Publishable Executive Summary

0.1 Executive summary

The NANOPOWER project has completed the third year of activity and has reached the end of the funded period. It was initially conceived in order to address the powering issue in microscale electronic devices and we are glad to communicate that it has been fully developed according the initial plan. The scientific objective of this project was to study energy efficiency with the specific aim of identifying new directions for energy-harvesting technologies. With this aim, three different classes of prospective power generators have been considered in a coordinated effort by the six research groups composing the NANOPOWER consortium. These are:

- nonlinear nanomechanical oscillators
- heat rectification devices
- quantum harvesters.

We are glad to conclude that for each device class we obtained significant results that are now the object of dissemination and exploitation activities. For what concern the intellectual property protection activities, three patents for three new concept devices have been prepared (one already filed regarding new nanoscale temperature sensor for autonomous ICT device integration and two to be finalized on nanoscale electric generators based on purely quantum effects and a novel method for storing tiny quantities of energy at microscales). Moreover new nanoscale prototypes based on vibration energy harvesting, heat rectification and quantum effects have been tested with preliminary very encouraging results. We have designed, realized and tested a novel integrated nanoscale ICT device that is capable of sensing temperature and communication, harvesting energy through the so called Buttiker-Landauer motor mechanism.

During the project we have made significant advances on fundamental science aspects (e.g. in the non linear transport of particle like systems and in the heat-to-electricity conversion in quantum dots) and on the realization of practical tools like the software code for simulation of the dynamics of stochastic nonlinear oscillators (see www.nanopwr.eu) and the large real vibrations data base (www.realvibrations.eu).

The NANOPOWER consortium has been very active also in promoting the field of nano energies with the organization of the interested community around the ZEROPOWER C.A. (Coordinated Action 2011-2013) and the recently started ICT-Energy C.A. (2013-2016).

Finally the NANOPOWER consortium has carried on a vast activity aimed at disseminating the project results through educational and scientific events (three yearly summer school – www.nipslab.org/summerschool, one international conference – www.nanoenergy.eu, participation to science festivals and the institution of the annual MICRO-ENERGY DAY – www.microenergy.eu.
Last but not least the NANOPOWER consortium has funded and maintained NANOENERGY LETTERS, a digital newsletter that has progressively widen its purpose and increased its collaborators to become an independent scientific journal – www. nanoenergyletters.eu.

The NANOPOWER consortium has been very active in the three years of the project devoting over 300 person months to activities organized in 7 Work Packages with 31 different Tasks. This work has generated a vast scientific activity that has involved universities, research centers, stockholders and the general public in more than one way with potential impact that will be evaluated in the years to come. The products of research generated in this project can be summarized in 31 deliverables (reports, software codes and instruments, prototypes) and 6 newsletters, 45 scientific articles on international ISI journals; around 100 talks at international conferences, lectures and seminars; 10 project meetings; 3 Summer School. NANOPOWER partners were involved as organizers in international Conferences and Workshops and in several dissemination activities.

0.2 Project objectives

The ambitious objective of NANOPOWER project was the introduction of a new class of nanoscale devices capable of harvesting energy from the environment and transforming it into electric energy, available for powering the next generation of autonomous Information and Communication Technology (ICT) devices.

The efficient powering of small-scale electronic mobile devices is still an open problem and its solution is a very active and competitive field internationally. We believe that our innovative approach based on a combination of new foundational ideas on nanoscale energy management and device design based on nonlinear stochastic dynamics will soon result in a strong impact for the entire field. The number of applications for which micro-to-nanoscale devices are required is increasing every day and covers fields as diverse as mobile communications, position tracking of goods, persons and animals, health monitoring, building control, defense applications, smart sensing, just to mention a few. On the other hand, although the power requirement of such devices has decreased significantly in the last twenty years up to the point that just few tens of μW are required today to operate a networked wireless sensor, we are still missing a reliable power source that is light, small, disposable and long lasting; all these qualities measured versus the scale of the new generation of micro-to-nano devices.
For such reasons, a new approach based on the exploitation of energy harvested where and when available has attracted considerable attention in recent years[1,2]. Interestingly, most of the studies on energy harvesting techniques focused on macroscopic power generators and very little has been proposed in the micro-to-nano scale range years[3]. One of the reasons for such a lack of results is the difficulty related to the management of the energy issues that is intrinsic once the nanoscale is approached. At the nanoscale, in fact, thermal fluctuations, negligible at higher scale, become the most relevant factor and non-equilibrium thermodynamics approaches are required as opposed to the traditional concepts based on equilibrium energy balances[4]. However, in recent years, assisted by new research tools[5], scientists have begun to study nanoscale interactions in detail. *Non-equilibrium work relations,* mainly in the form of "fluctuation theorems", have shown to provide valuable information on the role of *non-equilibrium* fluctuations. This new branch of the fluctuation theory was formalized in the chaotic hypothesis by Gallavotti and Cohen[6]. Independently, Jarzynski and, then, Crooks derived interesting equalities[7], which hold for both closed and open classical statistical systems: such equalities relate the difference of two equilibrium *free energies* to the expectation of an ad hoc stylised *non-equilibrium work* functionals.

[1] J. A. Paradiso and T. Starner, *Energy Scavenging for Mobile and Wireless Electronics*, IEEE Pervasive Computing 4, 18 (2005).
[2] R. Byrne and D. Diamond, Nature Mater. 5, 421 (2006).
[3] L. Gammaitoni, There is a lot of energy at the bottom, Contemporary Physics 53 (2), 119-135 (2012).
[4] Bustamante, C., Liphardt, J. and Ritort, F., *The nonequilibrium thermodynamics of small systems*, PHYSICS TODAY, 2005, 58, p.43-48.
[5] F. Ritort, *Work fluctuations, transient violations of the second law and free-energy recovery methods: Perspectives in Theory and Experiments*, Poincare Sem. 2 (2003) 193.
[6] Gallavotti G., Cohen E.G.D., *Dynamical ensembles in nonequilibrium statistical mechanics*, Phys Rev Lett, 2694 (1995).
[7] Jarzinsky C., *Nonequilibrium equality for free energy dfferences*. Phys Rev Lett,vol. 2690 (1997).

