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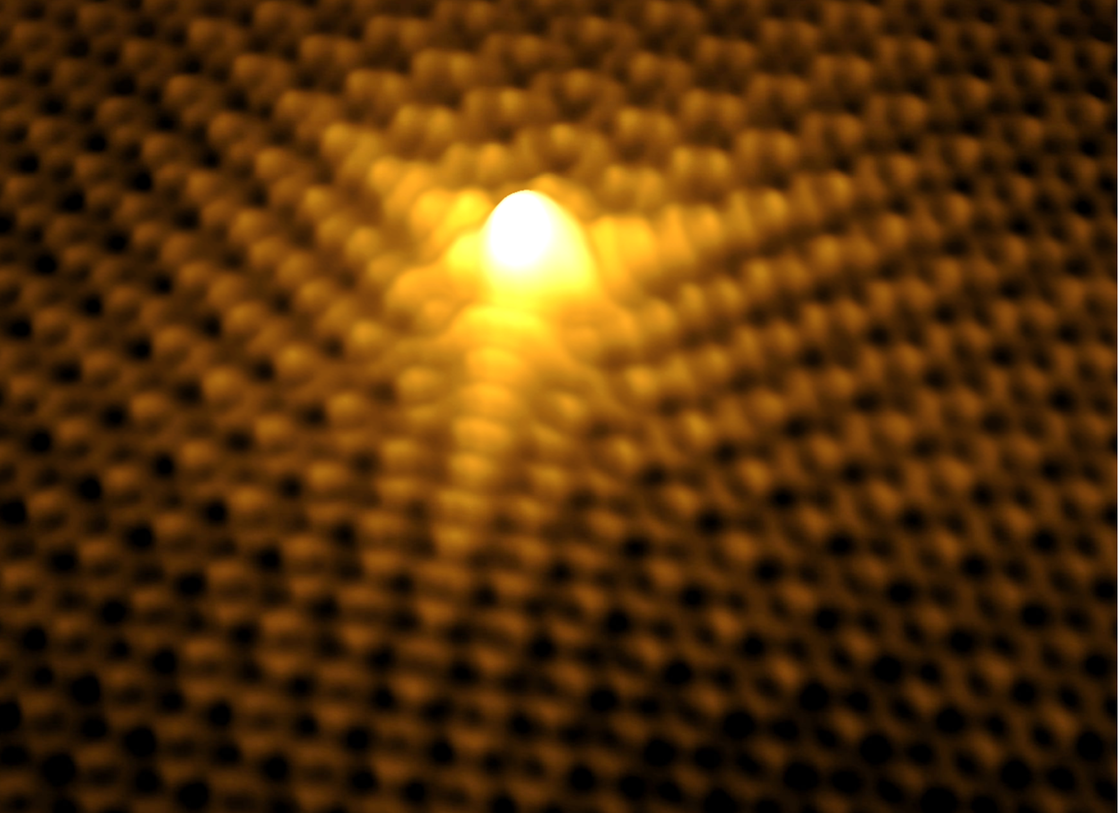

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dear readers,

Dear Readers,

This E-nano Newsletter issue contains the Roadmap for Nanophononics, one of the main outputs of the EUPHONON coordination action (www.euphonon.eu); EU project with the mission to build a European Community for Nanophononics. The objective of this Roadmap is to summarize 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.

In addition research highlights from top-level research institutions worldwide such as MANA/NIMS (Japan) and CIC nanoGUNE (Spain) are presented.

We would like to thank all the authors who contributed to this issue as well as the European Commission for the financial support (ICT/FET FP7 EUPHONON Coordination Action No. 612086).

> Dr. Antonio Correia Editor - Phantoms Foundation

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EUPHONON Roadmap

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1. Vision and objectives

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.

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.

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.

Basic research TRL 1-2	Applied research TRL 2-3	First application TRL 3-4

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

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.

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	[blue]	[blue]	[green]
Roughness control down to 2 $\pm$ 1 nm	[blue]	[blue]	[green]
Room temperature phononic phenomena suitable for applications	[green]	[orange]	
Identification and implementation of "green" materials and nanofabrication for phononic applications	[blue]	[green]	[orange]

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

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 [1-4], 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.

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	■	■	■

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

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 [5]. 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 [6]. 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 [7]. Nevertheless the fabrication of truly low-dimensional materials, such as graphene, opens up to experimental verifications of models and theories [8].

