Understanding and engineering of phonon propagation in nanodevices by employing energy resolved phonon emission and adsorption spectroscopy

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Abstract: With this PhD project we address *phononics in nanodevices*, a new field with great prospects for applications relating to sound and heat. While there is excellent control over electromagnetic degrees of freedom, the control of phonon transport in nanostructures is in its infancy. We propose a new scheme with which phonon transport in nanowires (NWs) can be studied with high spectroscopic resolution. This is done by embedding quantum dots (QDs) into the NW. Inelastic transport through states in the QDs can be used to both emit and detect phonons. This can be done energy resolved, allowing to characterize the energy-dependent phonon transmission. Once established, a periodic axial material modulation can be realized during NW growth, allowing to tune the phonon bandstructure. A challenging milestone would be the demonstration and engineering of phononic band-gaps.

In the last decades, the power to control photons and electrons paved the way for extraordinary technological developments in electronic and optoelectronic applications. The same degree of control is still lacking for quantized lattice vibrations, *i.e.* phonons. The understanding and ability to manipulate phonons as quantum particles in solids enable to control phonon transport, which is of fundamental interest, on the one hand, but can also be exploited in applications where control of heat flow is desirable, e.g. in thermoelectric conversion.

Unlike electrons, the manipulation of phonons is challenging, since there are no efficient detectors. The reason why we can measure charge directly and with very high efficiency is based on the ability to realize capacitors with very low leakage currents, so that charge can be accumulated to a measureable amount. This ability roots on the property that both excellent conductors *and* insulators exists for charge. For phonons, i.e. heat transport, this is generically different. A piece of solid does always conduct heat. While there is a difference in the magnitude of heat conductance between different materials, this difference does not span many orders of magnitude as it does for the electrical conductivity. However, it is possible to engineer a material by a periodic modulation of, for example, the sound velocity, which can be controlled by the mass of the atoms. This superlattice will modify the phonon band structure in a distinct way, adding band gaps in certain propagation directions. These *phononic band-gaps*, similar to the well known photonic band gaps in so-called photonic crystals,[1] may then provide the insulation required to control heat in matter.[2,3] However, this control requires three things: coherent photons, a distinct modulation in materials properties and an efficient method to emit and detect phonons of appropriate energy. While heat properties of solids and the measurement of phonon band structures with the aid of e.g. neutron diffraction are well established, little is known on the propagation of *coherent phonons in nanostructure*, a target we aim at here.

The manipulation of phonons in nanodevices, while very challenging, holds great promises. It will add propagating phonons to the toolbox of quantum physics. While non-propagating mechanical resonators in the form of strings and beams have been developed starting from AFM cantilevers to MEMS/NEMS-based resonators reaching the quantum regime by optomechanical side-band cooling, there is a large gap in studies of the coherence of propagating phonons in *"phononic conductors"*, where the aim is to control sound and heat at the single quantum level. One notable exception is the measurement of the quantized heat conductance for a one mode wire.[4] The recently growing research field, called "*phononics*", bears great potential also for new technological applications. For example, it has recently been proposed to use phonon transistors to control heat flow.[5] This transistor is based on a negative differential thermal resistance that arises when the source and drain phonon band structures are different. Phonon transistors could also be building blocks of logic gates.[6]

Phonon engineering and manipulation requires new theoretical and experimental methods, especially when combined with low dimensional physics, which is one of the most promising routes for thermal management.[7-11] The most challenging part is the realization of local phonon spectroscopy on the nanometer scale below the scale of an optical confocal microscope. To realize energy resolved phonon spectroscopy and explore the propagation of phonons in low-dimensional matter, we propose to implement double quantum dots (DQDs), two coupled QDs in series, in semiconducting NWs both for the emission and detection of phonons.

Research Plan

Recently, the group of Jason Petta has demonstrated a maser driven by single-electron tunneling events through a DQD realized in a semiconducting NW.[12,13] The DQD supports zero-dimensional electronic states localized in the two QDs and inelastic electron tunneling between the two QDs is driven by an applied finite bias voltage.[12,13] To understand the principle of the DQD, Fig. 1a shows schematically how electrons are transferred in the DQD in a three step sequential process *via* the electronic states of the QDs. An electron is injected from the source contact to the eigenstate at energy E_1 of the first quantum dot QD_1, tunnels then from QD_1 to the eigenstate at energy E_2 of the second quantum dot QD_2, from where it is absorbed in the drain contact. This process requires that both eigenstates are within the so-called bias window eV, i.e. $0 \leq E_1, E_2 \leq eV$. If the states in the QD are resonant, i.e. $E_1 = E_2$, the process is elastic. In the inelastic case, however, the electron tunneling has to be accompanied by the emission of either a photon or phonon or a combination of both. The emission of photons/phonons occurs if $E_1 > E_2$. However, if the two eigenstates are detuned into the opposite direction $E_1 < E_2$, as shown in Fig. 1b, a current can only flow if the energy difference $\Delta E = E_2 - E_1$ is provided by the absorption of photons/phonons. A similar DQD can therefore be used as a versatile energy-resolving detector.