The NANOPOWER project focused on implications, roles and applications of system fluctuations at the nanoscale and their transformations into electric energy by proper designs and operation principles. The main concept and objectives are engaged with energy harvesting from nonlinear excitations dominant in nanoscale devices. The consortium has chosen three promising and challenging routes of devices exploiting nanofabrication technologies, advanced designs, applied as well as fundamental physical models.
The project focussed on the realization of a number of key devices, which are characterized by following properties:

- They feature nonlinear dynamics
- They exploit noise (non-equilibrium fluctuations) for energy harvesting
- They are nanofabricated with three-dimensionally shaped geometries
- They can be integrated with ICT architectures

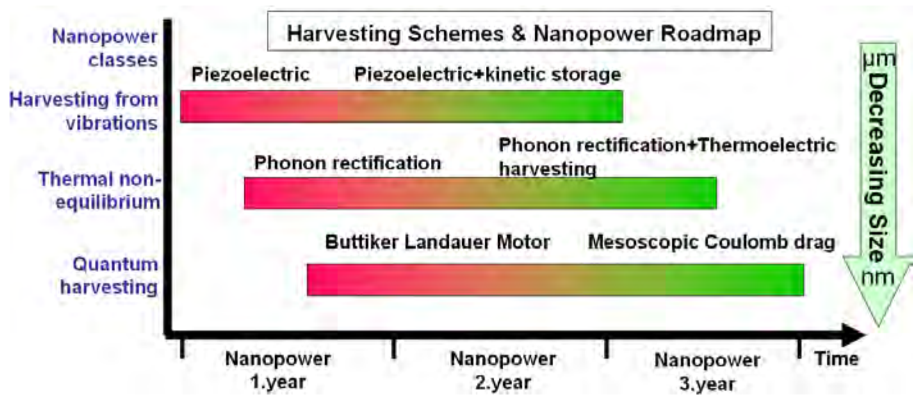


Fig.1: NANOPOWER *devices time-table: Fabrication technologies cover the µm-nm regime. From the very beginning piezoelectric/kinetic storage devices have been fabricated, modelled and analysed.*

The scientific objective of this project was to study energy efficiency with the specific aim of identifying new directions for energy-harvesting technologies at the nanometre and molecular scale. The technological objective of the project was to integrate such technologies into autonomous nanoscale systems to allow new, low-power ICT architectures to find their way into devices. In particular three classes of nanoscale energy harvester have been designed, tested and analysed for their capability to power future ICT electronics:

- Nanomechanical nonlinear vibration oscillators
- Phonon rectifiers
- Quantum harvesters

The three classes of micro-to-nanoscale energy harvesters have been studied in a joint effort, by experts in the fabrication of Si and III-V semiconductor nanodevices, fundamental and applied modelling as well as design and integration of ICT architectures, as sketched in the NANOPOWER *Roadmap* (Fig.1).
The consortium followed three new routes and concepts in piezoelectric *nonlinear vibration*, *guided phonon transport* and *Buttiker-Landauer motors* to be operated in the nonlinear mesoscopic transport regime.

Nanomechanical nonlinear oscillators: Vibration energy harvesting is traditionally achieved by means of inertial generators with the mechanical component attached to an inertial frame that acts as the fixed reference. The inertial frame transmits the vibrations to a suspended inertial mass, producing a relative displacement between them. Such a system possesses a resonant frequency that can be designed to match the characteristic frequency of the application environment.

This approach magnifies the environmental vibration amplitude by the quality factor of the resonant system. Thus most of the present working solutions for vibration-to-electricity conversion are based on linear, i.e. resonant, mechanical oscillators that convert kinetic energy via capacitive, inductive or piezoelectric methods by tuning their resonant frequency in the spectral region where most of the energy is available.

However, in the vast majority of cases the ambient vibrations have their energy distributed over a wide frequency spectrum, with significant predominance of low frequency components and frequency tuning is not always possible due to geometrical/dynamical constraints.

Here we focussed on a novel structure that realizes a non-linear bistable piezoelectric energy harvester. The principle is based on driving an oscillating membrane into a number of different stable states. Recently[8] such bistable/multistable nonlinear oscillators have been demonstrated to have noise-activated switching with an increased energy conversion efficiency. In order to reach multi-stable operation condition, clamped membrane have been realized under a small compressive strain. The membrane vibrates between the two potential minima and has also intra-minima modes. The kinetic energy of the nonlinear vibration is converted into electric energy by either AlN or PZT membrane sandwiched between the electrodes. The voltage is then rectified by a nanodiode integrated to the SOI film.

Phonon rectifiers: Another promising route for NANOPOWER devices are *phonon rectifiers*. We worked on two classes of devices. The first class of phonon rectifier devices, which we fabricated within the NANOPOWER consortium, is related to the discreteness of phonon modes in cavities. By playing on the mismatch between the energy levels between a small cavity and a bigger one enabling the continuum to be reached, one could find that the transmission are not equal from left to right and *vice versa*. The ICN group is a pioneer in the study of confined phonons in cavities as shown by the two references.[9,10] The second class is based on the concept of phononic crystals, which are suitable to help in the design of component to control phonon transmission and storage. Sound refraction control, slow modes and localisation have been also foreseen. A simple device envisioned is a membrane perforated with an array of anisotropic shapes. Phonon rectification occurs as the heat flow between the cavities becomes imbalanced due to non-matching phonon energy levels in it.

Quantum harvesters: In NANOPOWER we addressed a new class of energy harvesting devices based on mesoscopic systems, where quantum effects play a relevant role.

A significant **example** of this new device class is based on a working principle proposed by Buttiker[11] (now leading the UNIGE partner in this project) already in 1987, dealing

[8] L. Gammaitoni, I. Neri, H. Vocca, *Nonlinear oscillators for vibration energy harvesting*, Appl. Phys. Lett., 94, 164102, 2009.
[9] C.M. Sotomayor Torres et al, Physica status solidi (c) 1 (11) 2609-2612 (2004).
[10] J. Groenen et al, Phys Rev B, 77, 045420 (2008).
[11] M. Büttiker, Transport as a Consequence of State-Dependent Diffusion, Z. Phys. B 68, 161 (1987).

with a Brownian particle moving in a sinusoidal potential and subject to non-equilibrium noise and a periodic potential with a spatial modulation showing an equal period but with a non null phase. The motion of an underdamped classical particle subject to such a periodic environmental temperature modulation was investigated by Blanter and Buttiker in 1998[12].