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	■	■	■

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

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 [8]. Other methods such as for the determination of the Seebeck coefficient are not included as commercial apparatus already exists.

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	[blue]	[blue]	[green]
Methods for 2D temperature imaging with sub 100 nm spatial resolution	[green]	[orange]	
Dynamic measurements of a few nm's resolution temperature fields	[blue]	[green]	[orange]
Transfer the concept of local non-linear energy to thermal measurements	[blue]	[green]	[orange]
Simpler near-field radiative experimental methods	[blue]	[green]	[orange]

Table 5 > Timeline of scientific and technical challenges in 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 [9] 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.

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

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

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 [10], albeit at very low temperatures, and for other alternative schemes of information processing [11].

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 [12]. On the other hand, phonons of THz frequencies can be used for all optical cooling of solids and bridge the gap to photonics [13]. 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 [14].

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 [15-19]. 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 [20].

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 [21] as well as heat assisted magnetic recording in order to surpass the trilemma of magnetic recording, especially with respect to the superparamagnetic limit [22].

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 [23]. 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 [24] 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 [25]. 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			

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.

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

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

	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

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
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.

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 [26].

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

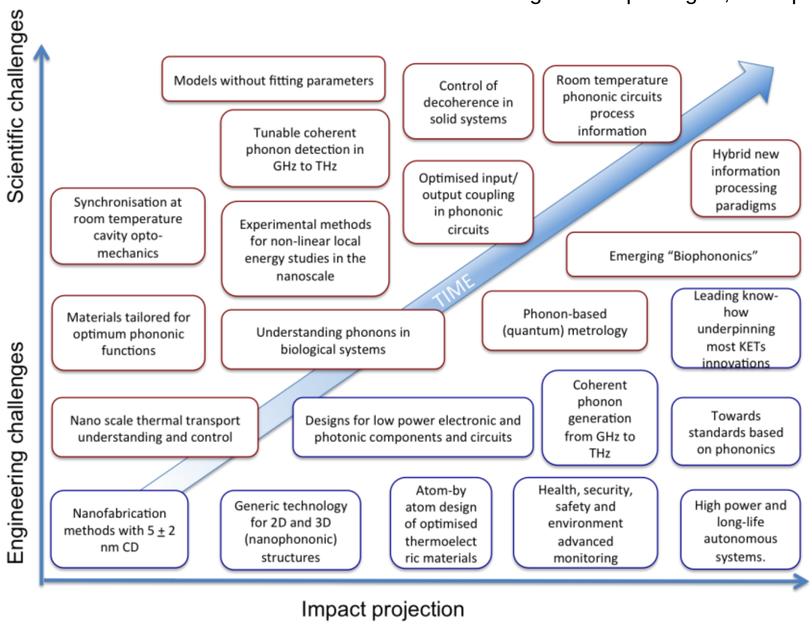

Fig. 1 > Summary of the research challenges and timeline of emerging nanophononics./

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.

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EUPHONON
Building a European NanoPhononics Community

