NANOPHONONICS

position paper
strategic research agenda
roadmap

december 2014

PART III - ROADMAPPING

executive summary

Executive summary

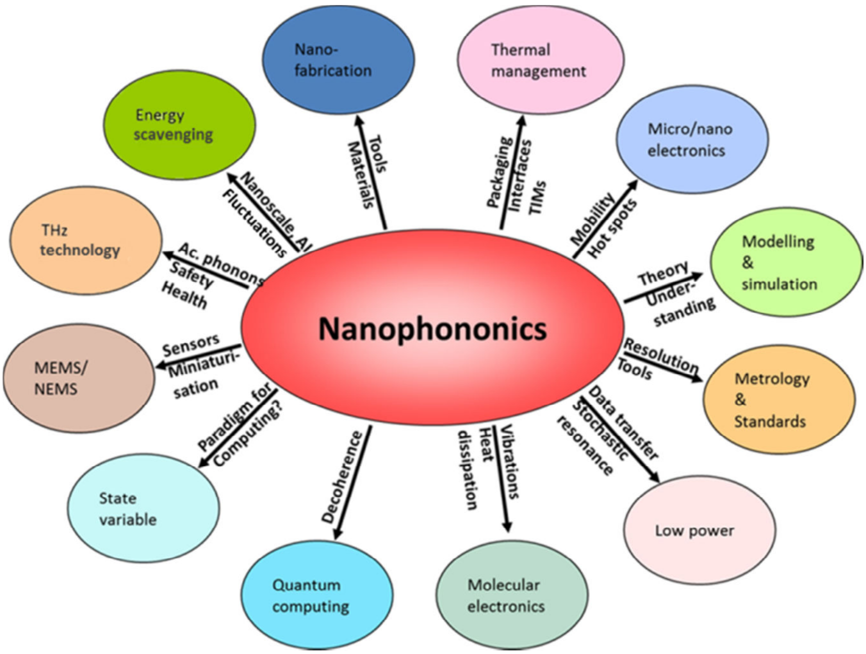
This document aims at presenting Nanophononics to attract all the relevant stakeholders and help them to synergize into a vast but sound and well defined field. This call is made in direction of academic members, industries, SMEs and governmental organizations to join the European nanophononics community (www.euphonon.eu) [1].

Nanophononics gathers the research fields targeting investigation, control and application of vibrations in solids or liquids that manifest themselves as sound or heat. This synthesis aims at defining Nanophononics, bringing forth the urgent need to aggregate a Nanophononics community in Europe and boost its consolidation. This report seeks to demonstrates that phonons are at the conceptual heart of several scientific communities such as TeraHertz Phonons, Phononic Crystals, Micro-Nanoscale Heat Transfer, NanoMechanics and Optomechanics, Thermodynamics and Statistical Physics (see the Figure below). The accumulation of knowledge in these fields is bringing the groups together and a recent convergence in terms of scales and tools makes it timely 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 the competition into intensive networking with our Chinese and American colleagues. The impact of building the 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

- The communities need **more time to gather** and consolidate. The 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.
- The importance and impact of nanophononics are increasing in **thermal management** to enhance the operation and speed of ICT devices and to reduce their power consumption. In controlling the heat, it is crucial to understand the **propagation of phonons** in different media and across interfaces. This reflects directly, for example, to the efficiency of **data processing and lighting**.

- The **emerging fields** include **health**, **medicine** and **security** for which phonons provide new approaches and applications for imaging and spectroscopy.
- **Nanophononics tackles** also the **very fundamental issues in physics** and forms an interesting and broad topic for **education**.
- **Priority funding for areas where Europe is already strong**:
  - tailored **(nano)phononic materials**.
  - theoretical and experimental **nano-scale thermal transport** targeting
  - **information processing, Safety and security.**
  - **coherent phonon sources.**
- Implementation in the s**hort time scale exploratory research**, in a **cluster of projects**.
  Addressing **basic excellent research** combined with **targeted topics** such as, for example, **low power consumption in ICT devices**- from atomic energy transfer to the Internet of Things.
- **Explore the synergies with emerging communities.**



position paper

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

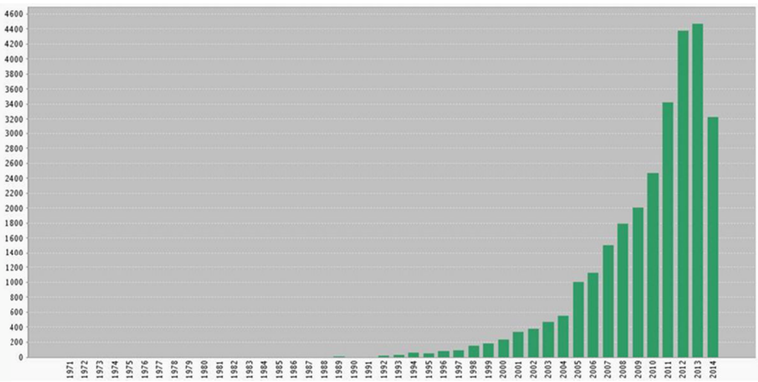

Fig. 1 > Yearly number of papers published with "Phononics" as associated keyword (ISI).

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 *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.

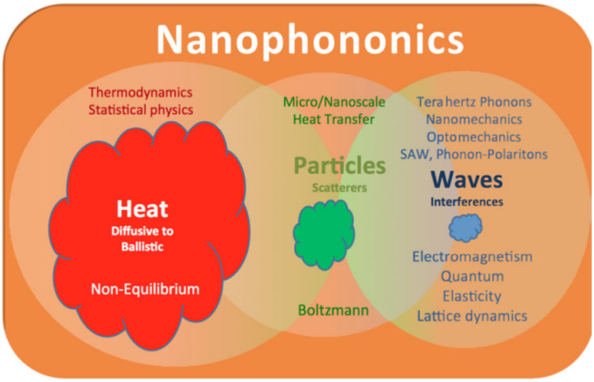

Fig. 2 > Schematic of the fields, the key physical mechanisms and scientific tools considered in the nanophononics consortium.

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.

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*.

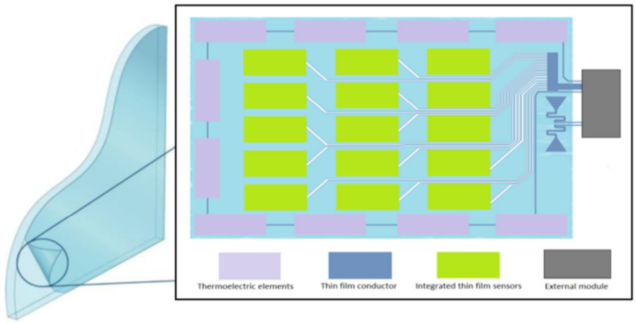

Fig. 3 > Integration of thermoelectric modules, thin film sensors and external control module in a smart window application.

The video "A day made of glass" http://youtu.be/6Cf7IL_eZ38 shows a detailed illlustration 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

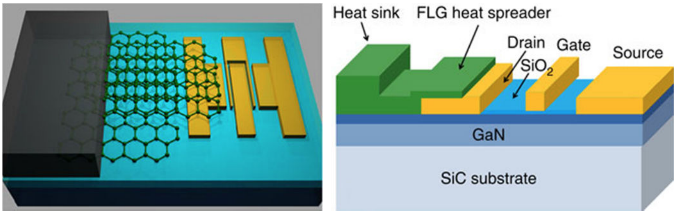

Fig. 4 > (Left) Schematic of the FLG–graphite heat spreaders attached to the drain contact of the AlGaN/GaN HFET. (Right) Device structure schematics showing the graphene–graphite quilt used in the simulation for the heat spreader optimization. Dark blue indicates the AlGaN barrier layer [2].

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.

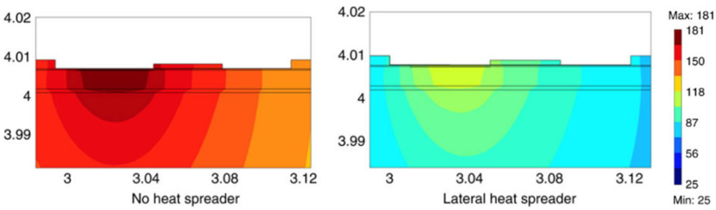

Fig. 5 > (Left) Temperature profile in AlGaN/GaN HFET on sapphire substrate powered at 3.3 W mm^{-1} without the heat spreader. The maximum temperature is T=181 °C. (Right) Temperature profile in an identical AlGaN/GaN HFET on sapphire substrate powered at 3.3 W mm^{-1} with the graphene–graphite heat 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 [2].

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.

In this last case, graphene was demonstrated to be a very efficient heat spreader [2] 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.

3.3 Gyroscopes and accelerometers

Illustrating an application in mobile ICT devices and security

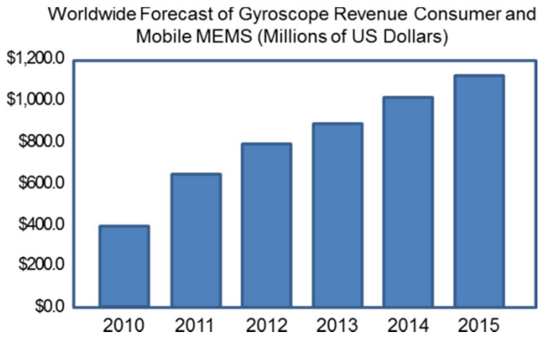

Fig. 6 > MEMS revenues in mobile applications [4].

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 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 [3].

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 [5] 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.

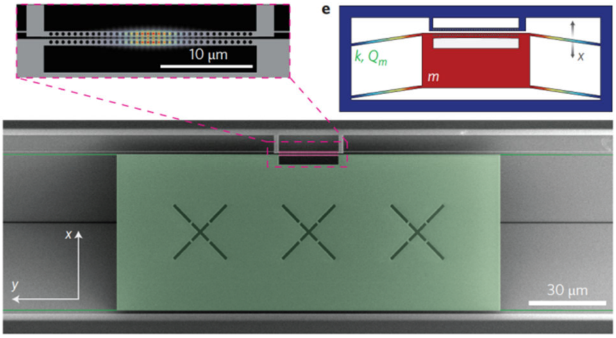

Fig. 7 > (Top-left) Zoom-in of the optical cavity region showing the magnitude of the electric field. (Top-right) Schematic displacement profile of the fundamental in-plane mechanical mode. (Bottom) SEM image of a typical optomechanical accelerometer. A test mass (green) is suspended on SiN nanotethers. On the upper edge of the test mass, a zipper photonic-crystal nanocavity (pink) is implemented [5].

