NANOPHONONICS

position paper

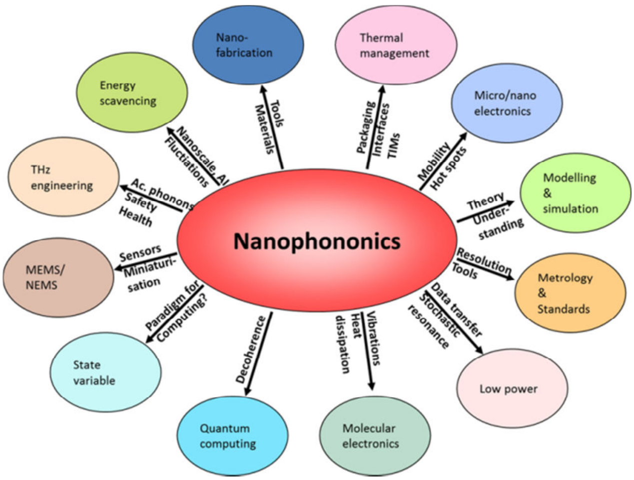
EUPHONON

Building a European NanoPhononics Community

Table of Contents

Executive summary

The EUPHONON coordination action (www.euphonon.eu) has the mission to build a European Community for Nanophononics. Nanophononics gathers the research fields targeting investigation, control and application of vibrations in solids or liquids that manifest themselves as sound or heat. This position paper aims at defining Nanophononics, bringing forth the urgent need to aggregate a Nanophononics community in Europe and boost its consolidation. This report seeks to demonstrate that phonons are at the conceptual heart of several scientific communities such as the Terahertz Phonons, Micro/Nanoscale Heat Transfer, Nanomechanics and, Optomechanics, Thermodynamics and Statistical Physics communities, see the Figure below. The accumulation of knowledge in these fields is bringing these groups closer together and a recent convergence in terms of scales and tools offers a unique opportunity to unite them. The field is very competitive and, for example, the US and China have already made extensive and long term investments. It is time to transform this competition into intensive networking with our Chinese and American colleagues. The impact of building a Nanophononics community is reaching beyond the core phononics communities since the EU's pivotal fields like Nanoelectronics, Quantum Technologies and Neuroinformatics are strongly dependent on knowledge in phononics.



Recommendations

Essential actions in the form of, for example, a FET pro-active initiative in Nanophononics would energize and galvanise active collaboration to put forward outstanding research concepts to position Europe in an undoubted leadership position in this field, which underpins future communication technologies.

The communities need more time to gather and consolidate. The current EUPHONON has made an excellent start but a fresh initiative, including industry, is a condition for long-lasting impact.

Intense networking with our Chinese and American colleagues through bilateral research projects, joint workshops and research exchanges should be seriously considered.

Foreword

This position paper originates from the discussions held during the series of "Phonons and Fluctuations" workshopss initiated in 2011. These workshops highlighted the necessity to consolidate a community to foster Nanophononics research in Europe. The EUPHONON coordination action, established in 2013 with a one-year duration, was an answer to this necessity. The consortium includes members identified as leaders in Micro/Nanoscale Heat Transfer, Terahertz Acoustics, Nanomechanics and Optomechanics. The EUPHONON coordination action had set a clear agenda of events, i.e., a Nanophononics Day held in Lille in May 2014 and an international Nanophononics Workshop held in LeMans in September 2014. During those events, consultations among the invited speakers, representing international authorities, contributed to this document, together with discussions among the EUPHONON consortium members. The EUPHONON consortium is composed of Jouni Ahopelto (VTT, Espoo), Antonio Correia (Phantoms Foundation, Madrid), Thomas Dekorsy, Martin Schubert and Eva Weig (University of Konstanz), Davide Donadio (MPIP Mainz), Pascal Ruello (Université du Mans), Clivia Sotomayor Torres (ICN2, Barcelona) and Sebastian Volz (CNRS). We thank the European Commission for the support and hope that this position paper takes European Research one step towards strengthening the European Research Area.

1. Introduction

This position paper aims to introduce Nanophononics, place it in context and exemplify its impact on ICT illustrated with representative applications.