EUPHONON	Building a European NanoPhononics Community
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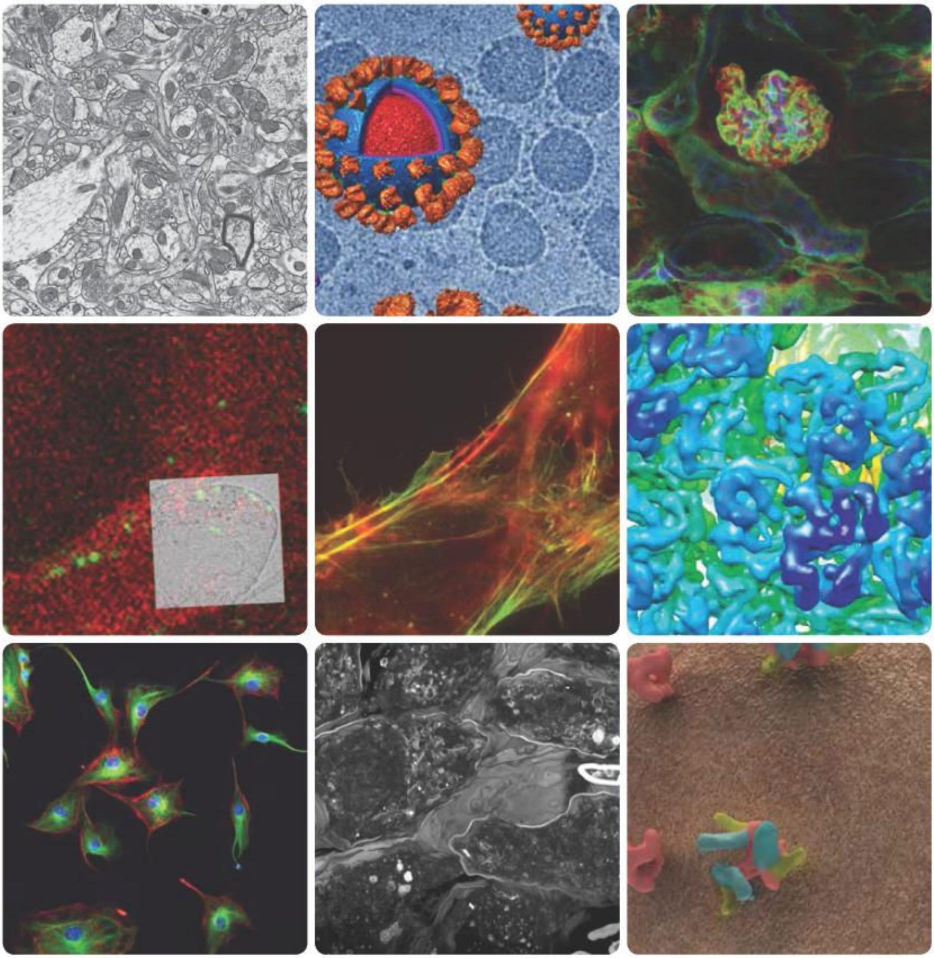

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The intermediates in a chemical reaction photographed 'red-handed'

Researchers at the Materials Physics Center CSIC-UPV/EHU, the DIPC, and CIC nanoGUNE, in the framework of an international collaboration, have for the first time imaged and identified the bond configuration of the intermediates in a complex sequence of chemical transformations of enediyne molecules on a silver surface, thus resolving the microscopic mechanisms that account for their behaviour. This piece of research has been published in the latest issue of the journal Nature Chemistry.

One of the long-standing goals being pursued by chemists has been to succeed in following and directly visualising how the structures of molecules change when they undergo complex chemical transformations.

Reaction intermediates, which are highly unstable substances that form in different steps in a reaction before the products are obtained, are particularly difficult to identify and characterise owing to their short lifetimes. Getting to know the structure of these intermediate species may be very helpful in understanding the reaction mechanisms and, what is more, could have a great impact on the chemical industry, materials science, nanotechnology, biology and medicine.

In the framework of this international collaboration, the bond configuration of the reactants, the intermediate and final products of a complex, organic reaction have been imaged and resolved at the single-molecule level. The prestigious journal Nature Chemistry has published this research in its latest issue.

The team has obtained the images of the chemical structures associated with different steps in the reaction cascade involving multiple steps of enediyne molecules on a silver surface, using non-contact atomic force microscopy (nc-AFM) with a particularly sensitive tip: it uses a very fine needle that can detect the smallest bumps on an atomic scale (in a way not unlike reading in Braille) as it absorbs a carbon monoxide molecule that acts like a "finger" on the text to increase its resolution.

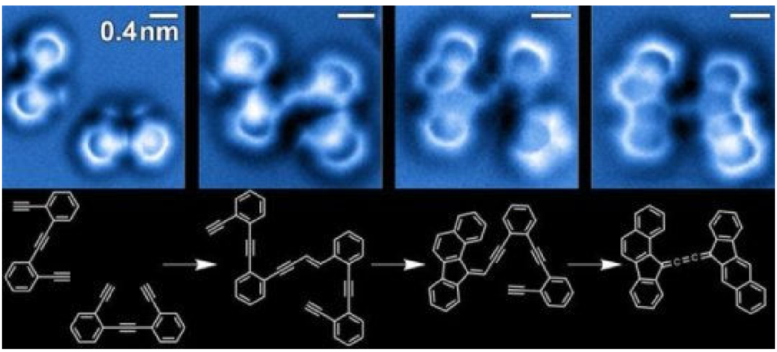


Fig. 1 > Sequence of images of the steps in the reaction of enediyne molecules on a silver surface. (A. Riss / Technische Universität München)./

Stabilizing the intermediates

By combining the latest advances in numerical calculus and the classical analytical models that describe the kinetics of sequential chemical reactions, an area that explores the speed of the reactions and the molecular events taking place in it has been proven. So to explain the stabilization of the intermediates, it is not enough just to consider their potential energy, it is essential to bear in mind the energy dissipation and the changes in molecular entropy, which measures how far a system is organised. The surface, and in particular the interaction of the extremely unstable intermediates with the surface, play a key role for both the entropy and the dissipation of energy, which highlights a fundamental difference between the surface-supported reactions and gas-phase or solution chemistry.