In a recent work[13] this new Brownian engine is addressed as a Buttiker-Landauer motor. The grating is shaped in such a way that it provides both the spatial variation for electron motion as well as a means to absorb radiation of much longer wavelength than the period of the grating. The experiment worked with large areas as well as with high power radiation. Within the project, optimization of the geometry like variations of the barrier distance and the trench width have been a major research topic. In order to mark a clear advance with respect to the state-of-the-art, our project designed, realized and tested an integrated system where energy generation is linked directly to an ICT oriented device.

In the following table we present a summarized view of the scientific and technological objectives of the project.

- To develop a model of energy management at the nanoscale that incorporates the intrinsic non-equilibrium character of random fluctuations and the description of the rectification process with reference to thermoelectric properties.
- To investigate the problem of a local kinetic energy storage.
- To design, build and test new-concept nanodevices:
    - **nonlinear vibration harvester**
    - **phonon rectifier**
    - **quantum harvesters**
- To introduce the class of “quantum harvesters”: mesoscopic structures that can be integrated on chips .
- To realize an autonomous ICT device that integrates the three functions of the power generator (the energy conversion, the voltage rectification, the storage) into a single device aimed at powering a real ICT system.

[12] Ya. M. Blanter and M. Büttiker, Rectification of Fluctuations in an Underdamped Ratchet, Phys. Rev. Lett. 81, 4040 (1998).

[13] R. Benjamin and R. Kawai, Inertial effects in the Buttiker-Landauer motor and refrigerator at the overdamped limit, Phys. Rev. E 77, 051132 (2008).

0.3 Project main scientific and technological results

The scientific and technological results obtained during the project life time are described in details in the 31 deliverable that have been produced. Major progress was made in all tasks according to our work plan. However, the following achievements should be highlighted for their novelty and potential impact of the future of the field.
Here we summarize the main results by dividing them into three distinct categories:

- novel theoretical results
- novel tools
- novel conceptual devices

Each category presents a number of results that are listed within a common topic:

Novel theoretical results:

- Noise driven nonlinear transport phenomena
- Quantum harvesters based on mesoscopic Coulomb drag
- Heat rectification

Novel tools:

- Vibration sources digital library
- Numerical code for digital simulation

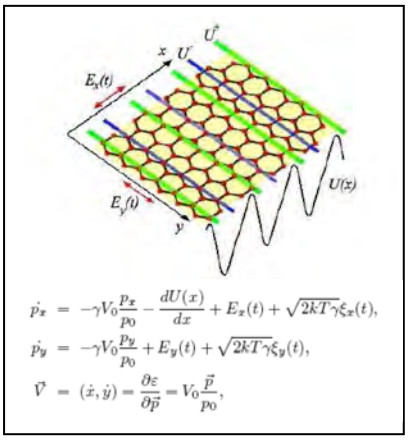
Novel conceptual devices:

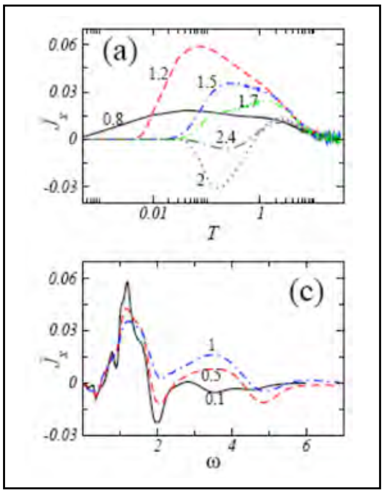
- Vibration harvesting based on nanomechanical nonlinear oscillators
- Kinetic energy storage at nanoscale
- Energy harvesting based on heat rectification
- Energy harvesting based on quantum effects
- ICT Integration

Novel theoretical results

- **<u>Noise driven nonlinear transport phenomena.</u>**
The theoretical description of charge and heat transport in nonlinear systems has been pursued under the coordination of UNICAM. More specifically, the aim this task is the description of transport coefficients for the engineering of new materials with the purpose of maximizing the resulting thermoelectric efficiency.
During the project a vast amount of work has been developed in this framework. The most relevant results have been published in high-impact factor journal. Among these results we list:

- Relativistic Brownian motion of graphene carriers and design of new graphene chips aimed at noise rectification.
Relativistc Brownian motion can be inexpensively demonstrated on a graphene chip [Pototsky A.;Marchesoni F., Kusmartsev F.V.; Hanggi P.; S.E. Savel'ev; *Relativistic Brownian motion on a graphene chip,* Eur. Phys. J. B (2012) **85**, 356; Pototsky A.; Marchesoni F.; *Periodically driven Brownian motion with dry friction and ultrarelativistic Langevin equations*, Phys. Rev. E (2013) **87**, 032132]. The interplay of stochastic and relativistic dynamics, governing the transport of charge carrier in graphene, induces noise-controlled effects such as (i) a stochastic effective mass, detectable as a suppression of the particle mobility with increasing the temperature; (ii) transverse harmonic mixing, whereby electron transport can be controlled by two orthogonal, commensurate ac drives; (iii) a transverse ratchet effect, measurable as a net current orthogonal to an ac drive on an asymmetric substrate, and (iv) chaotic stochastic resonance. Such properties can be of practical applications in the emerging graphene technology.