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).

Fig. 8 > Comparison of the performance of optical and mechanical detection in terms of analysis time and Molar sensitivity [6].

Category	Description	Detection conditions	Analysis time	Limit of detection
LFA: lateral flow assay	Pregnancy test	Urine	3 min	10 μM
IFA: Immunofluirescent 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	10min	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

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.

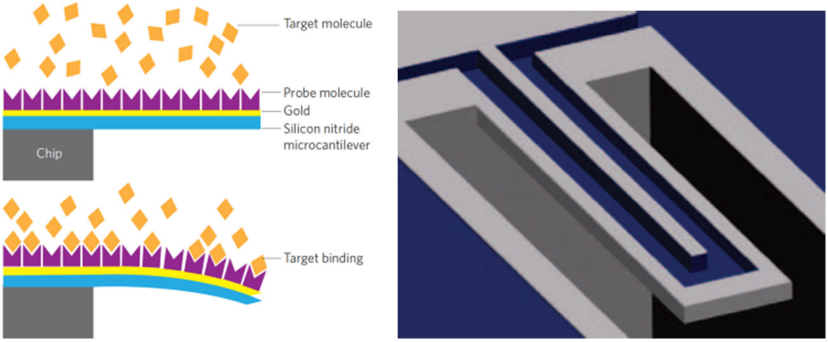

Fig. 9 > [6] (Left) Schematic of static-mode surface-stress sensing MEMS device. (Right) Suspended microchannel resonator (SMR). The fluid containing the target molecules flows through a channel inside the device and binds to the inner flow-channel walls, while the resonator oscillates in air or vacuum.

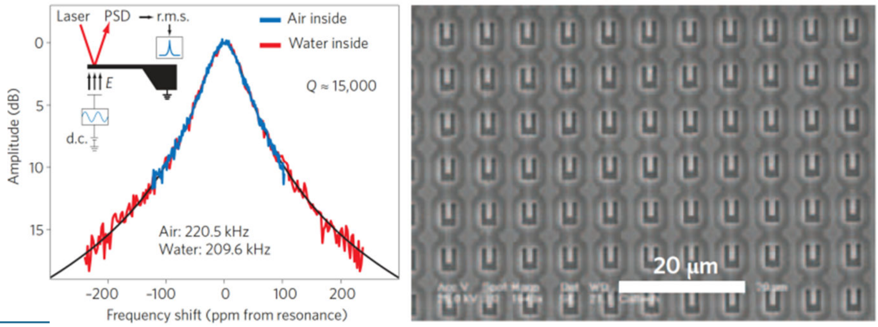

Fig. 10 > (Left) Resonance spectrum of a single mechanical resonator. The quality factor of the device is unaffected when the channel is filled with water (red line). (Right) Array of silicon cantilevers [6].

The concept of suspended microchannel resonators illustrated 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. 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, neuroinformaticsa 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 [7]).

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_BT. 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.

strategic research agenda

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1. Why nanophononics?

The length scales relevant in nanophononics typically range from a few nanometres to a micrometre. Only recently the fabrication technologies have been able to reach these dimensions, making the strong increase in nanophononics activities topical and timely. Also, the thermodynamics and statistical physics community is challenged by the reduced dimensions, leading to a demand of understanding systems locally at non-equilibrium. The progress has facilitated fabrication of nm-scale structures and devices to test theories and models for the behaviour of energy in small volumes, and paved the way to utilise the new know-how to improve the properties of integrated circuits, memories, energy scavenging devices and sensors, among others, and energy efficiency in general.

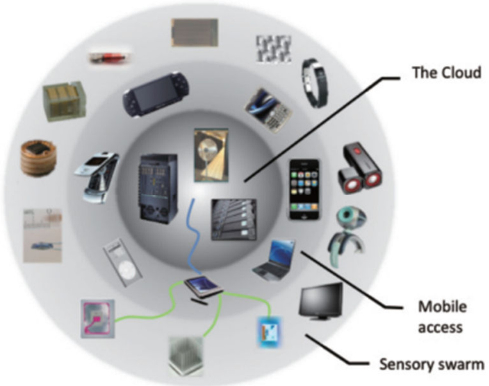


Fig. 1 > The hierarchy of emerging network of communicating systems consists of a layer of various sensors monitoring environment, health, safety etc. connected to mobile phones, tablets and other mobile applications and to the cloud. All the layers benefit from thermal management leading to low power consumption and from energy scavenging facilitating the expansion of the swarm [8].

The relevance of nanophononics is being slowly but steadily perceived also by the main stream semiconductor industry as one of the routes to tackle the problems arising from the ever increasing power density, and consequently temperature rise, and the contrasting need to increase the operation speed, the need to develop more and more efficient mobile devices with low energy consumption and long battery lifetime, not to mention the emerging of the internet of things. The latter requires development of new sensors and their powering solutions, creating the need for high efficiency energy harvesting tools. Communicating appliances, mobile devices and sensor networks form a basis for personal health monitoring and safety measures. In addition, nanophononics opens new avenues in medicine by enabling development of new diagnostics tools and locally focused treatments and medication.

In a simplified manner one can say that the phonons can manifest themselves as:

Heat: Phonons behave diffusively in systems with large dimensions and follow the laws of statistical physics.

Particles: Phonons are treated as wave packets which collide with other particles, defects, interfaces and surfaces.
Waves: Phonons are treated as lattice waves, or sound, which can be coherent and can interfere.

Heat is everywhere, in good and in bad. Heat is used in industrial processes, engines, housing and so forth. In information processing heat is usually a challenge because it leads to reduced efficiency, noise and, consequently sets the lower limit to the power consumption, i.e., operation voltages and speed. Nanophononics investigates the behaviour of heat in bulk systems, confined systems, at interfaces and provides tools to optimise the design of information processing devices and circuits. Heat is also a waste which can be recycled by efficient energy harvesting. The recent improvement of the figure of merit of thermoelectric devices stems much from the understanding of heat propagation, the role of different phonon wavelengths and the effects of reduced dimensions.

Ultrafast acoustic scattering uses the particle nature to probe thermal properties of materials and is the basis for development of new imaging methods for medicine, metrology and structural inspection. Targeted thermally activated treatments may become a new method to cure, e.g., malignant tumours.

Typical examples of exploiting acoustic waves are surface and bulk acoustic wave filters which are used in mobile devices. Sound amplification by stimulated emission to create coherent phonons will be the next generation equivalent to optical lasers, enabling realisation of phonon manipulation circuitry in which coherent phonons represent new state variables. The first demonstrations have required ultra-low temperatures but room temperature operation can be expected in near future in small phononic structures.

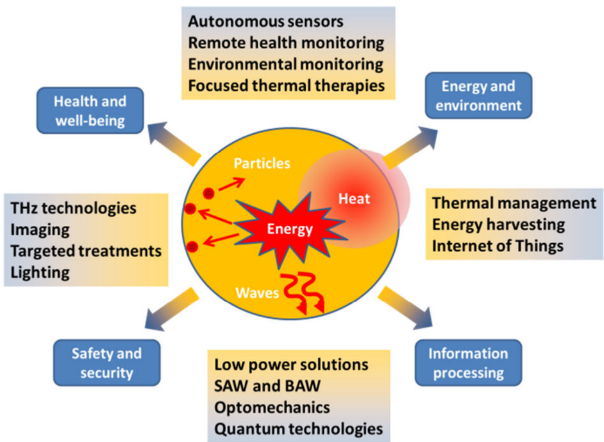


Fig. 2 > Manifestation of phonons and some examples of fields of research and applications founded on and benefitting from nanophononics.

The word nanophononics may generate an impression of something marginal, but as shown above and in the following Sections, this field of research has a profound meaning and vast impact in everyday life and very much in the future, particularly in the context of ICT.

2. Challenges and market area

There are several things in everyday life on which nanophononics has a strong impact and can be used to optimise and boost, for example, the energy efficiency, the speed of information processing and the development of new tools for medicine and safety. The main emphasis today can be seen to be on energy issues and ICT but new ideas and applications based purely on phononics are steadily emerging. In the following the role and potential of nanophononics are briefly illustrated.

Fig. 3 > Society is facing several challenges ranging from energy and environment to communication, from ageing to well-being and to security and safety. nanophononics represents a new field of research, capable in many cases to facilitate and accelerate finding solutions by shedding light on problems related to thermal issues and generating new approaches to data communication and ubiquituous technologies.

2.1 Energy and environment

While the exploitation of thermal energy and its conversion into mechanical energy with the invention of the steam engine represented the dawn of the technological era for mankind, heat is nowadays a form of energy, of which we have relatively poor control, both at the macroscopic and the microscopic scale. Phonons are the main heat carriers in semiconductors, insulators, and polymers. Therefore a better understanding of phononic transport over a broad range of size scales and in diverse materials is essential to tackle the challenges related to thermal management and energy scavenging.

With the downsizing of microelectronics systems to below ten nanometre, handling heat dissipation from the hotspots at the nanoscale has turned to be crucial to guarantee the stability of devices and to prevent performance degradation. Similarly, overheating also affects the performances and the reliability of batteries and memories, and, furthermore, cooling is a major issue in photovoltaics. Passive heat dissipation is a viable route to tackle the challenge of thermal management, and can be achieved by employing high thermal conductivity materials. Carbon-based nanostructures, such as graphene and carbon nanotubes, feature the highest phononic thermal conductivity among non-metallic materials, and represent the most suitable candidates for thermal management at the nanoscale [9]. While it is unlikely that the thermal conductivity of these materials can be much improved, it was observed that interactions with substrates may degrade the conductivity substantially [10]. In addition, the heat dissipating modules need to be interfaced well to the active devices by thermal interface materials (TIM) to achieve maximum dissipation efficiency. In this respect the main challenges lie in understanding the transport of thermal phonons at interfaces and eventually in designing better coupling schemes between the device that needs to be cooled and the dissipating modules and the surroundings. Similar issues apply to the active cooling devices, based on solid state Peltier modules [11]. Here the challenges lie also in the optimization of thermoelectric (TE) materials, promoting TE performances at around and above room temperature, and possibly replacing toxic and/or expensive elements (e.g. Pb or Te) with Earth abundant and environmentally friendly ones.