Nanophononics is the research field targeting the investigation, control and application of vibrations in solids or liquids that manifest as sound or heat, it involves a broad spectrum of products such as cell phones and other mobile devices (via CPUs, signal converters and gyroscopes), and devices related to the "Internet of Things" (via sensors and integrated energy converters). Nanohononics also covers the activities of several scientific communities, which are not strongly connected yet. However, they constitute a research collective in size comparable to the Nanoelectronics or Nanophotonics communities. *Terahertz Phonons, Energy, Nanomechanics-Optomechanics, Nanoelectronics, Quantum Technologies, Neuroinformatics* are indeed fields strongly dependent on the new knowledge in phononics.

An expanding community. The indicators of rapid expansion are clear for the Nanophononics related reseach. More than ten papers appear each year in top journals such as Nature and Science and the total number of papers published in the field is growing exponentially as shown in the Figure 1. Notably, professor and researcher

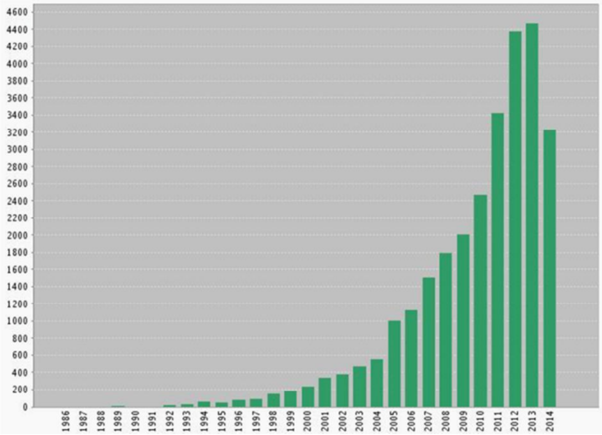


Fig. 1 > Yearly number of papers published with "Phononics" as associated keyword (ISI).

positions are opening every year in China, in the US and, unfortunately, to a lesser extent in Europe.

Why a position paper of nanophononics?

Cross-linking Knowledge. Building a Nanophononics community is crucial to consolidate a strong EU based Phononics knowledge base, which is the key to boost applications and production in Energy, Nanomechanics, Nanoelectronics, Neuroinformatics, Acoustics and Quantum Technologies. This consolidation comes naturally since the focus is on the same physical concept -phonons-, be it in the form of heat or in the form of coherent waves such as sound.

ICT applications. Thermal management remains a multiscale key issue for the integration and development of ICT devices and circuits including CPUs, memories and optical telecommunication systems. Energy harvesting through mechanical, thermoelectric or solar energy scavenging is the future solution to power the "*Internet of Things*" devices and transceivers. Understanding and controlling temperature fluctuations at nanoscale allows for pushing forward the limits of reliability of devices in nanoelectronics, neuroinformatics and quantum technologies. As ultra-sensitive probes, *micro- and nano-electromechanical systems* are following the exponential progression of mobile devices -smartphones, tablets (via gyroscopes). The *6 billions cell phones on earth include Surface Acoustic Wave and Bulk Acoustic Wave filters* transforming electrical signals to acoustic and back. The most promising applications of *Optomechanics* are also wavelength conversion and modulation of photonics signals.

In the following, the involved scientific communities and concepts are mapped to define the boundaries of Nanophononics. In the third part, four key examples are briefly exposed, which clearly illustrate the relevance of Nanophononic communities for ICTs. The fourth section presents figures and facts on the present international competition. Chapter six highlights the impact in terms of knowledge and ICT applications. Finally, recommendations close the paper.

2. Definitions

2.1 Heat at macro-to-nanoscales

Heat conduction. In solids, phonons or lattice vibrations exist as thermal energy fluctuations. At macroscales, those fluctuations are governed by the heat conduction law of

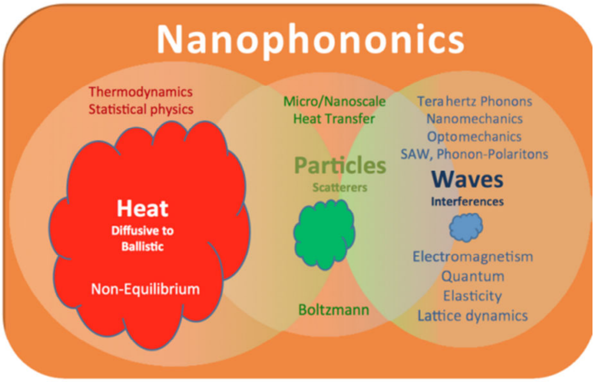


Fig. 2 > Schematic of the fields, the key physical mechanisms and scientific tools considered in the Nanophononics consortium.

diffusion well-known by mechanical engineering and bearing the underlying notion of local equilibrium.

