamic effective properties (mass density, compressibility) which possibly can become negative.

Starting with the case of linear chains and one-dimensional periodic structures, the presentation will describe the existence and behavior of band gaps (associated with either Bragg scattering or local resonances) in 2D phononic crystals, then the localized modes inside the gaps associated with different defects (waveguides, cavities), the extension of the band structure to plate phononic crystals (with holes or pillars), the refractive properties of the phononic crystals such as negative refraction and imaging. A short overview will be given about the acoustic metamaterials and their functionalities (negative refraction, focusing, cloaking, graded index materials, metasurfaces with coiling-up space structures,...). Some emerging topics such as active materials, non-reciprocal transmission and reflection, topological phononics will be briefly mentioned. The final part is devoted to phoxonic crystals where both photons and phonons can be confined in the same cavity, thus allowing an enhancement of their interaction for the purpose of optomechanic applications.

Introduction to Heat conduction

I. Introduction to heat conduction

S. Merabia, ILM Lyon, France

This 1h30 session will address the fundamental physical mechanisms giving rise to thermal resistivity and interfacial phonon transport in solids. An introduction to the phenomenology of heat conduction will be first presented. Some basics of vibrational properties of solids will be reminded (dispersion curves, group velocity). Then, we will show the connection between the thermal conductivity in bulk solids and phonon scattering processes, showing the necessity to determine the distribution of mean free paths. Finally, we will introduce phonon scattering processes at interfaces which control thermal transport in nanostructured materials.

II. Molecular dynamics, superlattices and thermal coherence Link 1st part and link 2nd part

S. Volz, LIMMS Tokyo, Japan

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The 1h30 session will address the mechanical and atomistic foundation of heat conduction. The first part will tackle heat as a thermodynamic quantity and the derivation of heat flux and thermal conductivity from the atomic motion will be proposed. The connection between the Boltzmann and the atomic definition of thermal conductivity will also be emphasized. In a second step, phonon properties (dispersion curve, group velocitiy, mean free path, coherence length, transmission) will also be expressed in terms of the atom positions, velocities and interatomic forces. Finally, the technique of Molecular Dynamics along with a few applicative examples will be developed.

Vibrations in disordered materials

Vibrational and thermal modes in disordered materials

V. Giordano, ILM Lyon, France

In this lecture, we will present from an experimental point of view an overview of vibrational properties in amorphous systems, in connection with their thermal transport properties.
A large frequency range will be covered for shedding light onto the glass-specific temperature dependence of the thermal conductivity, with a major focus on the THz dynamics, most important for room and high temperature properties. We will also introduce the audience to the x ray inelastic scattering technique, as the only one giving access to the THz acoustic dynamics in glassy systems with large speed of sound.

Phonon Scattering

Phonons mean free paths and sound absorption: Theory and Experiments

B. Perrin, INSP Paris, France

This lecture will be devoted to the study of phonon mean free paths and sound absorption on a large frequency range. Sound absorption will be first discussed within the frame of a macroscopic approach then using the Boltzmann equation. A quantum perturbation approach will be used for the calculation of individual phonon lifetimes and the connection between Boltzmann and quantum descriptions will be derived. In the second part of this talk, accurate measurements of phonon mean free paths in GaAs up to 1 THz will be described and the results compared with a detailed theoretical analysis.

Design of 2D phononic materials

Thermophononic crystals

M. Nomura, Tokyo University, Japan

Fundamentals and resent researches on thermal conduction control by two-dimensional phononic crystal nanostructures will be discussed. We mainly focus on Si, in which thermal phonon mean free path is very long, and thus we can play with the ballisticity and wave nature of thermal phonons in phononic crystal nanostructures. We also discuss some analogy between phonon and photon transport in phononic and photonic crystal nanostructures.

Inelastic Light Scattering

Probing phonons with inelastic light scattering

C. Sotomayor Torres, ICN2 Barcelona, Spain

An introduction to inelastic light scattering (Raman and Brillouin scattering) will be given and its application to the study of Si-based membranes and phononic crystals, in the quest to understand nano-scale thermal transport. One of our aims is to advance the understanding of how the volume-to-surface ratio, phononic crystal periodicity, disorder and air convection impact on thermal phonon propagation. We will discuss the physical regimes under which the dominance of each and all of the above takes place in our experiments.