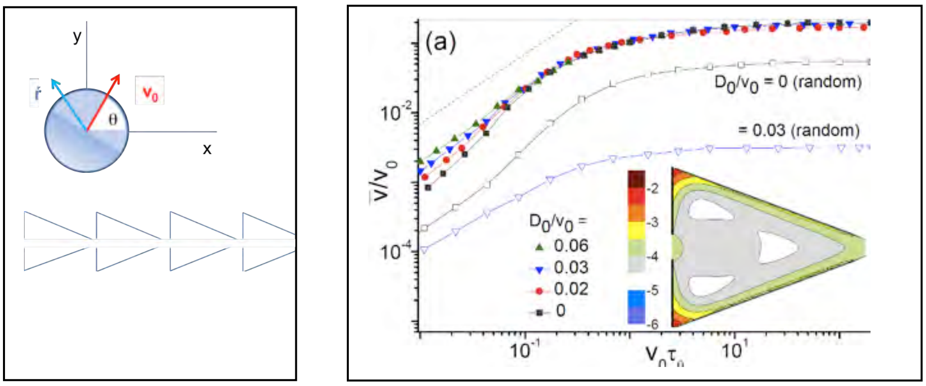


*Example of rectification current on an asymmetric graphene chip at temperature T, perpendicular to an ac drive with frequency ω (from A. Pototskii et al, Eur. Phys. J. B**85** (2012) 356).*

- Rectification of magnetic Brownian particles (magnetic ratchets).
The term ratchet refers to nonequilibrium phenomena that occur when one of the space-time symmetries which inhibit directed motion is broken. In this case, the symmetry breaking is realized by a nonvanishing mean torque, induced by a magnetic field, together with a spatially (not necessarily asymmetric) periodic channel geometry. The

torque leads to a circular motion and thus to an alteration of the random dynamics of the diffusive particles. Most remarkably, rectification was shown to take place only in the presence of time correlated (colored) noise (Marchesoni F.; S.E. Savel'ev, (2013) *submitted for publication*).

- *Enhanced rectification of Brownian diffusion in narrow asymmetric channels.*
Brownian transport of self-propelled overdamped microswimmers (like Janus particles) in a two-dimensional periodically compartmentalized channel was numerically investigated for different compartment geometries, boundary collisional dynamics, and particle rotational diffusion [Ghosh P.K.; Misko V.R; Marchesoni F.; Nori F.; *Janus particles in a ratchet: Numerical simulations*. Phys. Rev. Lett. (2013) **110**, 268301]. The resulting time-correlated active Brownian motion was proven to be subject to rectification in the presence of spatial asymmetry. Most remarkably, it was shown that ratcheting of Janus particles can be orders of magnitude stronger than for ordinary thermal potential ratchets and thus experimentally accessible. In particular, autonomous pumping of a large mixture of passive particles can be induced by just adding a small fraction of Janus particles.

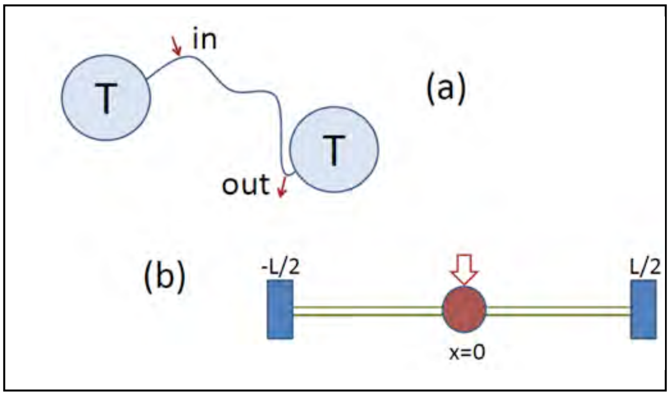


Rectification of a Janus particle with self-propulsion velocity v_0 and rotational diffusion time τ_θ confined in a 'triangular' channel. As the persistency length $l_\theta = v_0\tau_\theta$ grows larger than the size of the triangular unit cell, the rectification power of the device approaches the maximum conceivable value 0.5 (from P.K. Ghosh et al, Phys. Rev. Lett. ***110*** *(2013) 268301).*

- *Suppression of Brownian rectification by inertia.*
In view of the extension of the ratchet paradigm to charge carriers and phonons in solids we numerically investigated transport of suspended Brownian particles dc driven along corrugated narrow channel in the regime of finite damping [Ghosh P.K.; Hanggi P.; Marchesoni F.; Nori F.; Schmid G.; *Brownian transport in corrugated channels with inertia*, Phys. Rev. E (2012) **86**, 021112]. We showed that inertial corrections cannot be neglected as long as the width of the channel bottlenecks is smaller than an appropriate particle diffusion length, which depends on the channel corrugation and the drive intensity. With such a diffusion length being inversely proportional to the damping constant, transport through sufficiently narrow obstructions turns out to be always sensitive to the viscosity of the suspension fluid. The inertia corrections to the transport quantifiers, mobility, and diffusivity markedly differ for smoothly and sharply corrugated channels.

- *Drifts with zero currents*

The longstanding problem of Brownian transport in a heterogeneous quasi one-dimensional medium with space-dependent self-diffusion coefficient is addressed in the overdamped (zero mass) limit [Marchesoni F.; *Drifts in diffusion gradients*, Materials (2013) **6**, 3598]. A phenomenological mesoscopic description was obtained in the Langevin equation formalism by introducing an appropriate drift term, which depends on the system macroscopic observables, namely the diffuser concentration and current. The drift term is related to the microscopic properties of the medium. The paradoxical existence of a finite drift at zero current suggests the possibility of designing a Maxwell demon operating between two equilibrium reservoirs at the same temperature connected by a 1D filament, (a), with graded transport diffusion coefficient D(x) such that D'(x)>0.



Contrary to the ratchet prescriptions, in the thought experiment sketched in figure, a net cargo (information) flow from the loading to the right hand side delivery station, (b), was established by taking advantage of Brownian diffusion in thermal equilibrium.

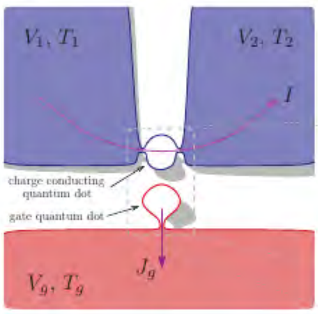
- *Transport through arrays of symmetric obstacles.*

We numerically investigated the transport of an overdamped Brownian diffuser which is driven through a two-dimensional rectangular array of circular obstacles with finite radius [Ghosh P.K.; Hanggi P.; Marchesoni F.; Martens S.; Nori F.; Schimansky-Geier L.; Schmid G.; *Driven Brownian transport through arrays of symmetric obstacles,* Phys. Rev. E (2012) **85**, 011101]. Two limiting cases were considered in detail, namely, when the constant drive was parallel to the principal or the diagonal array axes. This corresponds to studying the Brownian transport in periodic channels with reflecting walls of different topologies. The mobility and diffusivity of the transported particles in such channels were determined as functions of the drive and the array geometric parameters. Prominent transport features, revealed by numerical simulation, like negative differential mobility, excess diffusion peaks, and unconventional asymptotic behaviors, were explained in terms of two distinct lengths, the size of single obstacles (trapping length), and the lattice constant of the array (local correlation length). Local correlation effects were further analyzed by continuously rotating the drive between the two limiting orientations. The extension of this study to phonon transport in 2D arrays is presently under way.