One of the fastest growing areas requiring thermal management is LED lighting in housing and in cars [12]. The efficiency varies typically between 15 and 30 % , which is at least 75 higher than the efficiency of incandescent lamps, and is strongly dependent on the operation temperature, as is the lifetime of the LEDs. Only in the United States the expected saving of energy in 2027 arising from widespread use of LED for lighting is 348 TWh, i.e., equivalent to 44 GW power plants [13]. The proper design and control of the heat in the lighting modules will be of crucial importance to achieve the targeted savings in energy.

Fig. 4 > Use of LEDs in lighting is increasing very rapidly. To maintain the efficiency and the long lifetime of the LEDs, thermal management of the packages is becoming crucial.

In engines and power plants a significant amount of energy is lost as waste heat. It was estimated that more than 60% of the energy produced by fossil fuels goes into waste heat. Similarly, heat dissipation represents a major cost for households. Thermoelectric devices that convert heat to electric power, even though at fairly low levels of efficiency, typically below 10% , may turn into a valuable resource to harvest waste heat. So far, the use of TE modules has been limited to niche applications by the intrinsic limits of materials performances, which is usually express as the figure of merit ZT. ZT is given by the ratio between the electronic power factor and thermal conductivity, mostly dominated by phonons. The main issue is that crystalline materials with high TE power factor also have a relatively high thermal conductivity, which limits the ZT. The paradigm would be to design materials that behave as electron crystals and phonon glasses [14]. This can be achieved by nanostructuring [15]. The idea is to introduce phonon scatterers at length scales that would block the propagation of heat but would not perturb significantly the electronic transport. This approach has produced encouraging results for traditional TE materials, e.g., bismuth telluride, as well as for silicon [16]. More recently hierarchical nanostructuring from the atomic to the mesoscopic scale yielded exceptionally high TE figure of merit [17]. In spite of these success stories, materials design still relies on simplistic models [18] that have been challenged by recent experimental "spectroscopic" measurements of phonon mean free paths [19]. Much deeper understanding of the effects of nanostructuring and dimensionality reduction on phonon transport is needed to design ultimate TE materials and TE generators, tuned to targeted applications, with good control on the temperature and power ranges. This is a multidisciplinary task that will greatly benefit from collaboration of statistical physicists, molecular modellers, experimental physicists, engineers, and materials chemists.

Temperature control is an important factor in photovoltaics. In silicon photovoltaics cells the efficiency drops on average -0.45%/ºC, calling for passive or active cooling to keep the cell temperature in the range of 20-60 ºC and maintain the power production [20]. The temperature control can again be achieved by proper design of the heat flow in the PV cell casing and to the surroundings. This will be an important market when the energy production is shifting from the fossils to solar energy.

Key findings and outcome from the EUPHONON workshops

Topic	Details and relevance
Heat	Manipulate the spectrum of heat
Thermal management	Manipulate heat exploiting rectification and nanostructures
Energy harvesting	Decouple electrons and phonons using nanostructuring

2.2 Information processing

It is well known that phonons are the main cause for carrier scattering in **transistors** at around room temperature, limiting the mobility. Electron-phonon scattering represents a rather fundamental phenomenon and is more or less unavoidable. It has been shown that driving the devices in volume inversion mode the phonon scattering can be reduced due to reduced number of available states in the k-space [21]. The size of today's transistors is smaller than the mean free path of phonons, leading to a situation that the energy dissipation is not anymore concentrated in the hot spot at the drain side of the channel but the dissipation can take place anywhere in the volume with size of the phonon mean free path. This is very challenging to the thermal management of the devices and circuits. The temperature defines the distribution of the carriers and, consequently, sets the lower limit to the operation voltage and the power consumption, and the speed. Nanophononics provides tools to understand the propagation and scattering of phonons in these small volumes with a large number of different materials and interfaces, and helps to build a picture of the flow of energy and accumulation of heat, facilitating the optimisation of the operation of transistors and circuits.

The heat dissipation in **ICs** is a cumulating effect that materialises in the operation of data centres in which more than half of the power is nowadays consumed in cooling the computers and data banks. The power consumption of data centres only in the US was 91 billion kWh in 2013 [22]. Here the problem is not restricted only to the thermal budget arising from the operation of billions of transistors. The packaging, including thermal interfacing, constitutes the main problem and even a small improvement in the thermal management would produce huge savings in energy and, consequently, reduce the environmental load.

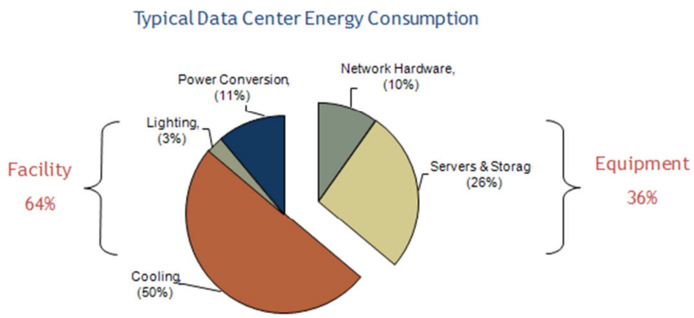


Fig. 5 > Typical distribution of the energy consumption in a data centre [23].

Surface and bulk acoustic wave devices (SAW, BAW) represent a good example of the utilization of "sound" in microelectronics. The devices transform electric signals to acoustic field, or standing waves in an acoustic cavity, for filtering and back to electric signal again, being the corner stones of current mobile applications. The operating frequencies at the moment are below 10 GHz, but can be brought higher with proper design.

The modulation of electrical current at high speed, or **electron pumping**, can be realized with coherent phonons. The carriers are usually photoexcited and locally trapped by the strain field of the SAW which propagates in a controlled direction. By playing with different surface acoustic waves, multiplexing the electronic signal on chip becomes possible [24, 25]. There are current limitations for the optimization of such functionality like the efficiency of optical pumping, to create high enough strain to have high enough potential energy variation to trap the spin polarized carriers. Phonon-induced fast strain fields can also be used to manipulate barrier heights in junctions and the effect has been demonstrated in Schottky junctions [26].

The emerging field of **spintronics** intends to develop information devices based on spin current and spin waves or magnons, having the advantage of preventing the joule heating which is one of the main problems in charge current based devices. Spin valve devices based on giant magnetoresistance, i.e., hard disks have been around already for long times. The spintronics community works in a different direction and intend to employ coherent acoustic phonons to manipulate the spins, either to launch spin waves [27, 28] or to modulate the magnetization [29-31]. These phenomena arise from the magneto-elastic coupling but the current understanding of generation of spin waves by strain as well as the fast manipulation of spins with strain are both in their infancy. The spins can also be manipulated by surface acoustic waves by transporting spin-polarised electrons by the strain field induced troughs and crests in the energy topology of the band gap. This has been demonstrated in GaAs [32]. The limitation is the low spin current level.

Cavity **optomechanics** explores the parametric coupling of an electromagnetic cavity field with a mechanical degree of freedom [33]. The photons are circulating in an optical cavity and interact with a micro-or nanomechanical resonator. Similarly, on-chip coupling between a microwave cavity and a mechanical mode is employed. Optomechanics is a fast growing field which consisted of 3 or 4 research groups a decade ago and now active with more than 60 groups. Phonons serve two purposes: First, they are employed to describe the discrete mechanical mode, e.g., a flexural mode of a micro- or nanostructured device or a localized acoustical mode in a phononic crystal cavity. Secondly, phonons play an important role in the decoherence of optomechanical devices in which energy radiation into the clamping supports is typically one of the dominating dissipation mechanisms.

Controlling the interaction between light and phonons allows taking advantage of the best of both worlds. Furthermore, miniaturization enables devices such as on-chip whispering gallery devices or optomechanical crystals, which are highly integrable into arrays or **metamaterials**, or with semiconductor components such as waveguides or lasers. They show a real promise for integrated technologies taking advantage of the maturity of Si microelectronics and GaAs or InP optoelectronics technologies.

At the same time, optomechanics can be envisioned to act as building blocks for information storage and processing devices, both in the classical and quantum regime. In theoretical proposals, optomechanical concepts are discussed for photon routing, controlled photon-photon interaction, information storage and retrieval, both classically and quantum. The optomechanical interaction can induce optical non-linearities such as an effective Kerr interaction that can be engineered via the phononic degree of freedom. Like in non-linear optics, this enables photon processing (logic gates, multiplexing, amplification). More generally, in these emerging concepts, long-lived vibrational modes will be employed for information storage or transduction between optical photons used in communication and microwave photons easily compatible with chip-based data processing.

Another very active area of research is the field of **nanomechanics**. Nanoelectromechanical systems (NEMS) are scaled-down versions of the well-known MEMS. The technology of NEMS has vast potential for sensing applications, not only for their ultra-high sensitivity enabling these devices to resolve a single electron spin [34] or very few nuclear spins [35], forces down to the zeptonewton regime [36] or masses of only a few yoctograms [37], but also for mass-market applications [38] such as gyroscopes or other types of accelerometers [39]. Furthermore, NEMS can be engineered to be CMOS compatible such that full integration of sensors [40], switches [41] or narrow-band filters into CMOS architectures can be envisioned. Another area of interest is bioNEMS, with a vast potential in biosensing applications [42]. As for optomechanical systems, a clear connection between NEMS and phononics is apparent: The mechanical eigenmodes of the system, e.g., the flexural modes of a string resonator or a membrane, represent discrete acoustic phonons. Secondly phonons importantly contribute to the decoherence and dissipation of nanomechanical devices, which is frequently dominated by energy radiation into the clamping supports.

For information technologies based on photonics, the modulation of light and the acoustic surface resonators are key issues in the data processing and filtering. Light modulation takes place through different mechanisms like the electro-optic process, wavelength-division multiplexing and acousto-optic interaction with bulk and surface acoustic waves. The acousto-optic modulation is based on the interaction of light with acoustic phonons, is a well-established technique that works well in the MHz regime. These devices are usually based on biased-piezoelectric materials (ZnO, $LiNbO_3$, $PbZrTiO_3$) and are frequency is typically limited to a few GHz due to the electronics. Going higher in frequency range, from a few tens of GHz to THz, and towards integrated elasto-optic modulators as well as surface acoustic waves devices, have great potential in the next generation ICT devices [43-45]. To achieve this, efficient and miniaturized sources of coherent acoustic phonons. Only the ultrafast laser-induced processes can produce such high frequency and confined acoustic phonons are needed. The limitation at the moment is the small phonon strains (10^{-4}) obtained by optical excitation by lasers [46, 47]. Increasing the efficiency of the light energy conversion into mechanical energy is very challenging and new physical processes of light-matter interaction with high frequencies at GHz to THz and strain of 10^{-3} is required. The effort made in this direction will also certainly be useful for the community of optomechanics, to go beyond the radiation pressure approaches mainly used at the moment in the MHz-GHz optomechanics devices [48].

