Phononics 2025

7th International Conference on Phononic Crystals/ Metamaterials, Phonon Transport, and Topological Phononics

June 9-13, 2025 – Seoul, Korea

Felix Bloch (1905-1983)
Nobel Prize in Physics (1952)

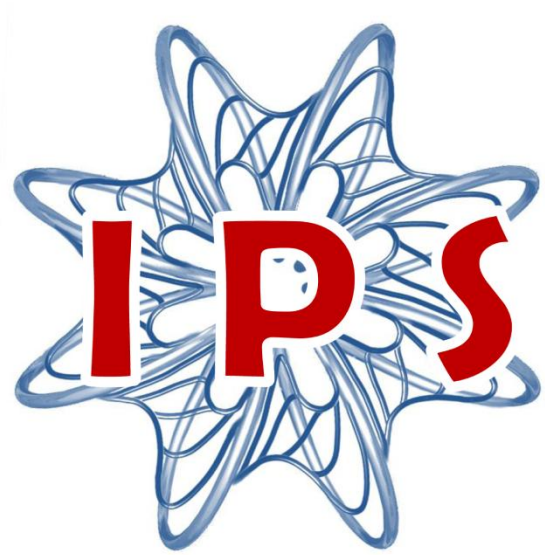
2025 Bloch Prize

Recipient:

Professor Clivia M. Sotomayor Torres

International Iberian Nanotechnology Laboratory, Portugal

Seoul, Korea



INTERNATIONAL PHONONICS SOCIETY

Front cover image:

"Korean paper lanterns"

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Bloch Prize

The Bloch Prize is a distinguished award offered by the International Phononics Society (IPS). It honors the eminent Swiss physicist who among many contributions to wave mechanics and theoretical physics formulated the underlying theory for electron wave propagation in periodic media. His theory, known as *Bloch theory*, laid the foundation for other theoretical developments ultimately leading to a formal classification of all crystals into metals, semiconductors and insulators. In recent years, Bloch theory re-emerged as the basic underlying mathematical condition for formulating the band structure of modern periodic materials such as phononic and photonic crystals. Felix Bloch, who was born in Zurich, Switzerland, on October 23, 1905, pursued his research career in Zurich, Heisenberg, Stanford, Los Alamos and Harvard University, and in 1954 took a leave of absence for one year to serve as the first Director General of CERN in Geneva. He received the Nobel Prize in Physics in 1952 jointly with Edward Mills Purcell "for their development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith".

At Phononics 2011, the *Bloch Prize* (originally called the *Felix Bloch Lecture*) was inaugurated to "honor individuals who have made outstanding and sustained contributions in the field of phononics (including phononic crystals, acoustic/elastic metamaterials, nanoscale phonon transport, coupled phenomena involving phonons, topological phononics, and related areas) over periods representing considerable portions of their scientific careers". The medal is awarded biennially at the time of the Phononics 20xx conference. The winner delivers the *Bloch Lecture* at the conference, and is also invited to write a 6-page *Bloch Paper* to be published alongside the conference proceedings.

The 2025 Bloch Prize recipient is Professor **Clivia M. Sotomayor Torres** who is honored for her invaluable contributions to "surface phonons, phonon confinement, thermal transport, optomechanics, and topological waveguides."

2025 Bloch Prize Committee

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Prof. Jinkyu Yang, Seoul National University (Korea)

Clivia M. Sotomayor Torres

Director General and Research Group Leader

International Iberian Nanotechnology Laboratory, Portugal

Education

1984 Ph.D. in Physics, Victoria University of Manchester, UK
1979 B.Sc. (Hons.) in Physics, University of Southampton, UK
1974 Licenciatura en Fisica (first two years), University of Chile-Santiago, Chile

Academic Appointments

2023- date Director General and Research Group Leader, International Iberian Nanotechnology Laboratory, Braga, Portugal
2008-2023 ICREA Research Professor, Catalan Institute of Nanoscience and Nanotechnology ICN2, Barcelona, Spain
2007-2012 Adjunct Professor, Physics Dept., Universidad Autonoma de Barcelona, Spain
2004-2008 Research Professor, University College Cork and Tyndall National Institute, Cork, Ireland
1996-2004 Chair of Materials Science in Electrical Engineering (C4), University of Wuppertal, Germany
1994-1996 Senior Lecturer in Electrical Engineering, University of Glasgow, UK
1987-1994 Lecturer, Electronics and Electrical Engineering, University of Glasgow, UK
1984-1987 Lecturer, Physics Department, University of St Andrews, UK
1983-1984 Postdoctoral researcher, Physics Department, University of St Andrews, UK