- **<u>Quantum harvesters based on mesoscopic Coulomb drag.</u>**
The theoretical description of quantum harvesters based on mesoscopic Coulomb drag has been pursued under the coordination of UNIGE. Main aim of this task was to investigate different heat engines based on quantum dots with the purpose of identifying setups that are both powerful and highly efficient at the same time.

In the course of the project a number of theoretical proposals for quantum-dot based energy harvesters has been developed. The results have been published in high-impact factor journals. In the following, we list the main results:

- *Optimal heat-to-current conversion in a Coulomb-coupled double quantum dot.*
Two quantum dots in the Coulomb-blockade regime where each dot hosts either 0 or 1 excess electron are considered. The two quantum dots are Coulomb-coupled to each other. This means they can exchange energy but no particles. The so called conductor dot is coupled to two cold electronic reservoirs while the so called gate dot is connected to a single hot electronic reservoir. Thermal fluctuations of the occupation of the gate dot are translated into charge fluctuations of the conductor dot. Due to an intrinsic nonlinearity of the system (energy-dependent tunneling rates) these fluctuations get rectified and drive a directed charge current through the conductor dot.
For specially designed asymmetries of the tunnel couplings, the device can act as an ideal heat to charge current converter that transfer one quantum of charge i.e. one electron from the left to the right for each quantum dot of heat, i.e. the charging energy transferred from the hot to the cold. As a result of this tight coupling of heat and charge currents the device reaches Carnot efficiency at the stopping voltage. Furthermore, at maximal power it reaches half the Carnot efficiency.
R. Sánchez and M. Büttiker, Phys. Rev. B **83**, 085428 (2011).

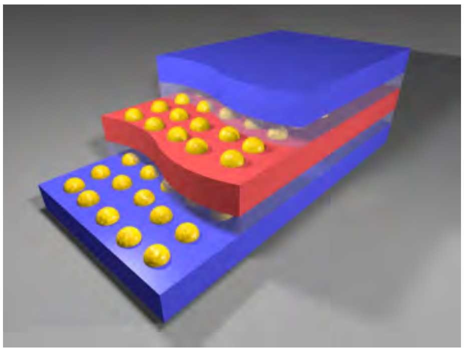


Schematic of the quantum-dot heat engine. Two quantum dots are capacitively coupled. The conductor dot is connected to two cold reservoirs while the gate dot is linked to a single hot reservoir.

- *Rectification of thermal fluctuations in a chaotic cavity heat engine.*
While a quantum harvester based on quantum dots in the Coulomb-blockade regime turns out to be highly efficient, it produces only small currents and output powers as transport occurs via the tunneling of single electrons.
In order to find heat engines that produce larger power, we considered a setup of two capacitively coupled chaotic cavities. Each cavities is connected to electronic reservoirs via quantum point contacts with a large number of open transport channels. The main aim was to find the dependence on current and output number of the channel number N.

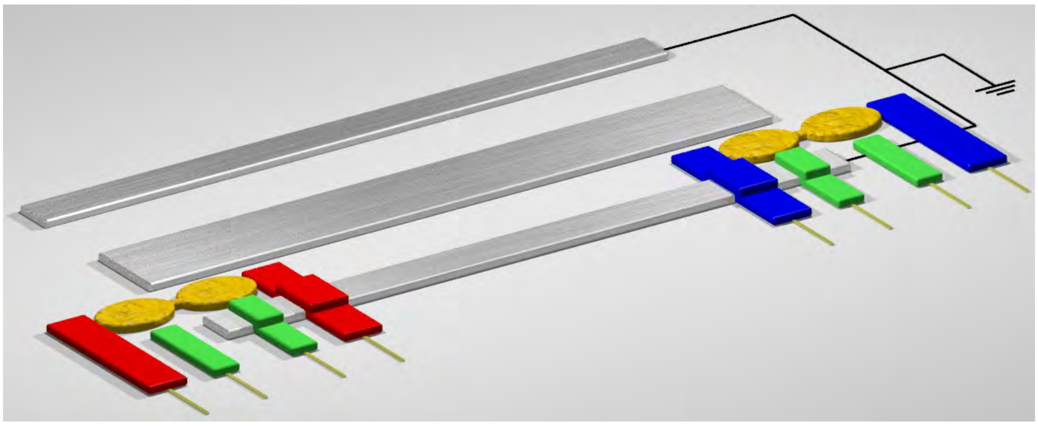
Using a semi-classical description based on a kinetic equation for the cavity distributions, we found that the current is independent of the channel number. For realistic parameters, it is of the order of 0.1 nA and therefore two orders of magnitude larger than what can be achieved in the Coulomb-blockade regime. The output power, on the other hand, decreases as 1/N while the efficiency even drops as 1/N^2. Hence, for a few open transport channels, the resulting output power is about as large as what can be achieved in the Coulomb-blockade regime. The reason for the low powers lies in the fact that only the single partially open channel is responsible for the thermoelectric response of the heat engine while all the other fully open channels only provide a background current that detrimental to the device performance.
B. Sothmann, R. Sánchez, A. N. Jordan and M. Büttiker, Phys. Rev. B **85**, 205301 (2012).