*[1] B. Graczykowski et al, Nature Comm, 4th September 2017. [2] M. R. Wagner et al, Nano Letters **16** 5661 (2016). [3] M. Sledzinska et al., Microelectronic Eng, **149**, 41 (2016). [4] B. Graczykowski et al., Phys. Rev. B **91** 075414 (2015). [5] E. Chavez Angel et al., Appl. Phys. Lett. Materials **2** 012113 (2014). [6] J. S. Reparaz et al., Rev. Sci. Instruments **85** 034901 (2014).*

Metamaterials

Soda cans: a toy model of an acoustic metamaterial

F. Lemoult, Institut Langevin, ESPCI, Paris, France

In this presentation, a brief historical review of phononic crystals and acoustic metamaterials will be made in order to better understand the differences in scales between these two types of propagation media. This will lead us to the study of a model medium of acoustic metamaterial made of soda cans. These are Helmholtz resonators which have a resonance frequency associated to a wavelength that is much larger than their characteristic size. Thus, they play the role of artificial atoms for acoustic propagation. A medium composed of several of these objects exhibit a polariton-type dispersion relationship, which can also be interpreted as a propagative medium with a large and/or negative effective compressibility. We will therefore show two different experiments which make it possible to exploit these unusual effective properties: a system focusing below the diffraction limit and another one guiding waves at dimensions independent of the wavelength. Finally, a special crystalline order will be added to this medium made of soda cans, which results in the appearance of properties that cannot be found with effective medium theory, showing that the boundary between phononic crystals and metamaterials is blurred.

Phononic cystals

Measurement of elastic and / or thermal transport properties in nanostructures

B. Bonello, INSP Paris, France

In the first part of this course, I will describe two recent studies having as a common target: the monitoring of Lamb waves propagating on a resonant system. In the first case, we investigate the transmission through a line of pillars erected on a plate when the frequency is tuned to a normal mode of the pillars (compression or bending). The second study deals with the dynamic of confinement of a Lamb wave, within a single defect in a phononic crystal slab.
The second part will be devoted to the operational principles of a laser-induced transient grating technique well suited for investigating the surface vibrations in a periodic microstructure or the vibrational modes of films of nanometric thickness on substrate, as well as the thermal transport in suspended membranes.

Acoustics generated electrically

Acoustic RF MEMS devices

B. Dubus, IEMN Lille, France

Piezoelectricity and longitudinal elastic wave propagation constitute the basic physical mechanisms involved in the classical Bulk Acoustic Wave resonators. Innovative acoustic MEMS will rely on other types of elastic waves (shear waves, guided waves in free plates or plates bonded on substrate, waves in periodic media) or transduction mechanisms (electrostriction) which are described in the first section of this talk. Operation and characteristics of emerging acoustic RF MEMS devices, such as shear and guided wave resonators, tunable resonators and phononic crystal based resonators and filters, are reviewed in the second part.

Heat conduction generated electrically

Electrothermal devices

O. Bourgeois, Institut Néel Grenoble, France

In this lecture, we will focus on thermal measurements (specific heat and thermal conductivity) made from an electrical experiment. First we will detail what is particularly specific to an electrical experiment: the type of thermometry (normal metal, semiconductor, metal-to-insulator transition materials) and the various measurements set-ups. Then we will give in details how to make a measurement using a dynamic signal: an oscillation of temperature (sensitivity, resolution and noise).
The 2f methods (or ac calorimetry) and the 3 omega methods will be illustrated by numerous examples obtained from the labs. Finally we will give an alternative technique to measure thermal and phonon transport in the ballistic regime using a differential sensor. This will be exemplified by recent experimental results obtained at low temperatures.

Low temperature and quantum devices

Phonon thermal properties at sub-Kelvin temperatures

I. Maasilta, University of Jyvaskyla, Finland

In my lecture, I will discuss the particularities of phonon thermal properties (conductance, heat capacity) at ultralow temperatures, meaning below 1K. At such low temperatures, bulk phonon scattering becomes negligible, and effects such as ballistic transport, surface scattering, quantum of thermal conductance and coherent modification of phonon dispersion become important. The second part of the lecture will focus, in particular, on the recent results of effect of periodic structures (i.e. phononic crystals) on the thermal properties.

Rectification and reciprocity

Thermal rectification: controlling heat flux via phonons Link 1st part and link 2nd part

B. Li, University of Colorado, Boulder, USA

Phonon is primitive communication tool for animals, birds, and human beings. It is also the primary heat carrier in semiconductor and dielectric materials. The frequency of phonons spans more than 14 orders of magnitude range from Hz infrasound for seismic waves, MHz diagnostic ultrasound, to THz Phonons for heat transfer. However, unlike electrons, phonons do not carry charge, thus the control of phonons is extremely difficult and challenging. About a decade ago, we proposed a phononic thermal diode model to rectify heat flux due to phonons in nanoscale [1]. A great progress has been achieved in this rapid developing field, including the experimental realization of solid-state thermal rectifier [2], thermal transistor [3], thermal logic gates [4], thermal memory [5,6], … and a new emerging field – Phononics [7] has been in shape. In this lecture, I will give an overview of past years' development in this direction. Emphasis will be given on the fundamental principle of thermal diode, and the extension of thermal diode concept to acoustic diode that switch and rectify acoustic waves [8,9] and elastic energy [10].