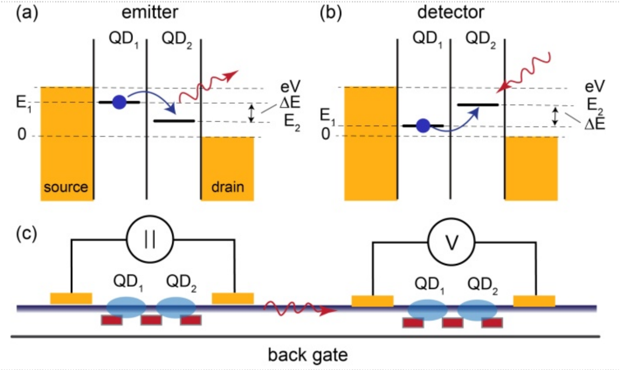

Fig. 1: (a) Schematic illustration of the phonon emission and (b) phonon detection using two coupled quantum dots (QDs) each. (c) Sketch of the envisaged NW device where both a phonon emitter (left) and detector (right) are implemented on a single NW. The back-gate and large electrodes at the contacts (not shown) add a high-frequency short suppressing photon emission.

In the work of Petta *et al.* the DQD is coupled to an electromagnetic microwave resonators (cavity). Due to the coupling to the cavity, monochromatic photons can be generated by inelastic tunneling and collected in the cavity. If ΔE is tuned to the cavity resonance frequency, a strong photon emission is observed that can even lead to maser activity. In case that there is no maser activity, phonon emission greatly dominates over photon emission. This then allows to realize a phonon source that can generate phonons with a well defined spectral distribution. In order to suppress photon emission, the microwave impedance of the device and its environment will be engineered appropriately.

Our plan is to use semiconducting NWs and define two DQDs separated by some distance from each other as illustrated in Fig. 1c. The four QDs will be defined by bottom gate structures, a technology that has recently been developed at the Physics Department of the University of Basel together with international partners from the Niels-Bohr Institute of Copenhagen (J. Nygaard) and the Physics Department of the Budapest University of Technology and Economics (S. Csonka). An example of a device that was fabricated along these lines to demonstrate so-called Cooper-pair splitting from a superconductor[15] is shown in Fig. 2.

For the current project, one of the DQD is used as phonon emitter and the other as phonon detector. Bottom gate-defined QDs allow to tune the confinement potential in the NW enabling to tune ΔE from gigahertz to terahertz frequencies. Applying a source drain bias in the emitter DQD detuned to $\Delta E_s < 0$ will initiate phonon emission. At a fixed distance, the voltage at the detector DQD can now be measured, while these two QDs are set into the phonon detection configuration where we would sweep $\Delta E_d \geq 0$. A design with multiple bottom gates enables not only the tuning of the electronic states of the DQDs, but also the variation in distance between phonon emitter and phonon detector. While bottom-gates have successfully been used in various studies, for examples also in the context of the search for Majorana bound states,[16] there are also some drawbacks. The most important one is that the range with which tunnel couplings can be tuned is limited. In order to achieve a larger confinement of the QDs, it is desirable to grow tunneling barriers directly into the NW. This technology of axial heterostructure in NWs is known. Within the coarse of the project we will also try to use NWs with axial heterostructures. This will not only be done to define tunneling barriers, but also to modulate the phononic bandstructure by engineering a phononic bandgap in between the phonon emitter and detector. A further alternative would be to add a superconductor as a detector for phonons. Phonons with energy larger than the superconducting binding energy can break Cooper-pairs leading to the appearance of quasi particles in the superconductor. These can be measured in tunneling spectroscopy. A further diagnostic tool that is available in this collaboration is the detection of local heat with the aid of noise thermometry.

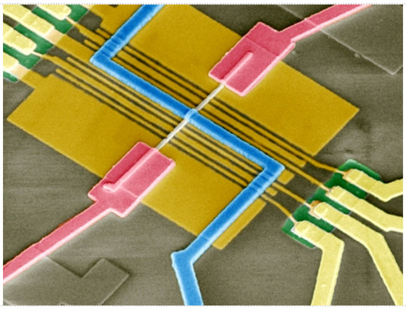

Fig. 2: An InAs NW device with bottom gates (yellow) and three contacts (red & blue) illustrating our capability to fabricate devices of the kind proposed here. The bottom gates are isulated by a thin Si-nitride layer.

We stress that this project has a strong collaborative aspect, where the knowledge and background of both partners is crucial for the success. I. Zardo is an expert in the growth and thermoelectric characterization of semiconducting NWs. Her science program is targeted towards thermoelectrics in nanostructures. On the other hand, C. Schönenberger's background is largely in electron transport, including quantum-dot physics and shot-noise measurements in nanodevices, including semiconducting NWs. The PhD student will therefore work in both labs and a strong collaboration with daily supervision from both sides will be established.