By means of light-induced back-action the mechanical mode under consideration can be cooled into the quantum regime. In recent years, major breakthroughs have been achieved with optomechanical crystal (phoXonic) structures (X=n,t) [49] as well as with microwave analogies of optomechanical systems, so called cavity electromechanical devices [50]. Reaching a regime where quantum behavior emerges both for light and for phonons enables not only boosting the performance of some target applications, e.g., information treatment, quantum states transfer between RF and optical fields, but also holds promise for a new type of "quantum technology". Exploration of non-classical phenomena allows targeting unresolved questions in fundamental physics such as the entanglement of macroscopic objects or tests of quantum theories involving gravity. Furthermore, optomechanical systems represent a versatile platform for the development of ultrasensitive, quantum limited sensing elements.

Quantum computing represents a long term paradigm to finally crack some of the hurdles related to information processing. It is capable to solve a few problems much faster than even the conventional supercomputers. Quantum information and quantum computation relies on the concept of entanglement of qubits. In reality the quantum systems are not isolated and will be influenced by surroundings and the interactions lead to decoherence of the entanglement. For solid state qubits, although operating at mK range, it is crucial to minimise or completely eliminate phonons and fluctuations in the vicinity of the qubits [51]. This again calls for proper understanding and design of the qubits and their coupling to the surroundings. Recently an opposite approach was reported. Here travelling phonons are coupled to an artificial atom and represent state variables to perform computing [52].

Key findings and outcome from the EUPHONON workshops

Topic	Details and relevance
Optomechanics, plasmonics and spintronics	Photon-phonon, plasmon-phonon and spin-phonon coupling

2.3 Health and well-being

THz spectroscopy has a great promise in the field of medical imaging [53]. It can reveal skin cancer and other tumours at early stage and give images of structures which are optically opaque. In addition to imaging, the THz radiation can couple to the vibrational modes of molecules and can provide information of bonds and used for spectroscopy. For example the four nucleobases of DNA have different vibrational spectra and can be differentiated.

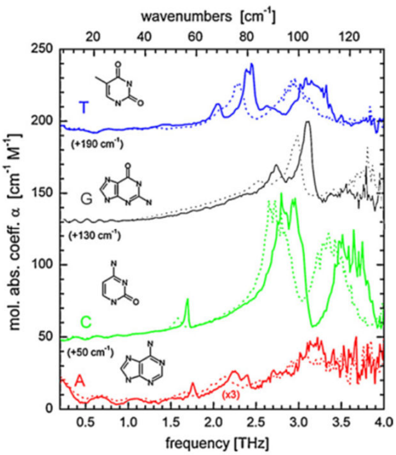


Fig. 6 > Absorption coefficients of the nucleobases A, C, G and T of DNA measured at 10 K (solid lines) and at 300 K (dashed lines) [from Ref 53].

THz technology can also provide tools to localised drug delivery and hyperthermia treatments [54].

Another dimension for well-being is the preventive health monitoring at home. Data can be collected by various autonomous sensors, e.g., blood pressure or glucose level, potentially even continuously, and the information is sent to medical centres and data banks for inspection, see Figure 1. This type of preventive monitoring would rely on internet of things and would need low power devices and, potentially, exploit energy scavenging.

Key findings and outcome from the EUPHONON workshops

Topic	Details and relevance
Ultra-fast phenomena	Sensing of mechanical properties for tumoral cell detection
Hyperthermia	Magnetic nanoparticles based hyperthermia treatments

2.4 Safety and security

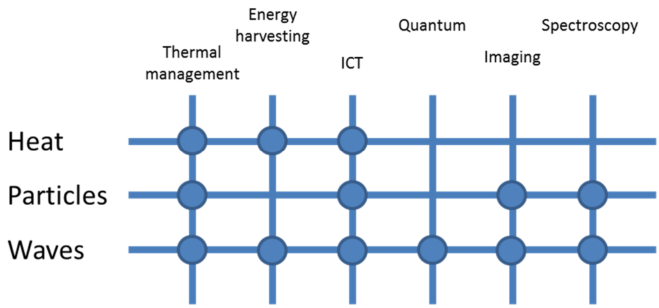
THz technology has also been used as screening technology, for example, at the airports to prevent people entering vehicles with concealed weapons, including non-metal edged weapons. The vibrational frequencies of the chemical bonds allows the recognition of, for example, explosives [55]. The need of security screening and loss-preventing applications for retail logistics has already led to establishing companies producing tools and equipment [56]. THz technology is also providing tools for metrology and standards. Although hampered currently by the lack of stable sources and detectors, the number of companies producing instruments for power measurement and time and frequency domain spectroscopy is steadily increasing [57].

Where the THz spectroscopy is falling short is the spatial resolution. The resolution of THz imaging is in the range of 100’s of m, the consequence of the electromagnetic wavelength used, while in several applications much higher resolution is needed. Ultra-fast acoustic phonons provide a means to achieve sub-micron resolution [58]. Ultra-fast optical pulses to generate thermoelastic excitation in a thin metal film are used to generate picosecond acoustic phonons which can be used to non-invasive imaging with sub-100 nm resolution. The phonons scatter from inclusions and interfaces in the matrix and enable even 3-dimensional non-destructive imaging of objects. This type nanoscale ultrasonics can be used in inspection of microscale cracks and inhomogeneous spots in, e.g., vessels used in chemical industry and in nuclear plants. The 3D imaging, however, requires new type of algorithms and heavy computation, making the approach challenging [59].

Key findings and outcome from the EUPHONON workshops

Topic	Details and relevance
THz spectroscopoy	Safety and screening

Fig. 7 > Interdependencies between different phonon presentations and key topics.



3. Global position

The global situation is described in more detail in the EUPHONON Position Paper. Briefly, at the moment the global competition mainly involves the US and China which have recently invested heavily in the nanophononics research. The USA National Science Foundation and the Chinese Academy of Science have already established ties for collaboration in the form of bilateral workshop and a school for post graduates.

In China Prof. Baowen Li has established the "*Center for Phononics and Thermal Energy Science*" [60] in Shanghai, recruiting 20 professors and organizing biannual international schools and conferences. The funding is several tens of millions $. In the US the Department of Energy (DoE) is funding of Centers of Excellence in Basic and Applied Energy Research running into several 10's of millions of dollars. For example, MIT received 15M$ over 5 years for one of its Arpa-e Center [61] and this sort of funding has been regular for 20 years. In Europe several teams have the position as international leaders and have pioneered several phononics related activities but the field has been rather fragmented and only recently a more integrated community has started to develop. The fragmentation has reflected also in the relatively limited resources available for research. One of the key targets of the EUPHONON coordination actions is to strengthen the integration and provide ideas how to further enhance the nanophononics activities in Europe.

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.

4. European ecosystem

The ecosystem of nanophononics in Europe is composed of groups in academia, research institutes, large companies and SMEs and start-ups. This is reflected in the list of members in the EUPHONON community, with the number of members currently exceeding 50 from 15 different countries [62]. The academic groups and research institutes cover a broad range of activities from very basic physics to experimental work and applied science. Included are solid state physics, statistical physics and thermodynamics, material sciences and biosciences as well as engineering.

The interests of industry include various aspects of thermal management related to packaging, temperature control and energy harvesting. Thermal interface materials play a big role in the electronics and in increasing amount in the lighting industry with several companies producing packages, the TIMs and their testing tools. The IC, memory and MEMS chip producers have to more and more take into account the thermal aspects in the circuit design, leading to the uptake of nanophononics in the mainstream industries.

There are also start-up companies emerging from academia and research institutes which produce new types of equipment for example for characterisation of ultra-fast phenomena and THz imaging [63].

The European Commission has supported the field by funding several research projects related to thermal management, energy harvesting, and projects focusing on nanophononics and optomechanics. These include projects such as NANOTEG, NANOPACK, NANOTHERM, ZEROPOWER, MERGING, TAILPHOX, NANOPOWER, UPTEG, MINOS, QNEMS, cQOM, iQOEMS and QUANTIHEAT [64]. The list is not exhaustive but gives an idea of the increasing activity and importance of the field. National funding agencies have also started to invest in phononics and related topics.

roadmap

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Probably, this Roadmap of Emerging Nanophononics is the first of its kind and thus, the consultation process has been limited to the participants of the events organised by the EUPHONON project. Naturally, it would benefit from a wider consultation with stakeholders and a subsequent significant update in the near future.

1. Vision and objectives

The timeliness of nanophononics research is only too patent. Major roadblocks in ICT are being encountered for which traditional approaches, experimental methodologies and theories are simply not enough to overcome them. New tools and new theories are needed, especially when the problem of heat transfer is put down to energy transfer between adjacent atoms or atomic planes, be this in ballistic or diffusive fashion, via near-field or far-field interactions. Above all it is imperative to understand the science behind a range of challenges involving nanophononics. It can be argued that nanophononics is at the base of fundamental problems in several ICT-relevant technologies when reaching the nanoscale.

The **vision** of EUPHONON is to gain and incorporate this new knowledge as an enabling one to harness the many advances offered by nanoscale science and technology in a wide range of areas, as nanophononics underpins the knowledge needed to meet the objectives of the Horizon 2020 KETs at the basic research level and thereby contributes to address societal challenges. In fact nanophononics is everywhere since atomic vibrations and their dissipation are ubiquitous by nature.

The **objective** of this Roadmap is to summarise the main research challenges and scientific questions in nanophononics, check the state of the art, identify the scientific and technological challenges to be addressed, estimate both the degree of complexity and the time scale to address them.