- *Powerful and efficient energy harvester with resonant-tunneling quantum dots.*
Based on the results obtained for quantum harvesters based on either Coulomb-blockade quantum dots or open cavities, one can conclude that the optimal performance for a mesoscopic heat engine occurs for transport through a single-channel conductor. A paradigmatic realization of such a single-channel conductor is given by resonant tunneling through a quantum dot.
We considered a central hot cavity connected via resonant-tunneling quantum dots to cold electronic reservoirs. Using scattering theory we could derive analytical results for the current and power produced by the device in the limit of small level width. We furthermore performed a numerical analysis in the whole parameter space to obtain the optimal device parameters. For such an optimal configuration, we find the device to deliver a power of 0.1 pW for a temperature bias of 1 K which outperforms heat engines based on Coulomb-blockaded dots and chaotic cavities by two orders of magnitude. In order to obtain a macroscopic output power, we devised a highly parallelized setup based on self-assembled quantum dots. For realistic parameters we estimated an output power of 10 W/cm^2 for a temperature difference of 10 K between the hot and cold reservoirs. At the same time it yields an efficiency at maximum power of about 20% of the Carnot efficiency. This reduction in efficiency compared to the Coulomb-blockade case is of course more than compensated by the gain in output power. We furthermore analyzed the robustness with respect to fluctuations in the dot properties and found that even a moderate scattering in level positions by 10% only reduces the output power to about 90% of its optimal value.
A. N. Jordan, B. Sothmann, R. Sánchez and M. Büttiker, Phys. Rev. B **87**, 075312 (2013).



Heat engine based on resonant tunneling through self-assembled quantum dots.

- *Powerful energy harvester based on resonant-tunneling quantum wells.*
An alternative realization of transport through a single-channel is given by resonant tunneling through a quantum well. As quantum wells offer a larger phase space for tuunneling electrons they are expected to yield larger currents. On the other hand, they are much less efficient energy filters which reduces their thermoelectric performance. Furthermore, quantum wells are easier to fabricate and less prone to fluctuations in the fabrication process. Finally, due to their large level spacings of several 100 meV they are ideally suited for room-temperature applications.
We considered a hot central cavity connected to cold electronic reservoirs via resonant quantum wells similar to the quantum-dot heat engine described above. We found the device to yield an output power of 18 W/cm^2 for a temperature difference of 10 K, therefore nearly doubling the output power of the quantum-dot heat engine. At the same time, we find that the efficiency is reduced by a factor of two to 12% of the Carnot efficiency. In order to ultimately decide which structure is most favourable for practical applications future work on scattering of phonons at the quantum dots/wells would be desirable.
B. Sothmann, R. Sánchez, A. N. Jordan and M. Büttiker, New J. Phys. in press.



Hybrid microwave cavity heat engine

- *Magnon-driven quantum-dot heat engine*
Recently, a number of phonon-driven heat engines has been discussed in the literature. However, coupling phonons in a controlled way to a quantum dot is a notoriously difficult task as it is hard to avoid leakage heat currents from the phonon source into the cold electronic reservoirs. To this end, it is interesting to address the question whether magnons can be used to drive a quantum-dot heat engine. Magnons offer the advantage of being confined to magnetic materials and interacting only via short-range exchange interactions, thereby reducing leakage heat currents. Furthermore, a magnon heat engine is interesting as it provides a bridge between the fields of energy harvesting and spin caloritronics that deals with how to drive and manipulate spin currents by heat.
We considered a single-level quantum dot connected to two ferromagnetic metals and a single ferromagnetic insulator. The latter serves as a hot reservoir of spin waves or magnons. The coupling between the dot and the magnons induces fluctuations of the dot occupation that get rectified due to the spin-dependent couplings to the ferromagnetic metals. Depending on the magnetic configuration, the system either produces a pure spin

current or a spin-polarized charge current. Due to the tight coupling between charge and heat currents that occurs in the setup, Carnot efficiency is reached at the stopping voltage. The efficiency at maximum power is given by half the Carnot efficiency in the linear response regime in agreement with general thermodynamic bounds while it can overcome this limitation in the nonlinear regime.
B. Sothmann and M. Büttiker, EPL **99**, 27001 (2012).

- *Powerful and efficient energy harvester with resonant-tunneling quantum dots.*
Recently, there has been a growing interest in connecting mesoscopic conductors such as double quantum dots to superconducting microwave cavities in order to study, e.g. nonlocal transport properties mediated by microwave photons. We proposed a setup that connects this field of circuit QED with energy harvesting. Our heat engine consists of two double quantum dots connected to a microwave cavity. While one double dot is connected to hot electronic reservoirs, the other one is connected to cold ones. The hot double dot will emit photons into the cavity that are subsequently absorbed on the cold side where an asymmetry in the double dot serves to rectify the induced charge fluctuations and drive a directed charge current.
We analyzed the thermoelectric performance of the device and found that optimal heat to current conversion can take place, leading to a Carnot-efficiency system. We furthermore estimated the heat-driven current taking into account realistic values for both dephasing and relaxation in the double quantum dot which normally turn out to be a major issue in current experiments. We find that even in the presence of these processes a current of about 1 pA can be generated, measurable with current technology.
C. Bergenfeldt, P. Samuelsson, B. Sothmann, C. Flindt and M. Büttiker, arXiv:1307.4833 (2013), submitted to Phys. Rev. Lett.

· **Heat rectification.**
The study of the thermal properties in nanometer sized plates for the prospect of a control of the directionality of the heat transport has been pursued under the coordination of ICN. The derivation of models of the thermal conductivity for two-dimensional systems has been developed within the project, which introduces the modified dispersion relation caused by the spatial confinement and effects of boundary scattering. This work required in turn the application of models to calculate the dispersion relations, heat capacity, and phonon lifetimes. The directional propagation of acoustic waves by breaking the spatial inversion symmetry in dedicated phononic systems was also addressed.