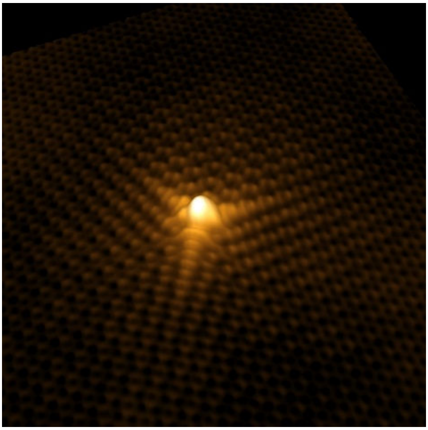
Additional information

The research has been carried out by various research groups led by Felix Fischer, Michael Crommie, and Angel Rubio (University of California at Berkeley, Lawrence Berkeley National Laboratory, EHU, and Max Planck Institute for the Structure and Dynamics of Matter in Hamburg), and by Ikerbasque researchers Dimas Oteyza (CSIC/EHU and DIPC) and Miguel Moreno Ugeda (CIC nanoGUNE).

Bibliographical reference

A. Riss, A. Pérez Paz, S. Wickenburg, H.-Z. Tsai, D. G. de Oteyza, A. J. Bradley, M. M. Ugeda, P. Gorman, H. S. Jung, M. F. Crommie, A. Rubio and F. R. Fischer. “Imaging Single-Molecule Reaction Intermediates Stabilized by Surface Dissipation and Entropy”. Nature Chemistry. 2016. DOI: 10.1038/nchem.2506

Atomic magnets using hydrogen and graphene



Autonomous University of Madrid researchers in collaboration with the Institut Néel of Grenoble and CIC nanoGUNE have shown for the first time that the simple absorption of a hydrogen atom on a layer of graphene magnetises a large region of this material. By selectively manipulating these hydrogen atoms, it is possible to produce magnetic graphene with atomic precision. The work has been published in the prestigious journal Science.

Graphene, a sheet one atom thick made up of carbon atoms, has a huge number of qualities but lacks magnetic properties. Yet the hydrogen atom has the smallest magnetic moment. The magnetic moment is the magnitude that determines how much and in what direction a magnet will exert force. “In other words, we can all remember having held a magnet in our hands and seeing how it was capable of attracting or repelling another magnet at a certain distance, which was greater or smaller depending on its power. Well, what really determined this behaviour was the magnetic moment of our set of magnets. The distance at which we began to feel the appearance of a force was specified by the spatial extension of their magnetic moments, and the fact that the force should attract or repel depended on the relative orientation between them; that is why when one of the magnets was turned round, they then attracted or repelled each other or vice versa,” explained Iván Brihuega, leader of this research.

“Our work reveals how when a hydrogen atom touches a graphene layer it transfers its magnetic moment to it," said Brihuega. “In contraposition to more common magnetic materials such as iron, nickel or cobalt, in which the magnetic moment generated by each atom is located within a few tenths of a nanometre, the magnetic moment induced in the graphene by each atom of hydrogen extends several nanometres, and likewise displays a modulation on an atomic scale,” he added. The experiments were carried out with the help of a tunnel-effect microscope. This microscope allows matter to be imaged and manipulated on an atomic scale. Likewise, the results show that these induced magnetic moments interact strongly with each other at great distances (compared with the atomic scale) while also abiding by a particular rule: the magnetic moments are added or neutralised depending critically on the relative position between the absorbed hydrogen atoms. What is more, and of equal importance, is that “we have managed to manipulate the individual hydrogen atoms in a controlled way, and this has enabled us to freely establish the magnetic properties of selected regions of graphene” stressed Brihuega.