Awards and Honors

2022 J. Mittlesten-Scheid Visiting Professor, University of Wuppertal, Germany
2020 Elected to the Academia Europaea
2020 European Research Council Advanced Grant 2021-2026
2015 Nanoimprint Pioneer Award
2013 Visiting Professor, Royal Institute of Technology KTH, Sweden
2007 ICREA Research Professorship Award
2004 Science Foundation Ireland Principal Investigator Award
2004 Visiting CNRS Researcher, University Paul Sabatier, France
2003 Visiting professor, University Paul Sabatier, France
1993 Research Fellowship, Royal Society of Edinburgh and Scottish Office Edu. Dept.
1990 Nuffield Foundation. A one-Year Science Research Fellowship.
1982 ZONTA International Amelia Earhart Fellowship for postgraduate studies

Research activities

Experimental research in topological phononics, optomechanics and nanoscale thermal transport. Other areas included phonons in Si nanostructures, membranes and thin films, 2D materials, NEOMS, photonic crystals, semiconducting thin films, quantum wells, wires and dots, nanoimprint lithography and self-assembly of micro- and nano-particles and block copolymers, dimensional and defectivity nanometrology and functional inorganic nanostructures. Professor Sotomayor Torres has supervised over 21 PhD students and mentored 65 postdoctoral researchers during her career to date, including international research fellowship holders. She has served in several commissions of trust in Denmark, Germany and the European Commission.

From Phonon Confinement to Topological Waveguides

Clivia M. Sotomayor Torres

[1] *Department, International Iberian Nanotechnology Laboratory, 4715-330 Braga, clivia.sotomayor@inl.int*

Abstract: An experimentalist journey is chartered covering part of the phononics landscape, from confinement to topology. The study of phonon confinement in quantum wells, wires and dots, led us to confined phonons in free-standing silicon nm-membranes, giving way to room temperature silicon optomechanics and set us in a path to explore bosonic matter based on phononic crystal interface waveguides.

Surface phonons in cylinders and inhibited phonon relaxation in quantum dots. The advances in epitaxial semiconductor growth and subsequently in nanopatterning gave rise to a flurry of research on confined electrons and photons, as well as excitons, plasmons and other excitations. Our study of phonons started with surface phonons in 80 nm diameter and 500 nm high GaAs free-standing cylinders showed finger prints of surface phonons[1] arising from the electromagnetic field discontinuity at the surface. However, we missed the interpretation in terms of surface polaritons arising from retardation effects. An initial proposer of optical phonon confinement in III-V semiconductor nanowires was Sakaki[2] with the concept of a discretised phonon density of states due to the nanowire dimension. The concept went on to be developed further by Boeckelmann and Bastard[3] and demonstrated in deep etched III-V quantum dots[4]. The "phonon bottleneck" concept involving acoustic phonons, with a consequence for limited intrinsic photon emission efficiency, led to a lively controversy that helped to advance the understanding of phonon scattering in nanostructures of various types, including self-organised III-V quantum dots. It showed that non-ideal surfaces, strain distribution, localisation and Auger processes had to be considered in structures departing from the ideal quantum well. This is a challenging situation as each quantum dots in an array can experience different surrounding in the case of self-organised as well as in the nanofabricated quantum dots. What matters then is the tolerances of the application envisaged and if these variations in emission efficiency can be tolerated.