2. Roadmap methodology

The information and content of this Roadmap come from material presented and discussed at the EUPHONON Consultation Workshop held in Lille on 29th and 30th May 2014 and the EUPHONON Workshop held in Le Mans from 2nd to 4th September 2014. In the former, a SWOT analysis was made of the knowledge areas and main scientific questions identified. This analysis is used here edited after the Le Mans event. In the latter, in-depth discussions on the state of the art and the current level of understanding were held. Additional written feedback was received from several participants and is incorporated in this document.

The **novelty** of this Roadmap is that during its preparation it became obvious how strongly nanophononics underpins research, development and innovations in a large set of research areas belonging to different disciplines, economic fields and societal challenges not anticipated by the consortium before. Hence, this is a first attempt to arrange the topics, the associated scientific and engineering challenges and a timeline coherently in a single document.

3. Roadmap

3.1 Overview of the Roadmap

The Roadmap includes the research topics presented in the Strategic Research Agenda and blends them with the SWOT analysis performed in the Lille Consultation Workshop. Three key terms will be used, namely:

Heat: Energy carried by phonons behaving diffusively in systems with dimensions large enough to allow the application of the laws of statistical physics.
Particles: Phonons are treated as wave packets, which collide with other particles, defects, interfaces and surfaces.
Waves: Phonons are treated as lattice waves (optical or acoustic phonons), or sound, which can be coherent and can interfere.

This subsection will start with phononic materials and structures, since these are the embodiment of phononics research. It will then address the interaction between phonons and a series of excitations in solids such as electrons, photons, spin and sound. Perhaps the most urgent challenge is phonons and heat propagation, as this is currently already recognised as a major show-stopper in the realisation of 3D device architectures and the impact in limiting the performance of micro and nanodevices. Then the role of phonons in information and communication technologies from alternative computation schemes to thermal management will be outlined. The impact of phonons in biology, medicine and health is analysed. The last set of topics includes phonons in measurement methods, metrology, safety and security.

A few selected scientific and engineering challenges are gathered as examples in order to illustrate degrees of complexity and or difficulties ahead. An approximate time line when results could be expected to emerge an embrace the opportunities offered by research in phononics and its impact on science and engineering is given in the series of tables below. The colour code is defined in Table 1.

Table 1 > Colour code for the timeline of the examples of scientific and technological challenges.

	Basic research TRL 1-2		Applied Research TRL 2-3		First Application TRL 3-4

3.2 Phononic materials and structures

Phonons are an integral feature of matter as expressed by atomic motions, giving rise to a series of forms in which the atomic lattice vibrates (modes) and the corresponding energies and directionality are determined by the structural and chemical properties of materials. Given that the length scales are closer to the nanoscale, there is a huge potential to realise tailored phononic materials with specific properties if only one could engineer matter at the atomic scale. At present tailoring of shapes, periodicity and domains in the few 10s of nanometres is becoming a reality and this augurs well for phonon engineering.

Table 2 > Timeline of scientific and technical challenges in phononic materials and structures.

Scientific and technical challenges to be addressed	< 5 years	5- 10 years	> 10 years
2-dimensional nanofabrication methods down to 5 $\pm$ 2 nm critical dimension in materials suitable for phononics			
Roughness control down to 2 $\pm$ 1 nm			
Room temperature phononic phenomena suitable for applications			
Identification and implementation of “green” materials and nanofabrication for phononic applications			

3.3 Phonon interaction with electrons, photons, spins and sound

One of the most salient features of phonons is their ability to interact with virtually any other excitation in solids and therefore they couple to “state variables” or “tokens” such as electrons, spins, photons, magnons and sound waves, among others. All these coupling mechanisms are at the core of several active fundamental research fields including opto- and nanomechanics [65-68], optoacoustics, spintronics. While this is in itself a wonderful advantage for exchanging energy and information, the actual situation is one in which the poor control of phonons energies and propagation leads to undesirable effects, such as producing noise and shortening the coherence of a wave packet.

Table 3 > Timeline of scientific and technical challenges in phonon interaction with other excitations.

Scientific and technical challenges to be addressed	< 5 years	5- 10 years	> 10 years
Orders of magnitude improvement in in- and out-coupling efficiency	■	■	■
Understand and control decoherence (electron/phonon/spin) in solid state systems at room temperature	■	■	■
Realisation of significantly simpler GHz and THz coherent phonon generation schemes	■	■	■
Optomechanic/acoustic devices working at room temperature	■	■	
Demonstration of suitable phonon-based devices for 3D imaging with nm resolution	■	■	
Development of concepts for biological, chemical and mechanical metrology	■	■	■
Demonstration of biological, chemical and mechanical metrology methods	■	■	■

3.4 Phonons and heat transport

This is the research area experiencing the fastest development as it affects a range of research and technological areas [69]. Here theoretical methods, experimental techniques, thermal management, energy conversion and energy harvesting are considered.

3.4.1 Theoretical methods

The SWOT analysis focuses on atomistic methods and includes Anharmonic Lattice Dynamics combined with the Boltzmann transport equation (BTE), Molecular Dynamics (MD), and the Green's Function methods. To treat problems at the mesoscopic scale we also consider Monte Carlo (MC), and parametrised models based on the BTE. In system with very few degrees of freedom thermodynamic concepts tend to lose significance and fluctuation dominates: such conditions require a major fundamental effort in statistical physics [70]. In addition, heat transport in low dimensional systems, a theme tackled in the 50s by the first computer simulations (Fermi-Pasta-Ulam model), remains elusive [71]. Nevertheless the fabrication of truly low-dimensional materials, such as graphene, opens up to experimental verifications of models and theories [72].

Table 4 > Timeline of scientific and technical challenges in theoretical methods used in heat transport by phonons.

Scientific and technical challenges to be addressed	< 5 years	5- 10 years	> 10 years
Accessible CPU power allow 10's of nm structures to be simulated in reasonable times			
Reducing fitting parameters in models			
Development of efficient multiscale methods to simulate devices at a suitable level of accuracy			
Tools to compute nanoscale heat transport in soft and live matter			
Transport in low dimensional systems: theory and tools			

3.4.2 Experimental methods

The SWOT analysis considered thermal properties measured by electrical methods such the 3-omega (3w), also scanning thermal microscopy (SThM), photothermal and (ultrafast) photocoustic techniques, time domain thermo-reflectance (TDTR) and Raman thermometry [72]. Other methods such as for the determination of the Seebeck coefficient are not included as commercial apparatus already exists.

Table 5 > Timeline of scientific and technical challenges in experimental methods.

Scientific and technical challenges to be addressed	< 5 years	5- 10 years	> 10 years
Methods to measure thermal properties locally (few nm's resolution) and dynamically over several orders of magnitude			
Methods for 2D temperature imaging with sub 100 nm spatial resolution			
Dynamic measurements of a few nm's resolution temperature fields			
Transfer the concept of local non-linear energy to thermal measurements			
Simpler near-field radiative experimental methods			

3.4.3 Thermal management, energy conversion and harvesting

This area of research underpins research, development and innovations in what is known as "More than Moore" and Heterogeneous Integration [73] due to, e.g., power consumption levels. It impacts dramatically on the realisation of energy-autonomous systems, as well as on the performance (stability and accuracy) of optoelectronic devices. Some of this analysis may belong also to the energy domain.

Table 6 > Timeline of scientific and engineering challenges in thermal management, energy conversion and harvesting.

Scientific and technical challenges to be addressed	< 5 years	5- 10 years	> 10 years
Predictive models of thermal conductance in nanostructures, and at interfaces			
Demonstration of high efficiency non-toxic thermoelectric materials for high and low temperature applications			
Autonomous systems with sufficient power and a lifetime compatible with its application			
Solutions for thermal management in current electronic and optoelectronic components and circuits (active and/or passive cooling)			

3.5 Phonons in ICT

Heat transport is probably the main area where phonons play a role in ICT due to the interaction with other waves in solids. However, the interactions with other excitations (also known as quasi-particles, tokens of information, etc.) discussed above, mean that they are relevant for many other, apparently unconnected areas. Further along the time line, research is picking up momentum on the use of phonons for quantum information processing [74], albeit at very low temperatures, and for other alternative schemes of information processing [75].

The understanding of phononics in electronics concerns ballistic and diffusive transport regimes. These affect charge motion and impact the limits of charge mobility, may contribute to failure and limit the operating speed. Thus, this understanding concerns detailed knowledge of ultrafast phenomena as in energy and momentum relaxation processes and is targeted in many European facilities such as (free-electron) laser facilities and synchrotrons. The manipulation of dispersion relations, coupled to scattering and phase changes, provides the tool to address the challenges in controlling noise and achieving low power, both essential for the operation at lower voltages.

In photonics, phonons are responsible for, e.g., the perils of wavelength locking, as the changes in temperature of the order of 40 to 70 K lead to gain spectrum shift in emitters, wavelength shift in modulators and require complex solution requiring control of local strain in wavelength demultiplexers [76]. On the other hand, phonons of THz frequencies can be used for all optical cooling of solids and bridge the gap to photonics [77]. The recent breakthroughs in large-scale cooling of buildings without additional energy consumption are excellent examples for the benefits of phononoc-photonics interactions with large societal impact [78].

In spintronics, the lifetime of a spin state before a spin flip is controlled by fluctuations or low frequency phonons. Moreover, the interaction of spins and acoustic phonons is at the centre of recent advances showing the control of electrical and spin currents by acoustic phonons and surface acoustic waves. The enormous advantage of spin current is to prevent the joule effect that is a main drawback in the electric charge current based devices. The manipulation of spin current in materials exhibiting magnetic orders with acoustic phonon (bulk – BAW- or surface acoustic phonons -SAW) is possible thanks to the general concept of magneto-elastic coupling but even if some proof of concept has been partially achieved, the current knowledge of generation of spin waves by strain as well as of the fast manipulation of spins, magnons with strain are both in their infancy [79-83]. Photo-injection of spin-polarized electrons in semiconductors thanks a selective optical pumping in semiconductor has been reported and SAWs have transported these spins over micrometric distance compatible with chips [84].

In future information storage concepts phonons and control over their dynamics play a pivotal role. This includes the further miniaturization and increase of speed of phase-change based solid-state disks [85] as well as heat assisted magnetic recording in order to surpass the trilemma of magnetic recording, especially with respect to the superparamagnetic limit [86].