In the quest for magnetism

Ever since 2004 when it was first possible to obtain graphene, laboratories across the world have been trying to add magnetism to the long list of properties of this purely two-dimensional material. This interest arises mainly out of the fact that graphene is, a priori, an ideal material for use in spintronic technology. This promising technology is aiming to replace traditional electronics by transmitting both magnetic and electronic information at the same time, which could give rise to a new generation of more powerful computers. So "the results obtained in this work, which indicate the possibility of freely generating magnetic moments in the graphene and showing how these moments can communicate with each other over great distances, are paving the way for a promising future for this material in the emerging field of spintronics," concluded Héctor González Herrero, first author of the work.

The experiments and complementary theoretical calculations were carried out in the Condensed Matter Physics Center (IFIMAC).

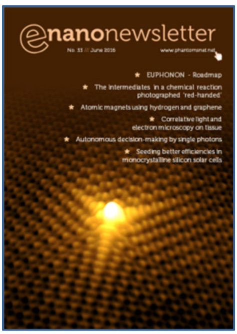
It is important to point out that both the microscope – a scanning tunnelling microscope operating at low temperatures (4K) in ultra-high vacuum conditions – and the theoretical software SIESTA – an efficient code based on first principles -, have been fully developed at the UAM.

The graphene samples were synthetized at l'Institut Néel in Grenoble (France).

Original publication

Héctor González-Herrero, José M. Gómez-Rodríguez, Pierre Mallet, Mohamed Moaied, Juan José Palacios, Carlos Salgado, Miguel M. Ugeda, Jean-Yves Veuillen, Félix Yndurain and Iván Brihuega

"Atomic-scale control of graphene magnetism by using hydrogen atoms" Science (22 Apr 2016) Vol. 352, Issue 6284, pp. 437-441, DOI: 10.1126/science.aad8038



Cover Image:
A picture of hydrogen atoms in graphene

Héctor González-Herrero UAM (Spain)
Departamento de Física de la Materia Condensada, Universidad Autónoma de Madrid, &
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nanoresearch

Correlative light and electron microscopy on tissue

Alex de Marco[1], Liesbeth Hekking[1], Anne Greet Bittermann[2], Maja Magrit Guenther[2], Roger Wepf[2]and Matthias Langhorst[1]

[1]FEI Company
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Imaging the same sample with multiple techniques provides valuable comparative information as well as easy targeting of regions of interest at different scales. In addition, correlative approaches help to overcome possible artifacts particular to any one specific analysis method.

Introduction

Correlative light and electron microscopy (CLEM) combines fluorescence microscopy with electron microscopy, allowing for the study of specific dynamic events in living cells with high-resolution data of the material in its entirety. The CLEM approach is being adopted by an increasing number of scientists and has proven to be a valuable tool for researchers in diverse fields of life sciences.

However, CLEM experiments are often challenging. Samples are prepared in different ways for optimal results in different modalities. For light microscopy, the sample is preferably kept in an aqueous environment, while for electron microscopy, the sample has to be fixed, embedded, and stained with heavy metals.

Imaging the same area throughout a workflow requires precise relocation. While imaging with different contrast methods and at different resolution scales, the data created has to be precisely matched and overlain. Creating an efficient workflow can be difficult due to the use of multiple microscopy platforms, varying data output formats, and challenging sample preparation techniques.

In this experiment, we exemplify how to use the FEI Correlative Suite to identify a region of interest and perform targeted imaging of this region in a DualBeam™ without fiducial markers. The FEI Correlative Suite includes the FEI CorrSight™, FEI MAPS™ 2.0, and an integrated link to all FEI SEM and small DualBeams.

Experimental approach and results

To demonstrate this workflow, we used mouse skin tissue, stained with a non-specific fluorescent dye that highlights the different layers and components of the skin tissue. The purpose was to identify a structure using CorrSight as a fluorescence microscope and retrieve the same structure using a DualBeam microscope. The sample was prepared for EM imaging using the typical steps of resin embedding, such as OsO_4 staining, dehydration, and Epon embedding. The block was pre-trimmed in order to be ready for block-face imaging. The block face has been scratched a few times with a razor blade in order to generate a visible pattern on the surface. (This trick is optional, but it can speed up the correlation procedure.)

The first imaging step was reflected light illumination on CorrSight. This procedure included acquisition of a tile set of images to generate a surface map on the block surface in the light microscope. Subsequently, a subsurface 3D volume of the fluorescence signal was acquired using the CorrSight's spinning disk confocal. Cells of interest could be easily located using this volume (Figure 1, top row). For the subsequent steps of this experiment, we decided to target a follicle (yellow arrowhead in Figure 1), which was clearly identifiable through the fluorescence signal.