However, these fluctuations behave very differently when system sizes and times are reduced to the micro and nanoscales since non-equilibrium states are required at those scales to describe the heat transfer. The development and implementation of non-equilibrium statistical physics then becomes mandatory to describe this transport regime, which is qualified in its limit as *ballistic*.

Radiation. When the space between two objects is reduced to below a micrometer, heat radiation is no longer described by the conventional Planck's Law of electromagnetic energy propagation but by a direct charge interaction excited by lattice waves. This mechanism is again described by statistical physics applied to electromagnetic currents and is called *Near-Field Radiation*.

To sum up, **Statistical Physics** provides a broad framework to understand thermal Phononics at multiscales that is needed for future developments.

2.2 Phonon Particles

Lattice waves combine into wave-packets, or phonon particles, to transport energy. Heat conduction can in this limit be interpreted as a flux of phonon particles like in a gas. The Boltzmann kinetic theory of phonon transport hence applies to describe the diffusive-to-ballistic regimes. Like in a gas, the source of thermal resistance in bulk solids is the collision between phonon particles. However when sizes shrink, scattering with micro and nanoscale defects (roughness, alloying, boundaries, micro/nanoparticles) becomes predominant and the Boltzmann approach treats them as specific *scattering times*.

The determination of those times, especially their spectral distribution, remains incomplete and requires tools to describe the fine interaction between the phonon-wave and the scatterer. The community of Micro and Nanoscale Heat Transfer is developing this knowledge, both experimentally and theoretically, to understand and define those scattering parameters.

2.3 Phonon Waves

Lattice waves can be decomposed into eigenmodes, the quantum of which is the phonon. These phonon modes constitute the base on which energy can manifest itself as sound or heat. In Terahertz Phononics, phonon modes are excited using a picosecond mechanical pulse and their interaction is analyzed with nanostructures that can act as a mirror or as a frequency transducer. The phonon velocities, scattering times and nature, whether thermal or coherent, can be precisely understood. The mode interaction with other quanta -and spins- is also examined. In gigahertz phononic, the surface phonon modes, Surface Gigahertz Acoustic Waves (SAW), have been used to manipulate excitons or plasmons. When terahertz surface phonon waves couple to the surrounding electromagnetic field, surface phonon-polaritons are generated that can efficiently propagate heat around nanoscale structures. Phonon modes in the Megahertz range also represent key concepts of Nanomechanics and Optomechanics, which address the vibrations of free-standing micrometre scale objects activated through electrical or optical signals.

3. Key Examples of Nanophononic Applications

3.1 Smart Windows - Internet of Things

Illustrating: Energy Harvesting and ICT Interface

Smart windows are a new wireless sensing concept using multifunctional large area transparent thin film flexible devices that can be placed on windows and walls to harvest energy. It is achieved by using non-toxic thermoelectric elements embedded in the windows and walls of buildings and even on windows and sunroofs of automobiles to power remote and smart sensors to detect CO_2, fine particles, temperature and humidity in order to provide data to monitor and enable control of environmental comfort.

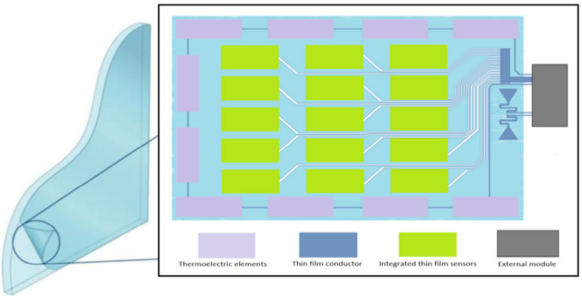


Fig. 3 > Integration of thermoelectric modules, thin film sensors and external control module in a smart window application.

In addition to the power generated from thermal energy harvesting, the thermoelectric elements are also used as temperature sensors distributed over a large area, which provides a natural way to make a touch interface between computers and people. It was indeed demonstrated that *standard oxide-based materials are sufficient for detecting heat originating from the touch of a human fingertip*.