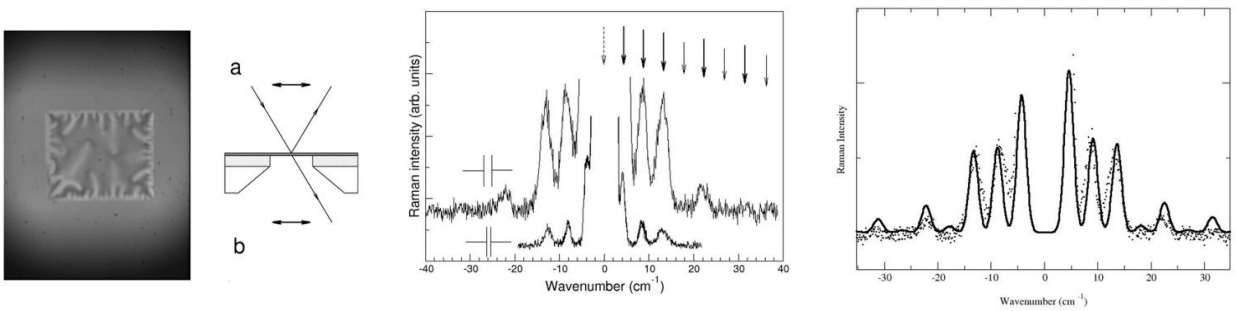

Figure 1 Raman spectrum of confined phonon in free-standing silicon membrane. Left: Sample image and cross-section. Middle: Experimental Raman spectra of a 32.5 nm membrane recorded with two different resolutions at room temperature and ambient conditions. Right: Simulation of the Raman spectrum of a 31.5 nm-thick membranes[6].

Confined phonons in silicon membranes. The work of A. Balandin on confined phonons in supported silicon membranes[5] inspired us to explore phonon confinement in free standing membranes based on silicon-on-insulator. If we could corroborate their existence, what would be the impact in decreasing critical dimensions in electronics? We demonstrated the presence of confined phonons in wedged membranes by high-resolution Raman scattering for membranes of thickness between 24 and 32 nm[6] and interpreted the data in the frame of the photo-elastic model. The results are depicted in Figure 1. A deeper study of confined phonons in free-standing membranes from 6 to 400 nm by Brillouin light scattering (see Figure 2) showed dramatic trends due to confinement compared to phonons in the bulk: a series of discrete symmetric and antisymmetric dispersion bands[7] was found, exhibiting a linear to quadratic dispersion relations

and orders of magnitude reduction in lifetime[8] when going from 400 nm to 6 nm thick free-standing membranes as shown in Figure 3. The immediate implication was then that thermal energy dissipation by acoustic phonons in membranes of few to 10s nm thickness would not help in the averting the "heat wall" in nanoelectronics with transistor feature size reaching the 10s or less nm scale. However, what we found was that below about 50 nm the role of confined phonons is minimal and that instead they are impacted by roughness scattering which, in the diffusive regime, is known as the Casimir limit. On the other hand, the power consumption in electronics continues to be a serious issue, now exacerbated by the massive use of artificial intelligence[9].

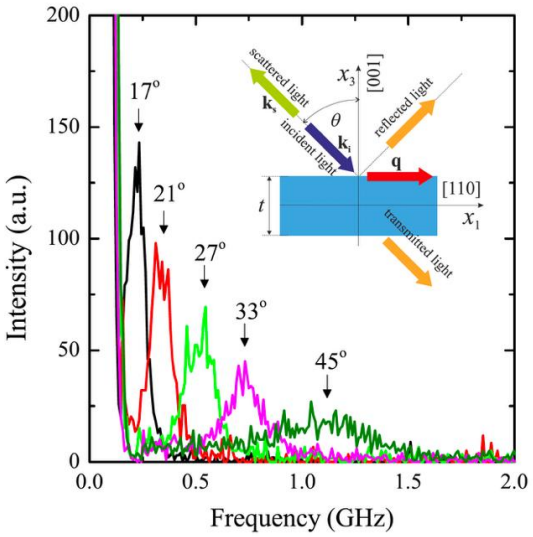

Figure 2 Brillouin Spectra of the 9 nm Thick Si Membrane: Anti-Stokes components of the A_0 mode obtained for different light scattering angles q. Inset: t stands for the membrane thickness, k_i, k_s and q denote incident, scattered and scattering wavevectors respectively[7].