- *Phonons in Slow Motion: Dispersion Relations in Ultrathin Si Membranes.*
Numerical dispersion relations were calculated with an anisotropic continuum model and compared to the experimental data. It allowed for the understanding of the in-plane propagation of confined acoustic modes in Si membranes. *See J. Cuffe, E. Chavez, A. Shchepetov, P.-O. Chapuis, E. H. El Boudouti, F. Alsina, D. Dudek, J. Gomis-Bresco, Y. Pennec, B. Djafari-Rouhani, M. Prunnila, J. Ahopelto, C. M. Sotomayor Torres. Nano Letters,* ***12*** *(7), 3569–3573 (2012).*

- *Calculation of the specific heat in ultra-thin free-standing silicon membranes.*
The specific heat was calculated taking into account the dispersion relations of the discrete set of acoustic modes in the system. Numerical calculations show that the temperature dependence of the specific heat in the low-temperature regime departs from a T^3 to a T dependence in nanoscale Si membranes. The change in behaviour is related to the large contribution from the fundamental flexural wave, which presents a quadratic

dispersion relation for small values of the in-plane wave-vector. The specific heat of membranes is found to be larger than the bulk one in the low temperature regime. *See E. Chávez, J.Cuffe, F. Alzina, and C. M. Sotomayor Torres. Journal of Physics: Conference Series **395**, 012105 (2012).*

- *Lifetimes of Confined Acoustic Phonons in Ultrathin Silicon Membranes.*
  Calculations of the relaxation times in ultrathin Si membranes taking into account the phonon-phonon interactions and the scattering at the surface boundaries including a wavelength-dependent specularity. The former processes were calculated explicitly with a theory based upon three-phonon normal interactions. It was found that the combination of these models described the trend in phonon lifetimes over several orders of magnitude, changing from being dominated by intrinsic effect for thicker membrane, to being limited by surface roughness for thinner membranes. *See J. Cuffe, O. Ristow, E. Chávez, A. Shchepetov, P-O. Chapuis, F. Alzina, M. Hettich, M. Prunnila, J. Ahopelto, T. Dekorsy, and C. M. Sotomayor Torres, Phys. Rev. Lett., **110**, 095503 (2013).*

- *Modelling of thermal rectification in Si and Ge thin films.*
  Calculations of the thermal rectification coefficient in Si-Ge films-based systems using the well-known mechanism for thermal rectification based on the different temperature-dependence of the thermal conductivity in a two-component system. The directionality of the in-plane heat flow in a Si plate can be achieved by tuning the thickness and the impurity concentration along the cross section of the plate. *(Proceedings of the ASME 2013 International Mechanical Engineering Congress & Exposition IMECE2013 November 15-21, 2013, San Diego, USA (accepted))*

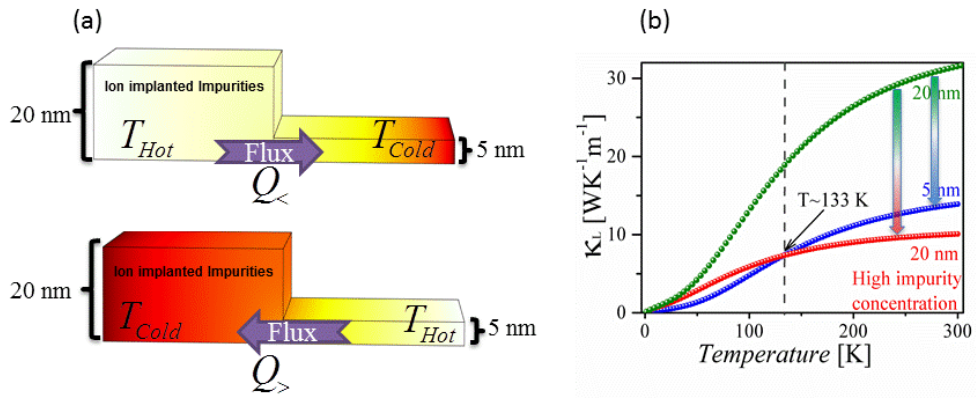
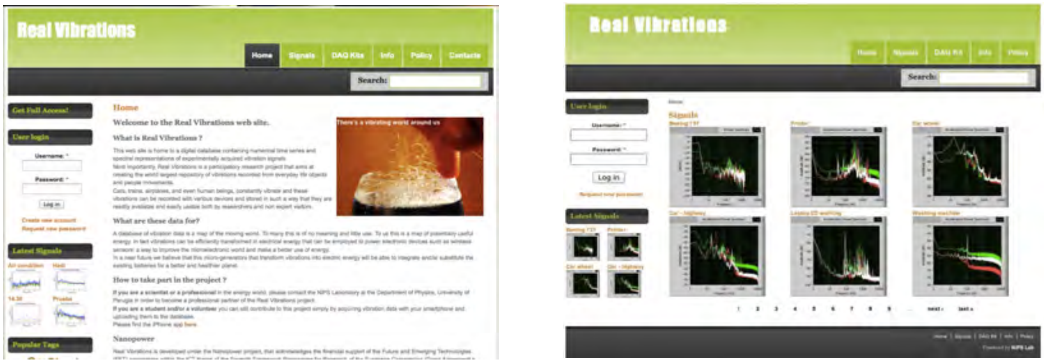


Figure: (a) Scheme of the thermal rectifier based on a modified membrane with varying thickness and impurity concentration. (b) Temperature dependence of the in-plane thermal conductivity of 20 nm (green circles) and 5 nm (blue circles) thick Si membranes. The effect of the presence of impurities in the 20 nm thick membrane is exemplified (red circles).

- *Controllable unidirectional transmission of the Lamb elastic waves propagating in a plate*
  Numerical simulations allowed a proof of principle for controllable unidirectional transmission of elastic waves propagating in the plane of a membrane by an appropriate combination of mode coupling and filtering. The connection with the phonon diode concept was discussed. *(Manuscript in preparation)*

Novel tools

- **<u>Vibration sources digital library.</u>**
  The kinetic energy available for mechanical harvesting comes most often in the form of random vibrations. In order to optimize the design of vibration harvester we realized that a deeper knowledge of the time/frequency characteristics of such vibrations was necessary. For this reason we have set up a large database containing digital time series and spectral representations of experimentally acquired vibration signals. The work started during the first period with a careful planning of the database to be built and proceeded with the acquisition and characterization of a large number of real signals. The outcome of the work is a public database available online at the address *http://realvibrations.nipslab.org*.



Web site (http://realvibrations.nipslab.org) that provides access to the vibration sources digital library. Database web interface: overview of collected signals.