*[1] B. Li, L. Wang and G. Casati, Thermal diode: Rectification of heat flux, Phys. Rev. Lett. **93**, 184301 (2004). [2] C. W. Chang, D. Okawa, A. Majumdar, A. Zettl, Solid-State Thermal Rectifier, Science **314**, 1121 (2006). [3] B. Li, L. Wang and G. Casati, Negative Differential Thermal Resistance and Thermal Transistor, Appl. Phys. Lett., **88**, 143501 (2006). [4] L. Wang and B. Li, Thermal logic gates: Computation with phonons, Phys. Rev. Lett. **99**, 177208 (2007). [5] L. Wang and B Li, Thermal memory: a storage of phononic information, Phys. Rev. Lett. **101**, 267203 (2008). [6] R.-G Xie, C- T. Bui, B Varghese, M.-G Xia, Q.-X Zhang, C.- H Sow, B Li, and John T. L. Thong, An Electrically Tuned Solid-State Thermal Memory Based on Metal-Insulator Transition of Single-Crystalline VO2 Nanobeams, Advanced Functional Material **21**, 1602 (2011). [7] N.-B Li, J. Ren, L Wang, G. Zhang, P. Hanggi, and B. Li, Colloquium: Phononics: Manipulating Heat Flow with Electronic Analogs and Beyond, Rev. Mod. Phys. **84**, 1045 (2012). [8] B. Liang, B. Yuan, and J.-C. Cheng, Acoustic Diode: Rectification of Acoustic Energy Flux in One-Dimensional Systems, Phys. Rev. Lett. **103**, 104301 (2009). [9] B. Liang, X.S. Guo, J. Tu, D. Zhang and J.-C. Cheng, Acoustic rectifier, Nature Materials **9**, 989 (2010). [10] N. Boechler, G. Theocharis, C. Daraio, Bifurcation-based acoustic switching and rectification, Nature Materials **10**, 665 (2011).*

Numerical methods for Elastic Waves

PWE, FDTD, Green's functions for waves

J.F. Robillard, IEMN Lille, France

This lecture will give an overview of most popular numerical methods used to calculate elastic waves dispersion curves as well as simulate wave propagation itself. It is a follow-up of the lectures "Introduction to Elastic Waves" and "Introduction to Phononic Crystals and Metamaterials". After a brief overview, we will detail about the Plane Wave Expansion (PWE) and Finite Difference Time Domain methods (FDTD). Each method will be detailed on very simplistic cases and illustrated by applications in the fields of Tunable Phononic Crystals and Acoustic Super-Resolution respectively.

Numerical methods for thermal conductivity

Phonon thermal transport from first-principles

M. Lazzeri, IMPMC Paris, France

We will describe a numerical approach to describe the phonon thermal conductivity in a generic system. The approach is based on: i) the calculation of the intrinsic anharmonic phonon-phonon scattering coefficients entirely from first-principles (that is by solving the equations of quantum mechanics within density functional theory); ii) the exact solution of the linearized Boltzmann transport equation (that is, overcoming commonly used approximations such as the single mode relaxation time approximation, SMA). As an example of application we will describe thermal transport in graphene and other two dimensional materials, systems in which SMA fails in predicting thermal conductivity aven at room temperature.

Pump-probe spectroscopy

Pump-probe measurements of acoustical and thermal properties

B. Perrin, INSP Paris, France

The basics of pump-probe measurements of acoustical and thermal properties in solids will be detailed in this lecture. At first, a description of generation processes of very short acoustic pulses will be described as well as the detection of transient thermal and acoustic phenomena. Then standard experimental techniques will be reviewed and it will be shown how to extract acoustic and thermal data from the experiments. At the end, the emphasis will be given on terahertz coherent acoustics and the way we can fill the gap in between acoustic waves and thermal phonons.

Opto-mechanics

Cavity optomechanics

R. Braive, C2N Paris, France

Cavity optomechanics explores the interaction between electromagnetic radiation and nanomechanical or micromechanical motion. The recently achieved progress relies on the miniaturization of mechanical resonators at the nanoscale, enabling strongly decreased sensitivity towards classical decoherence mechanisms. We will cover the basics of optical cavities and mechanical resonators, their mutual optomechanical interaction mediated by the radiation-pressure force, the large variety of experimental systems which exhibit this interaction and optical measurements of mechanical motion... In addition, the perspectives for fundamental quantum physics and for possible applications of optomechanical devices will be described.

List of posters available online

- Dhruv SINGAL (Institut Néel and CEA, Grenoble, France)
  Thermal conductivity of forest of nanowires
- Jessy PATERSON (Institut Néel, Grenoble, France)
  Thermal conductivity measurements of a nanostructured crystalline semiconductor
- Rahul SWAMI (Institut Néel, Grenoble, France)
  Scanning thermal microscopy using micro-fabricated thermometric tip