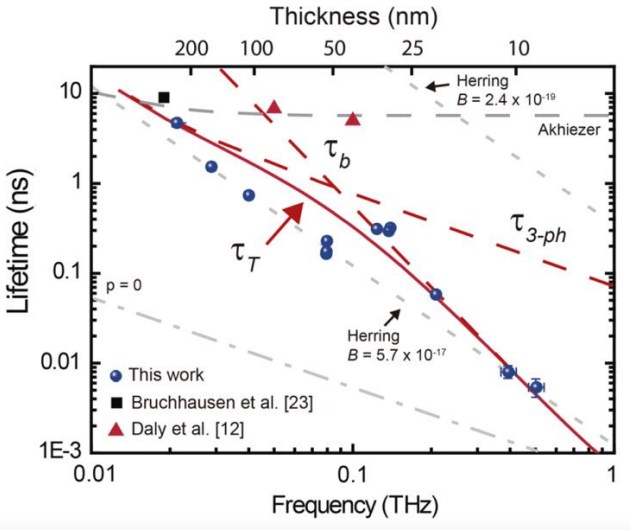

Figure 3 Lifetime of the first dilatational mode as a function of frequency (or membrane thickness). Values of lifetime below about 50 nm are better described by intrinsic phonon scattering, while above the main mechanism is ascribed to boundary scattering. The lifetimes of this mode decrease by over three orders of magnitude with decreasing thickness[8].

Thermal conductivity in the micro-nanoscale. A series of advances in methods to measure thermal conductivity in electronics-relevant nanostructures has taken place as the standard industry-accepted methods were found to be limited in reliability and the exploration of the wealth of interactions when reducing the lateral size of the materials[10]. Among the outcomes we contributed with combined Laser Raman thermometry[11] and non-equilibrium molecular dynamics we demonstrated the decrease of the thermal conductivity by two orders of magnitude with thickness from about 1 μm to 6 nm. From a methodology perspective we demonstrated the importance of measuring in vacuum to avoid the impact of surface reconstruction and convection losses which could overestimate the thermal conductivity in sub 50 nm membranes up to a factor of two[12]. Earlier theoretical[13] and experimental[14] work by the groups of Maasilta and Nomura, respectively, in silicon membranes patterned into phononic crystals, had already suggested that heat guiding could be mediated by suitably patterning of the materials. It was already known that surface-to-volume ratio impacted the values of the measured thermal conductivity[15] due to the commensurability of the acoustic phonon de Broglie wavelength acoustic phonon with patterned feature sizes and their variations due to fabrication variations. We contributed to these efforts noticing that thermal management in proposed heterogenous 3D integrated devices could include MoS_2, or other 2-dimensional materials, in the thermal management strategy[16]. Surface-to-volume ratio issues are minimal in 2-dimensional materials and we turned our attention to heat propagation and guiding in MoS_2 phononic crystals (see Figure 4). We demonstrated that heat can be confined by phononic crystals over an area of the order of 15 μm^2,

which was the area delimited by the phononic crystal as shown in Figure 5. We note that the upper and lower limits of the area the heat is confined in and the power and time the heat can be localised have not been explored. In the experiment the temperature differential was 200 degrees and the upper limits were neither explored. We also showed that heat guiding was possible at least over lengths of 15 to 20 μm by engineering the shape of phononic crystal area[17]. Much remains to be done in terms of design and testing, including the insertion of deterministic defects to ascertain their role in heat flow. Among the obvious challenges are: the roughness and amorphisation at the edges of the features, defects introduced by fabrication, such as metal ions if using FIB, or "doping" the surface by several molecules and ions when using physical etching, and strain control, among others. Essential though is the fact that if 2D materials were to be integrated in 3D stacks, they will have interfaces top and bottom, deviating from the ideal free-standing patterned layer. This requires sound modelling and extension of already complex theories which, and above all, need to be applicable to real 3D structures, i.e., beyond what is available in the software market.

Methods for across-plane thermal conductivity measurements had already been developed[18] and were deployed to measure heat transport in, for example, MoS_2[19] and PtS_2 [20]. Nevertheless, the role of defects remained to be simulated to a level that could be compared with experiments. Some of the emerging questions in the discussion of phonons at a surface is the concept of surface resonances, based on the quantity denoted the phonon participation ratio[21]. This involves the atoms on the surface in a given eigenmode at low frequencies and considers the components of a given mode relative to the coordinates of a given atom. The calculations go down to about 0.5 GHz and probably will be developed further if experiments could be designed to test this approach. This approach could have tremendous impact in challenges facing basic energy research involving, e.g, battery electrode surfaces in the nano-scale.