The video "A day made of glass" http://youtu.be/6Cf7IL_eZ38 shows a detailed illustration of how glass-based ICT applications are part of our daily lives and among which smart windows are key concepts.

The thermal design of the window and the optimization of the thermoelectric elements will require knowledge in phonon transport at small scales.

3.2 Packaging - Thermal Management of ICTs

Illustrating an application in ICT reliability

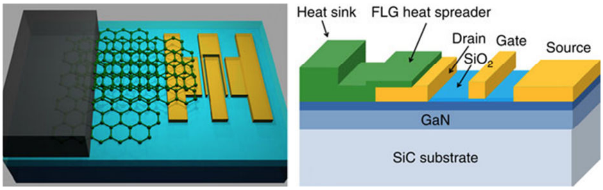


Fig. 4 > (Left) Schematic of the FLG-graphite heat spreaders attached to the drain contact of the AlGaN/GaN HFET. (Right) Device structure schematics showing the graphene-graphite quilt used in the simulation for the heat spreader optimization. Dark blue indicates the AlGaN barrier layer [1].

Size scaling of transistors and the increase of clock rates, according to Moore's law, led to an explosion in power-density for logic circuits, communication devices, and memories. Although the energy per operation is still decreasing, cramming more and more transistors in the same area increases the density of dissipated power to an unacceptable level that threatens the current fast rate of progress of the industry.

Along the path from the source in the drain region of individual transistors to the heat sink, whether in an air or in a liquid cooler, the heat flux crosses a multitude of interfaces some of them separated by bulk matter.

Still today, thermal interfaces are responsible for around 1/10 to 1/3 of the total thermal resistance in power single inline packages or microprocessor systems. Multiscale strategies are therfore very important to ensure efficient heat removal such as package-scale thermoelectric coolers, thermal interface materials including nano-objects and transistor level approaches. Those approaches all include phononics issues that still have to be addressed.

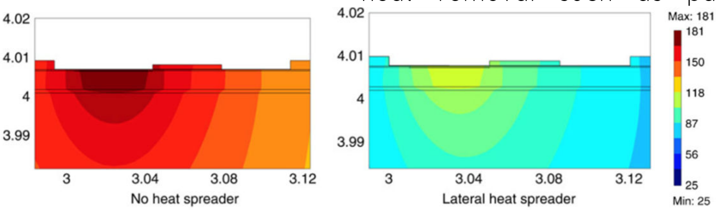


Fig. 5 > (Left) Temperature profile in AlGaN/GaN HFET on sapphire substrate powered at 3.3 W mm^{-1} without the heat spreader. The maximum temperature is T=181 °C. (Right) Temperature profile in an identical AlGaN/GaN HFET on sapphire substrate powered at 3.3 W mm^{-1} with the graphene-graphite heat spreader. The maximum temperature is T=113 °C. The stronger effect produced by adding the graphene quilt is explained by the much lower thermal conductivity of sapphire. The HFET dimensions and layered structure were kept the same in all simulations. The units used in the figures are ($m \times 10^{-4}$). The room temperature is assumed to be 25 °C [1].

In this last case, graphene was demonstrated to be a very efficient heat spreader [1] in high-power gallium nitride (GaN) electronic and optoelectronic devices. Thermal management of GaN transistors can be substantially improved via the introduction of alternative heat-escaping channels implemented with few-layer graphene. The temperature of the transistor hotspots can be lowered by ~20 °C, which corresponds to an order-of-magnitude increase in the device lifetime. Local heat spreading with materials that maintain their thermal properties at the nanometre scale represents a transformative change in thermal management.

This improvement is related to the high in-plane phonon conduction in graphene, which is strongly dependent on the direct force field environment of the carbon atoms to the material that needs to be cooled. Nanophononics related knowledge is able to predict the impact of substrate and nanoscale roughness on the properties of graphene.

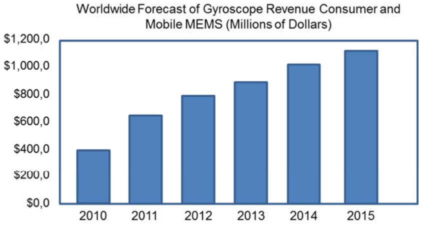


Fig. 6 > MEMS revenues in mobile applications [3].