The new field of opto- and nanomechanics has the potential to act as building blocks for information storage and processing devices, both in the classical and quantum regime. In theoretical proposals, opto- and nanomechanical concepts are discussed for photon routing, controlled photon-phonon interaction, information storage and retrieval, both classically and quantum. The optonanomechanical interaction can induce optical non-linearities such as an effective Kerr interaction that can be engineered via the phononic degree of freedom. Like in non-linear optics, this enables photon processing (logic gates, multiplexing, amplification). More generally, in these emerging concepts, long-lived vibrational modes will be employed for information storage or transduction between optical photons used in communication and microwave photons easily compatible with chip-based data processing.

Concerning other computing paradigms and quantum technologies based on entangled states, the issue of decoherence is associated to phonons.

Quantum computing faces a long standing challenge of decoherence control in order to allow as sufficiently long times for the series of operations needed in quantum computation. Coherence is lost via the interactions with the host medium of the qubits usually by interaction with the phonons of the system [87]. In other computation paradigms the interaction with phonons also plays a large role, such as the case of fluctuation-like phenomena of neuromorphic computing or in thermal computation proposals [88] and other phonon-related schemes proposed.

Scientific and technical challenges to be addressed	< 5 years	5- 10 years	> 10 years
Interaction of phonons with one or more kinds of waves for information processing			
Phonon engineering solves at least one power consumption problem in ICT			
Phonon engineering results in x10 better noise control in ICT			
Coherence control at room temperature by phonon engineering and or opto/nanomechanics			
Demonstration of at least two phononic devices (diode, memory, switch, waveguide, etc) suitable for integration in a phononic circuit			
New applications using a room temperature coherent phonon source			
New computer paradigm demonstrated using phonons as state variable on their own or coupled to other excitations.			

Table 7 > Timeline of scientific and engineering challenges in phonons in ICT

3.6 Phonons in medicine, diagnostic and biology

Already photo-acoustic imaging methods are being used in medical diagnostic. However, 3D imaging with sub-micrometre control is high in the list of desirable improvements for better medical diagnosis and also for therapy. Novel spectroscopy methods are increasingly finding expression in instruments which are undergoing clinical testing [89]. One of the barriers faced is standards concerning, e.g., energy, frequency and detectivity, for field trials which is an area needing much attention (see section 3.7).

Scientific and technical challenges to be addressed	< 5 years	5- 10 years	> 10 years
Demonstration of a 3D imaging technique with x 10 spatial resolution, cf. plasmonic laboratory devices, suitable for soft matter			
Elucidate role of phonons in cell division and use knowledge for therapy			
Elucidate phonon-mediated signalling in plants and use knowledge, for e.g., environmental control			

Table 8 > Timeline of scientific and engineering challenges in phonons in medicine, diagnostic and biology

3.7 Nanophononics in metrology, instrumentation, safety and security

Reaching ultimate spatial and time scales usually lead to breakthroughs in the characterization of matter and its control in the fields of material science and in, for example, medicine. Phonons as sound waves are well known for their use in echography inspection. As a matter of fact, nanophononics aims straightforwardly at the development of tools for non-invasive inspection of matter (inorganic, organic) at the nanometric scale in, for example, nanoelectronic components, biological system and cell membranes diagnostic to name but a few.

High finesse optomechanical cavities could be used to probe ultra-small quantities of matter with a range of applications in metrology in material science as well as in security applications.

Scientific and technical challenges to be addressed	< 5 years	5- 10 years	> 10 years
Demonstration of new metrology techniques with unsurpassed temperature and or spatial resolution			
High sensitivity detectors for GHz to THz range available for home and work security and health and safety applications			
Room temperature and user-friendly power sources in GHz and THz			
Methods and modelling protocols for x10 resolution available			
Standards based on new metrology, methods and instrumentation in GHz and THz ranges developed			

Table 9 > Timeline of scientific and engineering challenges in metrology, instrumentation, safety and security

3.8 Application fields overview

Selected concepts and or methods involving nanophononics research are listed and their application fields marked. This is a rough correlation and the items in the topic column need to be revised. The application fields are gathered under the label of societal challenges.

	Energy and Environment	Information Processing	Health and Well-being	Safety and Security
Thermal management	X	X	X	
Energy scavenging	X	X		
Low power strategies	X	X	X	X
Noise control		X		X
Ballistic phonons		X		X
THz technologies		X	X	X
Ultrafast coherent phenomena	X	X	X	X
Spectroscopy	X		X	X
Metrology and standards	X	X	X	X
Phonon sources		X	X	X
Decoherence control & quantum technologies		X		X
3D imaging	X	X	X	X
Phonons in biological matter	X	X	X	X
Phononic Crystals & acousto metamaterials		X		X
Opto- and nanomechanics		X		X

Table 10 > Nanophononic research topics and categories and their area of impact

4. Expected impacts

Topics	Emerging nanophononics Roadmap impact
Promoting science excellence	Nanophononics pushes the limits of theories, instrumentation, development of new concepts. Already the impact of near-field radiation is contributing to the understanding of energy (and heat) transfer at the nanoscale and not only in devices and solids but also in soft matter. The link to information storage and processing challenges some long-held views on heat transfer and leads to new frontier in the understanding of non-linear energy localised in the nanoscale, among others
Impact on KETs	Nanophononics research outcomes will become increasingly important to increase the value on innovations in practical all the KETs (Nanotechnologies, Advanced Materials, micro- and nanoelectronics, Photonics, Biotechnology and Advanced Manufacturing) since all of them rely, in one way or another, on energy being transferred, stored, transformed and generated, be this in a device or an industrial process or in defining properties of innovative (nano)materials. Research in nanophonics should lead to advanced knowledge that must be transformed for applications in high-tech innovations
Addressing Societal Challenges	Nanophononics in biology holds the promise for huge advances in imaging and theranostics, which are directly linked to Health and well-being. Similar arguments apply to energy and its impact on environment

Topics	Emerging nanophononics Roadmap impact
Standards and regulations	The nm-scale of acoustic phonon wavelengths made them ideal candidates for dimensional nanometrology. Likewise, their sensitivity to atomic and chemical bonds could lead to their use in novel biological and chemical nanometrology methods, in which Europe is uniquely positioned. Once the metrology methods are established, the next step is to apply them to future nanotechnology standards. Furthermore, quantum metrology also offers opportunities for reaching the limits of metrology and basic physicalparameters

5. Implementation

Concerning implementation, measures at several levels are proposed:

i) Priority funding for areas where Europe is already strong, for example:

- Materials research towards tailored (nano)phononic materials.
- Theory of nanoscale thermal transport accompanied by a strong experimental program targeting information processing and Safety and security.
- Coherent phonon sources.

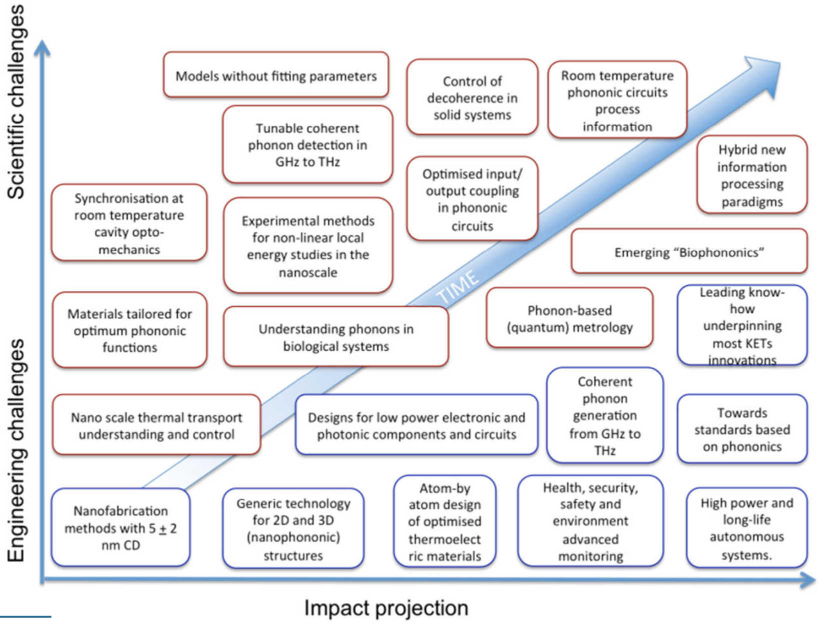

Fig. 1 > Summary of the research challenges and timeline of emerging nanophononics.

ii) Implementation in the short time scale exploratory research, in clusters of projects addressing ground breaking, basic excellent research combined with directed yet challenging targeted research in topics, for example, low power consumption in ICT devices-from atomic energy transfer to the Internet of Things. A variety of instruments and co-funding may be necessary.

iii) Explore the synergies with emerging communities, such as nanoarchitectronics [90].

6. Conclusions & future activities

Nanophononics is an emerging research topic which is a corner stone of much of the current research challenges at the cross-road of nanotechnology, materials science, information technology, energy research, biology and many more. This is no longer surprising as it involves energy transfer between atoms at the very root of it.

This Roadmap was prepared based on two consultations, mainly at European level, which provided a rather large coverage but did not go far enough to have the level of refinement of more focused or "traditional" research topics. Many connections remain to be made and a process of prioritising research topics needs to be undertaken. This process may be science excellence driven or applications driven. However, either way, it is a research area that, given its pivotal role, needs to be seriously considered in future H2020 work programs.

Above all, the intellectual property and innovations that can potentially come out of nanophononics, is likely to be of core character for a range of applications in areas identified as Key Enabling Technologies and Societal Challenges. With the prospect of the internet of things, and the swarm of gadgets, alone low energy strategies for devices, and the knowledge underpinning it, will provide Europe with a leading position in markets depending on energy, health and ICT.

Future activities should include methodological issues, which need immediate action:

- Making this Roadmap more comprehensive by a wider consultation with stake-holders, including related communities and industry.
- Improve the methodology to strengthen the link between the Strategic Research Agenda and the Roadmap.

final suggestions

Final suggestions

At this stage EUPHONON has shown that:

- There is a critical mass of research in Europe in Nanophononics.
- Nanophononics is likely to impact most high-tech oriented research areas.
- Nanophononics, if fostered, will accelerate innovation in a myriad of industrial sectors.

Based on the EUPHONON findings, we envisioned the following topics to be supported:

1) Thermal transport in the Nano scale. Thermal transport across interfaces at the atomic scale. Non-equilibrium phenomena where current thermodynamic approaches do not apply.
2) Materials for phononic components. Mastering length scales relevant for phonon control. Acousto-metamaterials and transformation phononics.
3) Opto-and nano-mechanics. Combining phononics and photonics for information technologies.
4) Phonons and Fluctuations in Biology. Unravelling energy-related processes in biological systems.
5) Three-Dimensional Imaging and nanometrology. Techniques and tools for sub 100 nm resolution 3D imaging for medicine, and safety and security. New metrology methods exploiting vibrations in a solid.