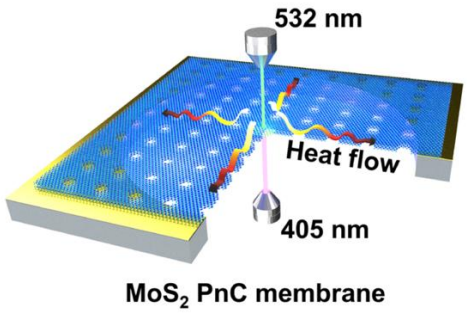

Figure 4 Schematic of the thermal conductivity measurement of a MoS2 phononic crystal membrane by 2-Laser Raman thermometry. The heating laser (405 nm) is focused onto the membrane center and the probe laser (532 nm) is scanned over the membrane central point[16].

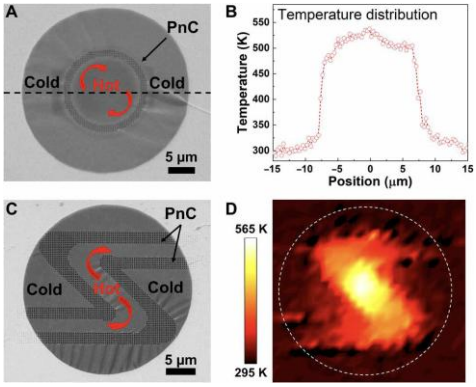

Figure 5 MoS2 thermal insulator and heat conduction channel. (A) SEM image of a freestanding MoS2 membrane patterned with a thermal insulator ring. The dashed line indicates the scan axis. (B) The corresponding temperature profile for the absorbed power P = 28.4 μW focused on the center of the sample. (C) SEM image of a freestanding MoS2 membrane with a Z-shaped heat conduction channel. (D) The corresponding temperature map for an absorbed power P = 8.5 μW focused on the center of the sample. The dashed line indicates the membrane edge[16].

Room temperature optomechanics The phonon-interaction is of interest to us since we use lasers in most of our research. This led us to study the opto-mechanical interaction with research question relevant to the efficiency of conversion of THz photons to GHz phonons and vice versa. As well as the possibility of realizing a phonon source. In order to ensure up-scaling we stayed with Si and room temperature conditions. By the early 2000s nano-optomechanics had gained huge prominence and was heralded to be an advanced mass sensor technology[22] as well as a quantum technology[23]. We contributed to this field with a series of advances. Among them, we demonstrated the excitation of acoustic modes in a one-dimensional OM crystal designed to display a full phononic bandgap for acoustic modes at 4 GHz[24]. We documented

the transition from synchronization to chaos in this highly non-linear system[25], self-pulsing-based phonon lasing[26], multimode optomechanics[27] (see Figures 6 and 7) and an electrically-driven optomechanical circuit based on Si operating at room temperature working at 2 GHz[28]. In the latter we could demonstrate that in the optomechanical beam one could estimate the presence of 2.6 coherent phonons at room temperature. When considering upscaling from a sample to a device and beyond, the nature of phonons shows the impact of variations in critical dimensions and how this affects the deviations from calculated band structures and opto-mechanical coupling strength. Our variability study optimising for the coupling coefficient g_0 has shown that there are key parameters that make the coupling more sensitive in particular, and as expected, the shape and dimensions of the "stub tuners" in a herring-bone shaped nanobeam, which give rise to the phononic properties, and the holes in the phononic/photonic high density of modes in the overlapping central area of the nanobeam, are the most critical parameters[29].

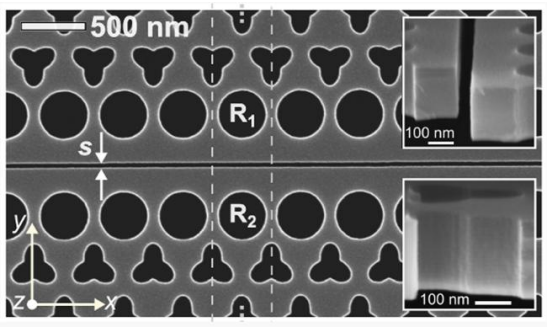

Figure 6 Scanning electron micrograph of an optomechanical crystal waveguide to couple two phononic waveguide modes, one on each side of the air slot, to a slot-guided optical mode. Insets: cross section of the slot (top) and a cleaved clover leaf[27].