3.3 Gyroscopes and accelerometers

Illustrating an application in mobile ICT devices and security

Sensors such as gyroscopes and accelerometers have many advantages, such as high resolution, wide dynamic range, and quasi-digital nature of the output signal. Gyroscopes were the top revenue generator in the last few years in the consumer and mobile segment of the electromechanical systems market, thanks to record sales of smart phones and tablets like Apple Inc.'s iPhone and iPad devices. Gyroscopes will continue to reap top revenues in the next few years, taking in $1.1 billion by 2015, as shown in the figure 6. In general, motion sensors like gyroscopes, accelerometers and electronic compasses will continue to dominate consumer and mobile electromechanical systems, the largest segment of an industry that has applications in the automotive (air bag triggering), medical, industrial, aerospace and defense sector [2].

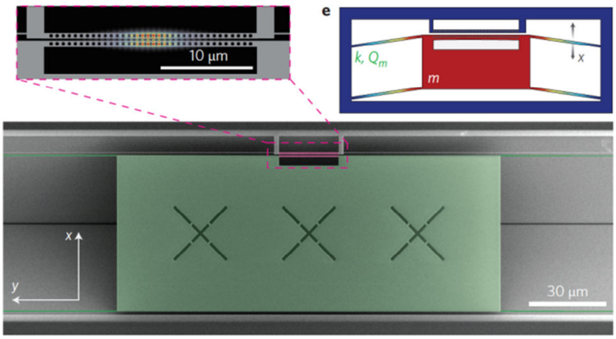


Fig. 7 > (Top-left) Zoom-in of the optical cavity region showing the magnitude of the electric field. (Top-right) Schematic displacement profile of the fundamental in-plane mechanical mode. (Bottom) SEM image of a typical optomechanical accelerometer. A test mass (green) is suspended on SiN nanotethers. On the upper edge of the test mass, a zipper photonic-crystal nanocavity (pink) is implemented [4].

The developments of accelerometers are likely to significantly gain from Nanophononics. With conventional MEMS techniques, displacements can only be measured at frequencies lower than the mechanical one, since otherwise this displacement is too small. Optomechanical cavities allow measurements of a displacements one at the quantum limit. An optomechanical accelerometer using a photonic-crystal nanocavity was demonstrated [4] achieving an acceleration resolution, power consumption, bandwidth and dynamic range comparable to that of the best commercial devices. The advantages being that this optical cavity in addition allows for an enhanced tunability, integrability and lower power consumption.

3.4 BioNEMS

Illustrating an application in health

Two widely used optical biodetection technologies are lateral flow assays and enzyme-linked immunosorbent assays. Lateral flow assays, which are routinely used for urine analysis provide quick analysis times (~minutes), ease of use and low cost. However, their concentration sensitivity is only ~0.1 µMolar. By comparison, enzyme based assays require a much longer analysis time (~1 hr), but offer much better concentration sensitivity (~1 pMolar).

Category	Description	Detection conditions	Analysis time	Limit of detection
LFA: lateral flow assay	Pregnancy test	Urine	3 min	10 µM
IFA: immunofluorescent assay	ELISA	Serum	60 min	0.1 pM
	Integrated blood barcode chip (IBBC) with DEAL	Whole blood	90 min	1 pM
	Microfluidic fluorescent immunoassay	Cell-culture supernatant	45 min	1 pM
	Bead-based microfluidic immunoassay with zM sensitivity	4 protein mixture in PBS with 1% BSA	210 min	0.4 pM
Mechanical detection				
Label-free real-time detection				
MC: microcantilevers	Static mode (surface-stress sensors, SSS), functionalized reference	HBST buffer	10 min	15 nM
	SSS, unfunctionalized reference, piezoresistive detection	0.1 mg ml^{-1} BSA	12 min	300 pM
	SSS, no reference cantilever	1 mg ml^{-1} HSA	100 min	100 pM
	Dynamic mode detection (mass sensing)	PBS	12 min	0.3 pM
SMR: suspended microchannel resonator	Protein detection in serum	Serum	1 min	300 pM

Fig. 8 > Comparison of the performance of optical and mechanical detection in terms of analysis time and Molar sensitivity [5].