At the end of ideally clustered projects in nanophononics the following is expected:

a) Engineering solutions towards reducing energy consumption (IoT, lighting, information processing, etc.)
b) Next generation 3D high resolution imaging technologies.
c) Build up core competences to incorporate accumulated knowledge in future products.

references

References

[1] Please contact sebastian.volz@ecp.fr for joining
[2] 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
[3] 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
[4] https://technology.ihs.com/389490/booming-iphone-and-ipad-sales-make-gyroscopes-the-top-consumer-and-mobile-mems-device-in-2011
[5] Alexander G. Krause, Martin Winger, Tim D. Blasius, Qiang Lin and Oskar Painter, A high-resolution microchip optomechanical accelerometer, Nature Photonics, 6, 768, 2012
[6] Jessica L. Arlett, E.B. Myers and Michael L. Roukes, Comparative advantages of mechanical biosensors, Nature Nanotechnology, 6, 203, 2011
[7] 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
[8] Jan M. Rabaey , 2011 Symposium on VLSI Circuits Digest of Technical Papers
[9] Balandin, A. A. Thermal properties of graphene and nanostructured carbon materials. Nat Mater 10, 569–581 (2011). ; Xu, X., et al., Length-dependent thermal conductivity in suspended single-layer graphene, Nature Communications (2014).; Yan et al. Nature Communications 3, 827 (2012)
[10] Seol, J. H. et al. Two-Dimensional Phonon Transport in Supported Graphene, Science 328, 213–216 (2010)
[11] Majumdar, A. Thermoelectric devices: helping chips to keep their cool, Nature Nanotechnology 4, 214–215 (2009)
[12] Lasance, C. J. M., and Poppe, A. 2014. Thermal Management for LED Applications, Springer Science+Business Media, NewYork
[13] http://energy.gov/energysaver/articles/led-lighting
[14] Snyder, G. J. & Toberer, E. S. Complex thermoelectric materials, Nat Mater 7, 105–114 (2008)
[15] Majumdar, A., Enhanced Thermoelectricity in Semiconductor Nanostructures, Science 303, 777–778 (2004)
[16] Poudel, B. et al. High-thermoelectric performance of nanostructured bismuth antimony telluride bulk alloys, Science 320, 634–638 (2008). ; Yu, J.-K., Mitrovic, S., Tham, D., Varghese, J. and Heath, J. R. Reduction of thermal conductivity in phononic

nanomesh structures, Nature Nanotechnology 5, 718–721 (2010)
[17] Biswas, K. et al. High-performance bulk thermoelectrics with all-scale hierarchical architectures, Nature 489, 414–418 (2012)
[18] Callaway, J. Model for lattice thermal conductivity at low temperatures, Phys Rev 113, 1046 (1959)
[19] Minnich, A. J. et al. Thermal Conductivity Spectroscopy Technique to Measure Phonon Mean Free Paths, Phys. Rev. Lett. 107, 095901 (2011)
[20] Dengfeng Du, Jo Darkwa, Georgios Kokogiannakis, Thermal management systems for Photovoltaics (PV) installations: A critical review, Solar Energy 97, 238–254 (2013)
[21] F. Gamiz, J. B. Roldan, A. Godoy, P. Cartujo-Cassinello, and J. E. Carceller, J. Appl. Phys. 94, 5732 (2003)
[22] http://www.nrdc.org/energy/data-center-efficiency-assessment.asp
[23] www.itbusinessedge.com/info/PP-BuildDataCenter-pg9.aspx
[24] S. Hermelin, S. Takada, M. Yamamoto, S. Tarucha, A. D. Wieck, L. Saminadayar, C. Bäuerle, T. Meunier, Electrons surfing on a sound wave as a platform for quantum optics with flying electrons, Nature 477, 435–438 (2011)
[25] S. Buyukkose , A. Hernández-Mínguez , B. Vratzov , C. Somaschini , L. Geelhaar , H. Riechert , W. G. van der Wiel , P. V. Santos, High-frequency acoustic charge transport in GaAs nanowires, Nanotechnol. 25 , 135204 (2014)
[26] D.M. Moss, A.V. Akimov, B.A. Glavin, M. Henini and A.J. Kent, Ultrafast strain-induced current in a GaAs Schottky diode, Phys. Rev. Lett. 106, 066602 (2011)
[27] M. Bombeck, A. S. Salasyuk, B. A. Glavin, A. V. Scherbakov, C. Brüggemann, D. R. Yakovlev, V. F. Sapega, X. Liu, J. K. Furdyna, A. V. Akimov, and M. Bayer, Excitation of spin waves in ferromagnetic (Ga,Mn)As layers by picosecond strain pulses, Phys. Rev. B 85, 195324 (2012)
[28] K. I. Doig, F. Aguesse, A. K. Axelsson, N. M. Alford, S. Nawaz, V. R. Palkar, S. P. P. Jones, R. D. Johnson, R. A. Synowicki, J. Lloyd-Hughes, Coherent magnon and acoustic phonon dynamics in tetragonal and rare-earth-doped BiFeO3 multiferroic thin films, Phys. Rev. B, 88, 094425 (2013)
[29] Kim, J.-W., Vomir, M. and Bigot, J.-Y., Ultrafast magnetoacoustics in nickel films, Phys. Rev. Lett. 109, 166601 (2012)
[30] M. Krawczyk and D. Grundler, Review and prospects of magnonic crystals and devices with reprogrammable band structure, J. Phys.: Condens. Matter 26 123202 (2014)

[31] Oleksandr Kovalenko, Thomas Pezeril, and Vasily V. Temnov, New Concept for Magnetization Switching by Ultrafast Acoustic Pulses, Phys. Rev. Lett. 110, 266602 (2013)
[32] A. Hernández-Mínguez , K. Biermann , R. Hey , P. V. Santos, Spin transport and spin manipulation in GaAs (110) and (111) quantum wells, Phys. Status Solidi B 251 , 1736 (2014)
[33] Aspelmeyer, Kippenberg and Marquardt, Rev. Mo. Phys. 86, 1391-1452 (2014); Cavity Optomechanics: Nano- and Micromechanical Resonators Interacting with Light, Eds: Aspelmeyer, Kippenberg & Marquardt, Springer, Berlin (2014)
[34] Rugar et al., Single spin detection by magnetic resonance force microscopy, Nature 430, 329 (2004)
[35] Degen et al., Nanoscale magnetic resonance imaging, PNAS 106, 1313 (2009)
[36] Moser et al., Ultrasensitive force detection with a nanotube mechanical resonator, Nature Nano 8, 493 (2013)
[37] Chaste et al., A nanomechanical mass sensor with yoctogram resolutio, Nature Nano 7, 301 (2012)
[38] see e.g. https://technology.ihs.com/389490/booming-iphone-and-ipad-sales-make-gyroscopes-the-top-consumer-and-mobile-mems-device-in-2011
[39] Chen et al., Sensors 9, 1330 (2009), Krause et al., Nature Photonics 6, 768 (2012)
[40] Bargatin et al., Large-Scale Integration of Nanoelectromechanical Systems for Gas Sensing Applications, Nano Lett. 12, 1269 (2012)
[41] Ng et al., High density vertical silicon NEM switches with CMOS-compatible fabrication, Electronics Lett. 47, 759 (2011)
[42] Arlett et al., Comparative advantages of mechanical biosensors, Nature Nano 6, 203 (2011)
[43] D. Shin, Y. Urzhumov, D. Lim, K. Kim, D. R. Smith, A versatile smart transformation optics device with auxetic elasto-electromagnetic metamaterials, Sci. Report 4, 4084 (2014)
[44] M. Schubert, M. Grossman, O. Ristow, M. Hettich, A. Bruchhausen, E. C. S. Barretto, E. Scheer, V. Gusev, T. Dekorsy, Spatial-temporally resolved high-frequency surface acoustic waves on silicon investigated by femtosecond spectroscopy, Appl. Phys. Lett. 101, 013108 (2012)
[45] A. Crespo-Poveda , R. Hey , K. Biermann , A. Tahraoui , P. V. Santos , B. Gargallo , P. Muñoz , A. Cantarero , M. M. de Lima, Synchronized photonic modulators driven by surface acoustic waves, Jr. Opt. Express 21, 21669 (2013)

[46] C. Thomsen, H.T. Grahn, H.J. Maris, J. Tauc, Surface generation and detection of phonons by picosecond light pulses, Phys. Rev. B 34 (1986) 4129
[47] P. Ruello, V. E. Gusev, Physical mechanisms of coherent acoustic phonons generation by ultrafast laser action, Ultrasonics, (2014)
[48] I. Favero, The stress of light cools vibration, Nature. Phys. 8, 180–181 (2012)
[49] See e.g. Eichenfield, Nature 462, 78 (2009), Safavi-Naeini, PRL 108, 033602 (2012), Safavi-Naeini, PRL 112, 153603 (2014)
[50] See e.g. Teufel, Nature 475, 359 (2011), Palomaki, Science 342, 710 (2013)
[51] V. N. Golovach et al., Phys. Rev. Lett. (2004) 016601
[52] M. V. Gustafsson et al., Science 346 (2014) 207-211
[53] E. Pickwell-MacPherson and V. P. Wallace, Photodiagnosis and Photodynamic Therapy 6 (2009) 128-134
[54] H.-K. Son, Nanotechnology Topical Review 24 (2013) 214001
[55] X.-C. Zhang, Phys. Med. Biol. 47 (2002) 3667-3677
[56] See, for example http://asqella.com/
[57] Z. Popovic and E. N. Grossman, IEEE Trans. Terahertz Sci. Technol. 1 (2011) 133-144
[58] B. C. Daly et al., Appl. Phys. Lett. (2004) 5180-5182.
[59] R. Li Voti et al., Intl. J. Thermophysics 26 (2005) 1833-1848
[60] http://phononics.tongji.edu.cn/en/Default.aspx
[61] http://s3tec.mit.edu/
[62] http://www.euphonon.eu/EPH/index.php
[63] http://www.menlosystems.com/en/products/synchronization-stabilization-and-asops-systems/asops/, https://www.thorlabs.us/newgrouppage9.cfm?objectgroup_id=4711 , http://asqella.com/ , Z. Popovic and E. N. Grossman, IEEE Trans. Terahertz Sci. Technol. 1 (2011) 133-144
[64] http://www.project-nanoteg.com/, http://project-nanotherm.com/
[65] D. Rugar et al., "Single spin detection by magnetic resonance force microscopy", Nature 430, 329 (2004)
[66] C. Degen et al., "Nanoscale magnetic resonance imaging", PNAS 106, 1313 (2009)
[67] R. W. Andrews et al., "Bidirectional and efficient conversion between microwave and optical light", Nature Physics 10, 321 (2014)
[68] A. Jöckel et al, "Sympathetic cooling of a membrane oscillator in a hybrid mechanical–atomic system", Nature Nanotech. 10.1038/nnano.2014.278 (Advance Online Publication)
[69] 2013 ITRS chapter on Emerging Research Devices. http://www.itrs.net/Links/2013ITRS/2013Chapters/2013ERD_Summary.pdf