Thanks to the data management of FEI MAPS 2.0, all images from CorrSight were pre-aligned upon data collection. This feature is critical since the data collected on the CorrSight can then be used to drive the navigation of the same sample in the DualBeam. Figure 1, second row shows a low-magnification overview of the sample surface collected in the DualBeam and a simple 2-point alignment between the LM overview and the EM overview. After this step, the CorrSight dataset was registered onto the DualBeam stage, and an Auto Slice & View volume acquisition of the targeted follicle could be set up easily (Figure 1 last row).

Methods

- Light microscopy imaging was done on an FEI CorrSight equipped with reflected light imaging and spinning disk confocal.
- EM imaging and Slice & View were conducted on a Helios NanoLab™ DualBeam.
- Data acquisition, as well as the image correlation of LM and EM images, was done through the use of FEI MAPS 2.0.
- The Slice & View dataset was collected using FEI Auto Slice & View.

Conclusions

This experiment demonstrates that in the absence of fiducials in the sample or on the sample holder, it is possible to easily follow a feature of interest through the different imaging steps of a CLEM

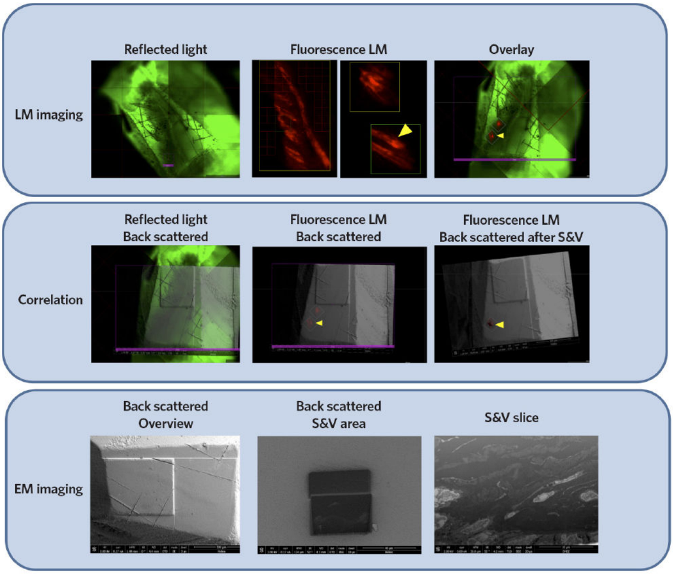

Fig. 1 > Images taken throughout the experiment. The top row shows images from the light microscope, and the bottom row shows images taken from the DualBeam. The middle row shows the overlays between the LM and EM images used to correlate. The yellow arrowhead indicates the cell followed throughout the workflow./

workflow using the FEI Correlative Suite solution.

The user interface on both the light and the electron microscope allows automated data acquisition of both overview images and detailed high-resolution images as tile sets. Data acquired during the experiment can be overlaid efficiently with high accuracy. The possibility of precise tracking of any differences in the cells' structure at all steps of the experiment enables easy navigation throughout the entire workflow.

The FEI Correlative Suite offers a complete workfloworiented solution for CLEM experiments that will help to advance biological research by bringing light and electron microscopy closer together.

Watch a video on CLEM and download additional information from our website: www.FEI.com/correlative-microscopy

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Autonomous Decision-Making by Single Photons

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Efficient and adaptive autonomous decision-making has been implemented based on a purely physical mechanism exploiting the quantum nature of photons.

Difficulty in decision-making to gain the maximal reward in uncertain, dynamically changing environments has been known as "multi-armed bandit problem (MAB)" in machine learning. In this type of problem, the fundamental difficulty consists of a trade-off between "exploration cost for new best" and "exploitation of known best".

To tackle the problem, Song-Ju Kim at the International Center for Materials Nanoarchitectonics, National Institute for Materials Science, Makoto Naruse at the National Institute of Information and Communications Technology, Serge Huant at the Institut NEEL, CNRS, and collaborators experimentally demonstrated that a single photon can be utilized to realize an autonomous physical decision-making machine. They successfully applied a theory of a decision maker based on the “tug-of-war (TOW) algorithm”, which was proposed by Song-Ju Kim and his colleagues, to artificially constructed decision-making machines by exploiting the particle and probabilistic nature of a single photon.