On the other hand, nanomechanical systems are particularly well matched in size to molecular interactions, and provide a basis for biological probes with single-molecule sensitivity. An outstanding challenge in biosensing is to engineer biochemical agents to capture the target biomarkers to be detected, which generally occurs only in the liquid phase. After capture, target detection is ideally performed in situ, within the fluid, but mechanical sensing in a fluid is strongly affected by viscous damping thus significantly reducing the mass resolution compared with that obtained in gas or vacuum. Consequently, microcantilever sensing typically requires 10 minutes analysis time to detect 15 nM, i.e., a sensitivity hundred times lower than the one of enzyme assays.

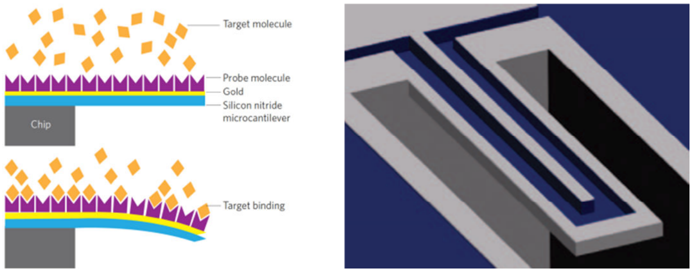


Fig. 9 > [5] (Left) Schematic of static-mode surface-stress sensing MEMS device. (Right) Suspended microchannel resonator (SMR). The fluid containing the target molecules flows through a channel inside the device and binds to the inner flow-channel walls, while the resonator oscillates in air or vacuum.

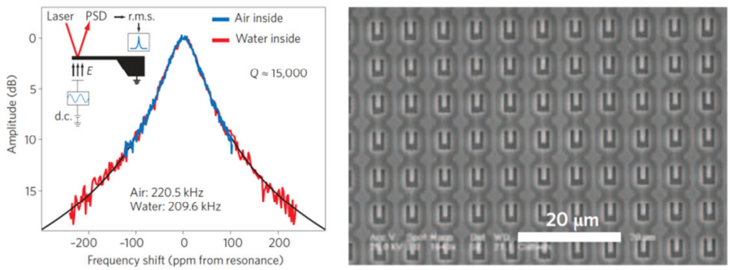


Fig. 10 > (Left) Resonance spectrum of a single mechanical resonator. The quality factor of the device is unaffected when the channel is filled with water (red line). (Right) Array of silicon cantilevers [5].

The concept of suspended microchannel resonators illustrated below in Figure 9 allows for a mechanical detection in air with a very small-immerged volume. The degrading effect of water viscous damping is then largely limited as shown in Figure 10 (left). A 20-fold increase in sensitivity and a ten-fold decrease in time compared to microcantilevers have been demonstrated. By multiplexing (see Figure 10 right), the cantilever type detection it is also feasible to increase the collision probability between targets and probe molecules or to detect several targets at once. This constitutes a notable asset that conventional methods do not afford.

4. International situation

The global competition mainly involves the US and China.

Prof. Baowen Li is leading the phononics community in Asia and has gathered *several tens of millions of dollars to establish the "Center for Phononics and Thermal Energy Science" [6] in Shanghai* recruiting 20 professors and organizing biannual international schools and conferences.

In the US, as in Europe, phononics is scattered among the transport physics (APS), materials (MRS) and heat transfer (ASME) communities, each having their own events, usually symposia in large international conferences, [7] and programs (NSF, DARPA, DoE, ARPA-e, ONR). A noticeable increase of research was sparked with the DoE funding of Centres of Excellence in Basic and Applied Energy Research running into several tens of millions of dollars. The total amount of funds is difficult to estimate but to provide an order of magnitude, MIT received 15 million dollars over 5 years for one of his Arpa-e Centers [8] and this sort of program has been regularly funded for 20 years now. US universities are also hiring professors at a high rate in the field of phononics, and the top ones do have dedicated phononics laboratories. Each year, US teams are also actively publishing in high profile journals such as Science and Nature.

The collaboration between the USA National Science Foundation and the Chinese Academy of Science has already seen a bilateral workshop and Postgraduate School held this year in China.