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Synopsis

Ilaria Zardo is assistant professor in the Department of Physics at the University of Basel, where she leads the *Nanophononics* group. She received her PhD in Physics in 2010 from the Technische Universität (TU) München and the Università degli Studi di Roma "Sapienza". She has 7 years' experience in nanowire growth, spectroscopy on single nanostructures, with focus on inelastic light scattering experiments, and investigation of thermoelectric properties of semiconductor nanowires, obtained in the TU München and the TU of Eindhoven.

Interests

Nanophononics: lattice dynamics and phonon transport; spectroscopy and inelastic light scattering; thermoelectrics; Novel material development and characterization.

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Education

2007-2010 PhD in Physics at the Technische Universität München
2000-2007 Physics degree (physics of matter) at Università di Roma "Sapienza"

Career

2015- Assistant Professor for Experimental Physics at the Univ. of Basel
2012-2015 Postdoctoral researcher at the TU Eindhoven, The Netherlands
2010-2011 Postdoctoral researcher at the TU München, Germany

Awards

2015 Medal "Giulio Cesare"
2015 DPG Hertha-Sponer Prize
2010 "Best PhD Defence" award

Impact

▶26 publications in peer-reviewed journals; 2 conf. proceedings; 1 book chapter; 1 patent. ▶H-index 15 with a total of citations larger than 750 with 28 avg. citations/publication (data from ISI Web of Knowledge). ▶15 invited lectures at international conferences and invited seminars or colloquia.
▶ (Co)organizer of two international conferences.

List of Selected Publications

1. S. Yazji, E. A. Hoffman, D. Ercolani, F. Rossella, A. Pitanti, A. Cavalli, S. Roddaro, G. Abstreiter, L. Sorba, and I. Zardo, *"Complete thermoelectric benchmarking of individual InSb nanowires by combined micro-Raman and electric transport analysis"*, **Nano Research** 8, 4048 (2015)
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3. S. Funk, M. Royo, I. Zardo, D. Rudolph, S. Morkötter, B.Mayer, J. Becker, A. Bechtold, S. Matich, M. Döblinger, M. Bichler, G. Koblmüller, J. J. Finley, A. Bertoni, G. Goldoni, and G. Abstreiter, *High Mobility One- and Two-Dimensional Electron Systems in Nanowire-Based Quantum Heterostructures*, **Nano Lett.** 13, 6189 (2013)
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5. I. Zardo, S. Conesa-Boj, F. Peiro, J. R. Morante, J. Arbiol, E. Uccelli, G. Abstreiter and A. Fontcuberta i Morral, *Raman spectroscopy of wurtzite and zinc-blende GaAs nanowires: Polarization dependence, selection rules, and strain effects*, **Phys. Rev. B** 80, 245324 (2009)

Prof. Dr. Christian Schönenberger CV and Track Record

Synopsis Christian Schönenberger is a professor in experimental condensed matter physics at the University of Basel, where he leads the nanoelectronics group. His research interest is *in unravelling fundamental aspects of charge transport in nanodevices* by conducting novel experiments. He is advisor for many public organizations and an elected life-time member of the Swiss Academy of Technical Sciences. He is also the director of the Swiss Nanoscience Institute.

Interests Nano electronics, charge- and spin-transport in low-dimensional systems, molecular electronics, spintronics, nanowire and quantum-dot physics, carbon nanotubes and graphene, shot-noise and charge-fluctuation phenomena, nanodevice based sensors.

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Education	1976-1979	Electrical Engineer of Applied Sciences
	1982-1986	Studies of Physics at the ETH-Zürich
	1986-1990	Ph.D. thesis at the IBM Research Laboratory at Rüschlikon, Switzerland on Magnetic Force Microscopy
Career	1979-1980	Molecular Spectroscopy Group at Physical Chemistry at ETH-Zürich
	1986-1990	IBM Research Rüschlikon
	1990-1992	Postdoctoral Fellow at Philips Research in Eindhoven
	1993-1995	Permanent Research Staff Member at Philips Research
	1995-	Full Chair in Experimental Physics at the Univ. of Basel
	2006-	Director of the Swiss Nanoscience Institute at Basel
Awards	1990	PhD medal ETHZ
	1991	Swiss Physical Society Price
	1994	Profil-II award of the Swiss National Science Foundation
	2010	Life-time member of the Swiss Academy of Technical Sciences
	2011	ERC advanced research grant.

Impact **~ 250 publications**, of which 225 are listed in ISI, **H-index = 52** with 47 citations per publication on average. > 130 invited lectures at international. Supervisor of > 20 PhD theses, (co) organizer of 11 schools, 6 international and 7 national conferences.

List of Selected Publications

1. M. Henny, S. Oberholzer, C. Strunk, T. Heinzel, K. Ensslin, M. Holland, and C. Schönenberger, *The Fermionic Hanbury-Brown and Twiss Experiment*, **Science** 284 (1999) 296.
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8. J. Schindele, A. Baumgartner, and C. Schönenberger, *Near-Unity Cooper Pair Splitting Efficiency,* **Phys. Rev. Lett.** (2012) 109:157002.
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