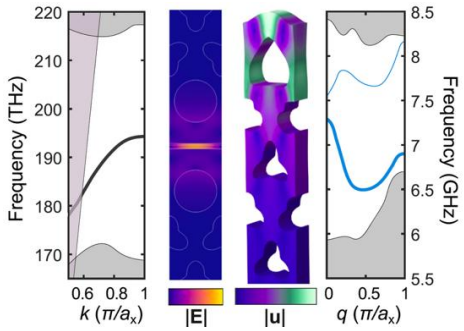

Figure 7 Optical (left) and mechanical (right) dispersion diagrams of the structure in Figure 6. The Bloch modes of interest are represented at $k = \pi/ax$ and $q = 0$.

Phonons as information transmitters in a waveguide Phonons in surfaces and in nanostructures of few nanometres have typical energy of acoustic phonons in, e.g., silicon of a fraction of a meV which, compared to photons of around 1 eV energy and electrons, requiring 1.5 V lines in electronic circuits, perhaps could be used as tokens of information. If phonons have a much lower energy, cf. photons and electrons, could they be used for information transmission for in-chip interconnects?

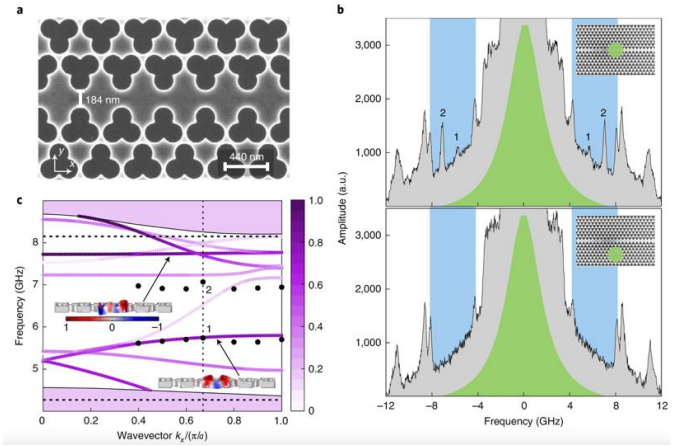

Figure 8 (a) Phononic waveguide SEM image (lattice period 440 nm, waveguide width 184 nm). Thickness and radius of the structure are 220 nm and $r = 0.22a$. (b) Brillouin scattering spectra of the waveguide (top) and surrounding phononic crystal (bottom) as shown in the insets, at an incident light angle of 23.8°. The blue regions denote the band gaps. The frequencies of the two peaks in the gap correspond to the guided modes (top). (c) Calculated waveguide dispersion relation. The intensity colour scale represents the normalized coupling coefficient for the moving-boundary perturbation. The horizontal and vertical dotted lines indicate the mechanical band edges and phononic wavevector, respectively. Black dots represent the frequencies of peaks 1 and 2, all for the top waveguide spectrum shown in (b). Insets: mode profiles for the indicated bands, colour denote the normalized out-of-plane displacement.

The Physics Nobel prize 2016 on topological phases of matter, raised the expectation that backscattering could be suppressed in carefully designed materials and structures, where symmetry considerations are carefully engineered to have the system governed by the invariants of the description in k-space. Could topology help to design phonon waveguides to avoid not only back scattering but effectively "protecting

the in-gap topological non-trivial modes? If these were possible then the prospect of lowering power consumption, by 1/3 at room temperature could be within reach.

The question of demonstrating guided mechanical modes in Si phononic waveguides, topological or not, had to be addressed first. The work of Massilta's[13] and Nomura's[14] group were solid basis for our work, which showed room temperature guiding of two phonon modes in a waveguide in the GHz range by Brillouin scattering[30,31] as shown in Figure 8. This work highlighted the challenge of deviations in critical dimension, in this case, the side-wall angle, which introduced a distinguishable difference between the experimental and simulated guided mode frequencies when constructing the phononic band structure (see Figure 8c).

For the topological waveguides, a design based on the analogy with the quantum valley Hall was selected and realised in Silicon-on-Insulator and in nanocrystalline silicon (nc-Si). The latter was selected since the Q-factors of optomechanical structures made out of it, exhibited a higher value, depending on the annealing temperature at which nc-Si had been grown. The role of the nanocrystallites and grain boundaries are currently under investigation as they may contribute to material losses[32].