Europe has strong assets as it has pioneered several phonon related fields and several European teams are considered as international leaders. Certain communities have their own national network, such as the French CNRS "Groupement de Recherche" on Thermal Nanosciences and Nanoengineering. They also have their own events including "Son et Lumière" workshops, Eurotherm seminars, THERMINIC, CECAM workshops, e-MRS symposia, the European Conference on Thermoelectricity [9] as well as regular nano- and optomechanics workshops held e.g. at ICTP Trieste or Monte Verita. An initiative of the EUPHONON consortium started the yearly Phonons&Fluctuations workshops in 2011.

The EC also has been funding large FET, ICT and ENIAC projects and ICTs such as NANOTEG, NANOPACK, NANOTHERM, ZEROPOWER, MERGING, TAILPHOX, NANOPOWER, QNEMS, MINOS, cQOM, SIQS, iQUOEMS and TherMiQ [10].

International conferences with *international boards* have to be highlighted such as the 40-years-old "Phonons" and the new "Phononics" [11] conferences or the ICHMT and ICHT [12] heat transfer conferences with periods of three to four years.

5. Impact

Cross-linking Knowledge. Building a Nanophononics community is crucial to consolidate a strong EU based phononics knowledge base, which is the key to boost applications in Energy, Nanomechanics, Nanoelectronics, Neuroinformatics, Acoustics and Quantum Technologies. Those domains indeed need to be considered from the phononics point of view. Optomechanics is a striking example: the field was launched by the Optics community, which saw radiation pressure as the key mechanism. However, photoelasticity, a phonon related property, was found to be predominant at the nanoscale.

Experimental and fabrication tools. Gathering a Phononics community now is a well timed initiative since the Terahertz Phononics groups have implemented metrology and fabrication tools that allow the manipulation of the frequencies in the range of thermal phonons, which are at the core of the heat transport community interests. Gathering and consolidating these communities thus becomes natural and urgent as the first papers appear showing the benefit of controlling Terahertz phonons for heat-related applications (The Economist, Channelling heat - Good conduct, Jan 26th 2013 and [13]).

ICT applications. Thermal management remains a mutiscale key issue for the integration and development of ICT devices including CPUs and photonics sources. Research in packaging is currently very active in several directions including thermoelectric devices and thermal interface materials (project-nanoteg.eu, project-nanotherm.eu) where phonons are the key carriers. Energy harvesting through mechanical, thermoelectric or solar energy scavenging is the perceived future solution for powering "*Internet of Things*" microdevices (source: STMicroelectronics). Due to *the very low power on the order of a few microW required for today's microsensors and actuators*, even low efficieny systems or conversion techniques extracting energy from the environment remain relevant. Phonons are here also crucial, for obvious reasons in the cases of mechanical and thermoelectric conversions but also for solar conversion as the electron-phonon decay drives the efficiency of the solar cell.

Understanding and controling temperature fluctuations at the nanoscale also necessitate knowledge in phononics in so far as those fluctuations are the direct expression of atomic vibrations. Temperature fluctuations are setting the limits of reliability in nanoscale systems where *the state modification is driven by energy comparable to the noise energy* $k_B T$. The developments in nanoelectronics, neuroinformatics and quantum technologies are therefore strongly dependent on the decrease of the phonon noise.

As ultra-sensitive probes, *micro- and nano-electromechanical systems* represent one of the key application fields in phononics, due to the exponential progression of *mobile devices,* such as smartphones, tablets, (via gyroscopes), or with *biosensors* at the molecular scale. The basic ability of those probes relies on their resonant vibrational modes, which constitute the core interest of the phononics community. As device sizes shrink to nanoscales, noise and reliability are still to be controlled.

Today's electromagnetic-to-electronic signal conversion for communication is essentially based on acoustic devices. At a given coupling frequency, the acoustic wavelength is several orders of magnitude smaller than the electromagnetic one, which allows for size downscaling. The *6 billions cell phones on earth therefore include a Surface Acoustic Wave device* for the electromagnetic-to-electronic signal conversion. The most promising applications of Optomechanics are also targeting the wavelength conversion of photonics signals.

As a conclusion, aggregating a community with the nanophononics concept at its heart will strengthen the impact of modern miniaturization on the main societal challenges such as health, energy, transport and security. It will enable the EU to take and maintain leadership in crucial areas and be a serious contender in future technological revolutions.