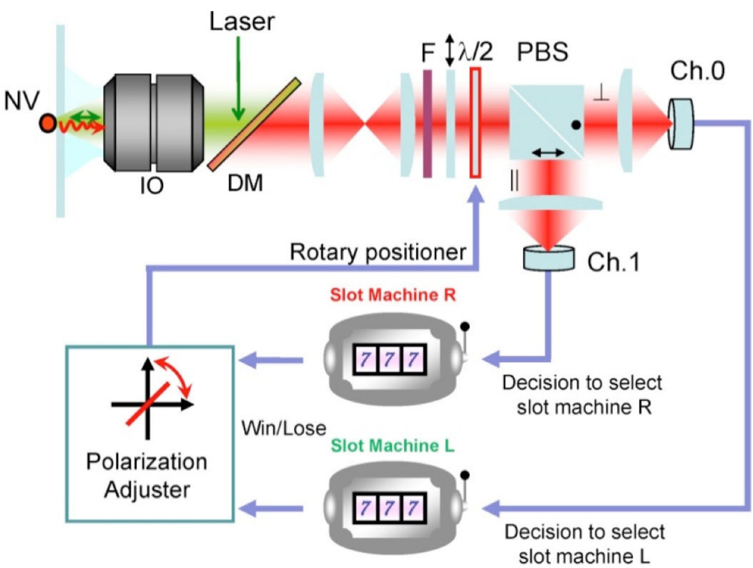

Fig. 1 > System architecture for single-photon decision maker and schematic diagram of experimental setup./

In their experimental architecture, the TOW mechanism is implemented with the notion of a polarization adjuster. As shown in the figure, a single photon emitted from a nitrogen-vacancy (NV) center in a diamond passes through a polarizer and then through a half-wave plate mounted on a rotary positioner, and impinges on the polarizing beam splitter (PBS). The two detectors (Ch0 and Ch1) are avalanche photodiodes (APDs). The detected signal is sent to a time-correlated single-photon-counting system where individual events are directly captured. The system associates the detection of a photon in Ch0 or Ch1 immediately with the decision to select slot machine R or L, respectively. Then the system adjusts the polarization of the photon by changing the angle of rotation of the half-wave plate based on the decision.

The study proposes a system to achieve an autonomous intelligent machine based on a purely physical mechanism, which is completely different from existing machine learning systems executed with software in a computer. This development of new solutions to MAB is highly expected to contribute to the creation of new information and communications technology (ICT).

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Seeding better efficiencies in monocrystalline silicon solar cells

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New 'single-seed cast method' for producing high quality monocrystalline solar cells has tremendous potential for the manufacture of low cost, high efficiency silicon solar cells.

Researchers at MANA have developed the 'single-seed cast method' that is a new method of silicon casting. Compared with conventional casting, the new method enabled dramatic improvements in the crystalline quality of the silicon that are expected to improve the efficiency of silicon solar cells.

The conversion efficiency of silicon solar cells - that are the mainstream of commercial photovoltaics - is now going to reach 20% using single crystalline silicon. Increasing conversion efficiency is recent target for adding higher value to the solar cells. However, it is not possible to achieve such high efficiencies using conventional cast multicrystalline silicon. Furthermore, since semiconductor grade single crystal silicon is too expensive for solar cells, there is strong demand for the development of a 'third type' of silicon as an alternative to multicrystalline and single-crystalline semiconductor silicon.

As a solution to this problem, a research team led by Takashi Sekiguchi, Group Leader of the Nano Device Characterization Group, Nano-Electronic

Materials Unit, International Center for Materials Nanoarchitectonics (MANA), National Institute for Materials Science (NIMS), and Koichi Kakimoto, Professor of Kyushu University, has developed the so-called ‘single-seed cast method’ using a seed crystal for the silicon cast method. The researchers succeeded in producing high quality, low impurity ingots of single crystal silicon (mono-silicon).

The new method consists of dissolving silicon feedstock inside a crucible and growing single crystalline silicon from a small seed. Notably, production costs can be reduced by this method compared with the method to produce dislocation-free single crystal silicon such as Czochralski method.

Importantly, solar cells produced using the new ingots yielded conversion efficiencies of 18.7%, which approach the value of 18.9% obtained with cells produced from semiconductor-silicon (CZ silicon) wafers.

In the future, further reductions of crystalline defects and impurities are expected to yield conversion efficiencies greater than 20 %.

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Fig. 1 > Photograph of the silicon ingot grown with the optimum conditions observed in the current study./