Furthermore, the phonon "collective" nature, defined as the description of a wave made out of atoms in the unit cell displaced from equilibrium, makes the phonon different from the electromagnetic quanta, namely, the photon. Thus, several atoms are involved in defining a given mode, which in turn may raise conceptual issues when addressing symmetry and the calculation of invariant vis-à-vis this semi-collective nature. Consequently, the description of phonons as bosons may need refinement. Nevertheless, we have designed interface waveguides formed by two phononic crystals following the sequence of simulating a photonic crystal band structure with C_6 symmetry and identifying a Dirac cone at Brillouin zone *K* and *K'* points, opening a gap by adjusting the masses or feature sizes in the unit cell, in other words, by breaking the C6 symmetry, in order to realise the band inversion and build the topological interface between the two phononic crystals. The edge states appear due to the Chern numbers of both phononic crystals[33], namely ½ and – ½. The edge state appears from the upper and lower band due to the change of the unit cell at the interface. In other words, due to the bulk-edge correspondence[34]. The unit cells are depicted in Figure 9.

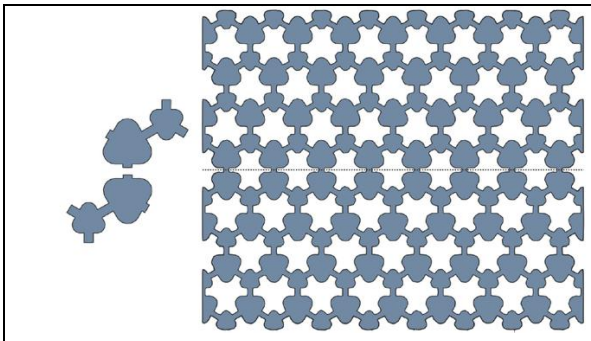

Figure 9 Construction of the Valley Hall topological interface made out of two phononic crystals placed in mirror symmetry. The unit cells are shown on the far left.

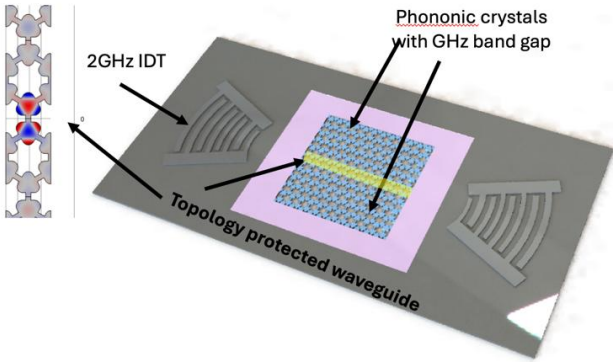

Figure 10 Schematics of experimental set up to detect the surface acoustic wave focused at the entrance of the interface waveguide (yellow area) and at the exit of the waveguide.

Ongoing experiments target the detection of the signal in electrically-driven surface acoustic waves focused at the entrance of an interface phononic waveguide, made up from two phononic crystals with Chern numbers around $\pm$ ½, where the propagation of the phonons, seen as displacement in the normal to the surface is tracked along the phononic waveguide by a laser Doppler vibrometer at 2 GHz at detected at the exit of the waveguide. The results are promising, however, the signal needs to be optimized to ensure that reflections do not become spurious signals. This is work in progress.

One aspect not discussed here, although crucial for much of this work mentioned here, is normal or phonon-phonon scattering, also sometimes called anharmonic scattering, which redistributes the wave front into a number of spatial regions and introduced variations in the density of states. The latter in turn is needed to calculate the thermal conductivity and the time and spatial dependence of dissipation mechanisms. Another simulation objective for the future.

Acknowledgements:

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"Atacama Desert, Valley of the Moon, Chile"

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Phononics 2025

7th International Conference on Phononic Crystals/ Metamaterials, Phonon Transport, and Topological Phononics

June 9-13, 2025 – Seoul, Korea

IPS Bloch Prize

2011:

Sia Nemat-Nasser*

2013:

Bahram Djafari-Rouhani

2015:

Tsung-Tsong Wu

2017:

José Sánchez Dehesa

2019:

Andrew N. Norris

2021:

Ping Sheng

2023:

Pierre A. Deymier

2025:

Clivia M. Sotomayor Torres

* In 2011, the award was called the “Bloch Lecture”

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