6. Conclusions and recommendations

This position paper has highlighted the crucial urgency of building a European Nanophononics community, which is the goal of the EUPHONON coordination action. Phononics, as the investigation, control and application of vibrations in solids or liquids that are expressed as sound or heat, is at the crossroad of several communities. Terahertz Phonons, Micro/Nanoscale Heat Transfer, Nanomechanics, Optomechanics, Thermodynamics and Statistical Physics share a continuum of knowledge and are reaching now the same space and time scales. US and China have started programs to support Phononics, and in the case of the US, needless to say, this happened a long time ago. Key ICT devices such as the ones involved in mobile applications but also fields critically depending on the control of thermal fluctuations like Nanoelectronics, Quantum Technologies and Neuroinformatics will benefit from Nanophononic knowledge and metrologies.

The EUPHONON consortium will soon deliver a Strategic Research agenda and a preliminary Roadmap.

Recommendations

Essential actions in the form of, for example, a FET pro-active initiative in Nanophononics would energise and galvanise the active collaborations to put forward outstanding research concepts to position Europe in an undoubted leadership position in this field, which underpins future communication technologies.

The communities need more time to gather and consolidate. The current EUPHONON project has made an excellent start but a fresh initiative, including industry, is a condition for long-lasting impact.

Intense networking with our Chinese and American colleagues through bilateral research projects, joint workshops and research exchanges should be seriously considered.

References

[1] Zhong Yan, Guanxiong Liu, Javed M. Khan & Alexander A. Balandin, Graphene quilts for thermal management of high-power GaN transistors, Nature Communication, 3, 827, 2012
[2] Deyong Chen, Zhengwei Wu, Lei Liu, Xiaojing Shi and Junbo Wang, An Electromagnetically Excited Silicon Nitride Beam Resonant Accelerometer, Sensors, 9(3), 1330-1338, 2009
[3] https://technology.ihs.com/389490/booming-iphone-and-ipad-sales-make-gyroscopes-the-top-consumer-and-mobile-mems-device-in-2011
[4] Alexander G. Krause, Martin Winger, Tim D. Blasius, Qiang Lin and Oskar Painter, A high-resolution microchip optomechanical accelerometer, Nature Photonics, 6, 768, 2012
[5] Jessica L. Arlett, E.B. Myers and Michael L. Roukes, Comparative advantages of mechanical biosensors, Nature Nanotechnology, 6, 203, 2011
[6] http://phononics.tongji.edu.cn/ehome.cn/en

[7] www.asmeconferences.org/congress2014, www.aps.org/meetings/march/index.cfm, www.mrs.org/spring2014/ (2006)
[8] http://s3tec.mit.edu
[9] www.ioffe.ru/sonetlumiere/index.htm, http://eurotherm103.scientific-event.com, http://therminic2014.eu, www.cecam.org/workshops.html, www.mrs.org/spring2014/ -symposium D, http://ectmadrid2014.com/
[10] www.project-nanoteg.com, http://project-nanotherm.com
[11] www.phonons2012.com, http://phononics2015.org
[12] www.ihtc-15.org
[13] Engineering thermal conductance using a two-dimensional phononic crystal, Nature Communications, 5, 3435, 2013 Nanophononic Metamaterial: Thermal Conductivity Reduction by Local Resonance, Phys. Rev. Lett. 112, 055505, 2014

Contributors

EUPHONON partners

Sebastian Volz	Laboratoire d'Energétique Moléculaire et Macroscopique, Combustion, (UPR CNRS 288), France
Clivia M. Sotomayor Torres	Catalan Institute of Nanoscience and Nanotechnology (ICN2), Spain
Jouni Ahopelto	VTT Microsystems and Nanoelectronics, VTT Technical Research Centre of Finland, Finland
Pascal Ruello	Institute of Molecules and Materials of Le Mans (IMMM UMR CNRS 6283, Université du Maine, France
Davide Donadio	Max Planck Institute for Polymer Research (MPIP), Max Planck Society (MPG), Germany
Thomas Dekorsy Martin Schubert Eva Maria Weig	Department of Physics, University of Konstanz, Germany
Antonio Correia	Phantoms Foundation, Spain

CNRS France

ICN2 Spain

Teknologian Tutkimuskeskus Finland

Université du Maine France

Max-Planck Gesellschaft Germany

Universität Konstanz Germany

Phantoms Foundation Spain

Funded by

SEVENTH FRAMEWORK PROGRAMME