[70] M. Esposito, U. Harbola, and S. Mukamel, “Nonequilibrium Fluctuations, Fluctuation Theorems, and Counting Statistics in Quantum Systems,” Rev. Mod. Phys. 81 (December 2009): 1665–1702, doi:10.1103/RevModPhys.81.1665
[71] S. Lepri, R. Livi, and A .Politi, “Thermal Conduction in Classical Low-Dimensional Lattices,” Physics Reports-Review Section of Physics Letters 377, no. 1 (2003): 1–80, doi:10.1016/S0370-1573(02)00558-6
[72] J. S. Reparaz et al., A novel high-resolution contactless technique for thermal mapping and thermal conductivity determination: Two-laser Raman thermometry, Rev. Sci. Inst. 85, 034901 (2014); E. Chavez Angel, et al., Reduction of the thermal conductivity in free-standing ultrathin Si membranes investigated by non-invasive Raman Thermometry, Appl. Phys. Lett. Materials 2, 012113 (2014)
[73] ENIAC Multi-Annual Strategic Plan 2010, http://www.eniac.eu/web/downloads/documents/masp2010.pdf ; AENEAS, Vision Mission and Strategy for European R&D in Micro-and Nanoelectronics, http://www.aeneas-office.eu/web/downloads/aeneas/vms_final_feb2011_1.pdf; Multiannual Strategic Reseaerch and Innovation Agenda for the ECSEL Joint Undertaking MASRIA 2015 http://www.aeneas-office.eu/web/documents/MASRIA 202015.php
[74] M. V. Gustafsson, T. Aref, A. F. Kockum, M. K. Ekström, G. Johansson and P. Delsing, Propagating phonons coupled to an artificial atom, Science 10 October 2014, Vol. 346 no. 6206 pp. 207-211 , DOI: 10.1126/science.1257219
[75] Colloquium: Phononics: Manipulating heat flow with electronic analogs and beyond, N Li, J Ren, L Wang, G Zhang, P Hänggi, B Li - Reviews of Modern Physics, 2012; S Sklan, JC Grossman, Beyond electronics, beyond optics: single circuit parallel computing with phonons - arXiv preprint arXiv:1301.2807, 2013 - arxiv.org
[76] M.M. Milosevic et al, Optics Letters, Vol. 36, Issue 23, pp. 4659-4661 (2011) and K. Okamoto, IEEE J. Sel. Topics Quantum Electron. Vol. 20, Issue 4 (2014)
[77] D.V. Seletsky et al., Laser cooling of solids to cryogenic temperatures, Nature Photonics 4, 161 - 164 (2010); M. Hase et al., Frequency comb generation at terahertz frequencies by coherent phonon excitation in silicon; Nature Photonics 6, 243–247 (2012)
[78] E. Rephaeli et al., Ultrabroadband Photonic Structures To Achieve High-Performance Daytime Radiative Cooling, Nano Lett. 13, pp 1457–1461 (2013);

L. Zhu et al., Radiative cooling of solar cells, Optica, Vol. 1, Issue 1, pp. 32-38 (2014)
[79] J.-M. Kim, M. Vomir and J.-Y. Bigot, J.-Y., Ultrafast magnetoacoustics in nickel films, Phys. Rev. Lett. 109, 166601 (2012)
[80] M Krawczyk and D Grundler, Review and prospects of magnonic crystals and devices with reprogrammable band structure, 2014 J. Phys.: Condens. Matter 26 123202
[81] O. Kovalenko, T. Pezeril and V. V. Temnov, New Concept for Magnetization Switching by Ultrafast Acoustic Pulses, Phys. Rev. Lett. 110, 266602 (2013)
[82] M. Bombeck, A. S. Salasyuk, B. A. Glavin, A. V. Scherbakov, C. Brüggemann, D. R. Yakovlev, V. F. Sapega, X. Liu, J. K. Furdyna, A. V. Akimov, and M. Bayer, Excitation of spin waves in ferromagnetic (Ga,Mn)As layers by picosecond strain pulses, Phys. Rev. B 85, 195324 (2012)
[83] K. I. Doig, F. Aguesse, A. K. Axelsson, N. M. Alford, S. Nawaz, V. R. Palkar, S. P. P. Jones, R. D. Johnson, R. A. Synowicki, J. Lloyd-Hughes, Coherent magnon and acoustic phonon dynamics in tetragonal and rare-earth-doped $BiFeO_3$ multiferroic thin films,Phys. Rev. B, 88, 094425 (2013)
[84] A. Hernández-Mínguez , K. Biermann , R. Hey , P. V. Santos, Spin transport and spin manipulation in GaAs (110) and (111) quantum wells; Phys. Status Solidi B, 251, 1736 (2014)
[85] Breaking the speed limits of phase-change memory, D. Loke et al., Science 336, 1566–1569 (2012)
[86] http://www.seagate.com/newsroom/press-releases/HMR-demo-ceatec-2013-pr-master/
[87] See, for example, https://ec.europa.eu/digital-agenda/en/comment/16381#comment-16381
[88] See, for example ref 82
[89] Series of papers presented at the 3rd Mediterranean International Workshop in Photoacoustic and Photothermal Phenomena, Focus on Biomedical, Nano-scale imaging and Non Destructive Evaluation, Erice, 2014, http://www.sbai.uniroma1.it/conferenze/photoacoustic-photothermal/Programme.html
[90] https://ec.europa.eu/digital-agenda/en/comment/15921#comment-15921

annex

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Short facts

EUPHONON	Building a European NanoPhononics Community
EC contribution	393.972 Euros
Contract number	FP7-ICT-612086
No. of partners	7
Chair person	CNRS (France) / Sebastian Voltz
Start date	November 01, 2013
Duration	12 months
Website	www.euphonon.eu

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CNRS	France	Chapuis, P-Olivier
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IEMN CNRS UMR8520	France	Devos, Arnaud
Max Planck Institute for Polymer Research	Germany	Donadio, Davide
Wroclaw University of Technology	Poland	Falat, Tomasz
CENIMAT/I3N	Portugal	Ferreira, Isabel
Heraeus Materials Technology GmbH & Co. KG	Germany	Fritzsche, Sebastian
THALES Research and Technology	France	Galindo, Christophe
KU Leuven	Belgium	Glorieux, Christ
Catalan Institute of Nanoscience and Nanotechnology	Spain	Gomis-Bresco, Jordi
IBM Research - Zurich	Switzerland	Gotsmann, Bernd
Saint-Gobain Research	France	Grigorova-Moutiers, Veneta
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CNRS	France	Volz, Sebastian
University of Konstanz	Germany	Weig, Eva
THALES	France	Ziaei, Afshin

Source: www.euphonon.eu/EPH/groups.php

Fig. 1 > Number of registered groups per type of institution.

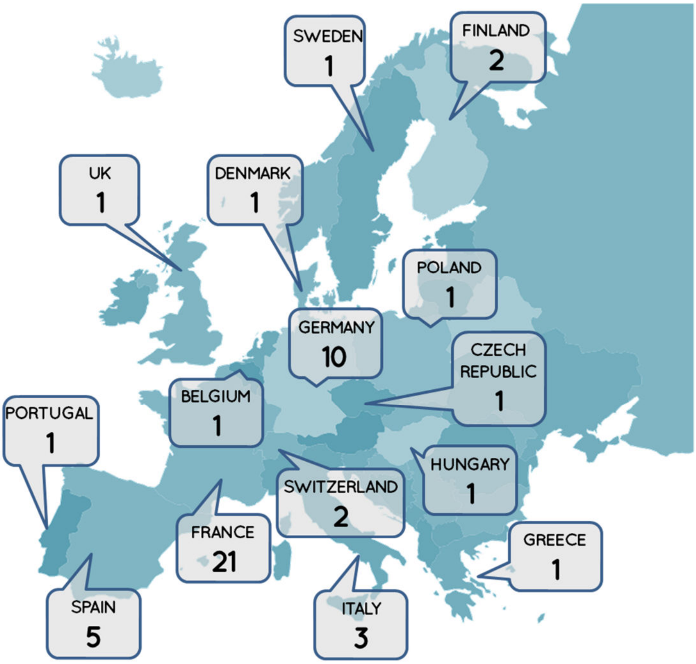

Fig.2 > Number of registered groups per country.

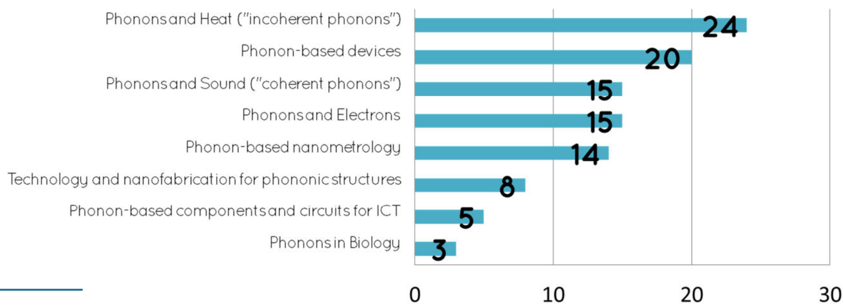

Fig. 3 > Number of registered groups per research topic.

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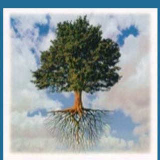

SEVENTH FRAMEWORK PROGRAMME