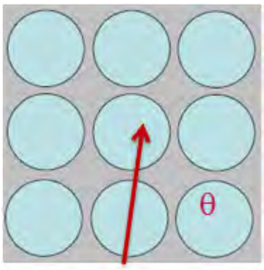
Currently we have 350 registered users and approximately 300 entries on the database.
In order to make the database most useful we have also developed an iPhone application to provide the users with the capability to acquire, store and upload vibration data to the database using their smartphone. The hardware and the software of the iPhone limit the quality and the characteristics of the data. The maximum acquisition rate is limited to 100Hz with a maximum range of ±2g of acceleration. By the way data acquired with this system can be used in preliminary test or investigation. Nevertheless those limitations are overcome by the large diffusion of iPhone devices. Users that upload vibration data contribute to the database grow, such data are marked as contributed and result free available to authenticated users. Following some iPhone App screenshots are presented.

Screen shots from the iPhone application.

- **<u>Numerical code for digital simulation</u>**
  We have developed numerical simulation tools, meaning computer codes, for the numerical solution of nonlinear differential stochastic equations that are necessary for modeling the dynamical behavior of two classes of systems:
  - nonlinear oscillators in the presence of random forces
  - ratchet-like potentials

  \- *Nonlinear oscillators in the presence of random forces*
  For the solution of stochastic differential equations we used the Euler-Maruyama method. The Euler-Maruyama method is a method for the approximate numerical solution of a stochastic differential equation. This code returns the standard deviation of displacement and voltage produced of a piezoelectric oscillator subjected to exponentially correlated noise. The dynamic of the oscillator, the physical properties and the coupling characteristics can be customized modifying the code.
  We have validated the simulation tool comparing the experimental result to the simulation whit good agreement. The commented MATLAB code to solve the nonlinear differential stochastic equations is available for download (in MATLAB format) in the project website.

  \- *Ratchet-like potentials in the presence of random forces*
  We have developed tools in the form of MATLAB code for the numerical simulations of stochastic dynamics in the presence of ratchet-like potentials. According to the needs emerged from the project, we focussed our attention to the numerical solution of the dynamics of Brownian-like particles moving in a 2D space in the presence of reflecting obstacles. Specifically we developed a numerical MATLAB code for the simulation of the motion of overdamped Brownian particle of unit mass diffusing in a 2D array, L_x x L_y of reflecting circular obstacle of radius radius r_0, as illustrated in the following figure.



The particle is subjected to a homogeneous force $\vec{F}$ oriented at an angle θ with the horizontal axis x. This dynamics can be described accordingly by a corresponding Langevin equation (continuous stochastic differential equation) in the presence of Gaussian noise. To check the reliability of the code we solved the corresponding Fokker-Planck equation by means of a finite-element algorithm and obtained a good comparison with the Langevin method. The commented MATLAB code is available for download (in MATLAB format) in the project website.

Novel conceptual devices

- **Vibration harvesting based on nanomechanical nonlinear oscillators.**
Recent studies carried on by the UNIPG group have demonstrated that for wide band random vibration the use of non-linear oscillators, instead of the traditional linear ones, for energy harvesting purposes, presents remarkable advantages (F. Cottone; H. Vocca; L. *Gammaitoni*, Phys. Rev. Lett., 02/2009, Volume 102, Issue 080601, (2009); Luca Gammaitoni Contemporary Physics Vol 53 (2) Pages 119-135).
Based on these studies we have fabricated (VTT) and characterised (UNIPG) nanoscale piezoelectric vibrational membrane harvesters based on free-standing Mo-AlN-Mo film stack. Pure membrane harvesters are suitable for lower frequencies and lower accelerations. The maximum power approaches 1 μW although the volume and mass of the harvesters is very small. To our knowledge this prototype sets the present world record in energy density conversion capability. The harvesters with extra mass, of the order of μgrams, operate at higher frequencies but can deliver several μWs. The harvesters rely on multistable nonlinear behaviour of the membranes, providing response to a broad range of frequencies and, interestingly, transforming or coupling the energy from the exciting frequency to a range of modes in the membrane, and consequently substantially increasing the efficiency of the harvester.

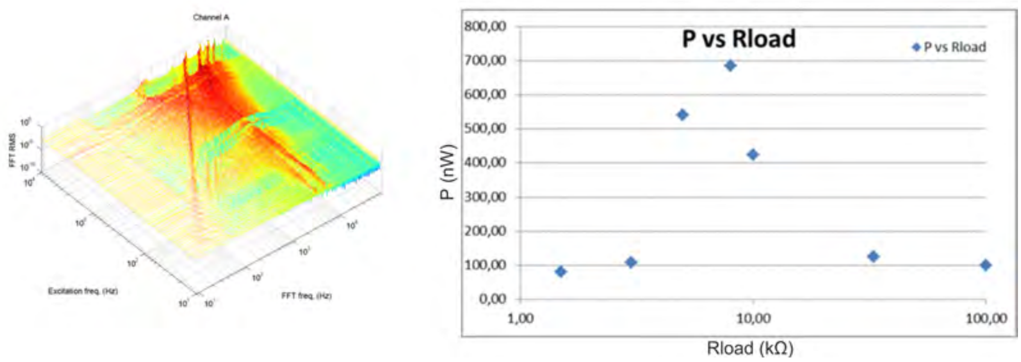
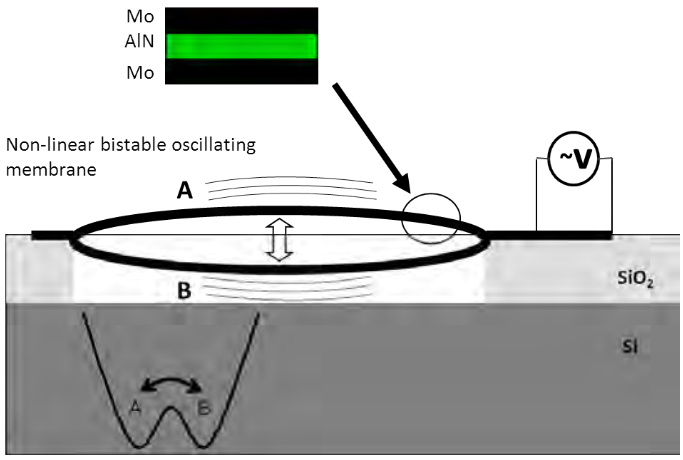
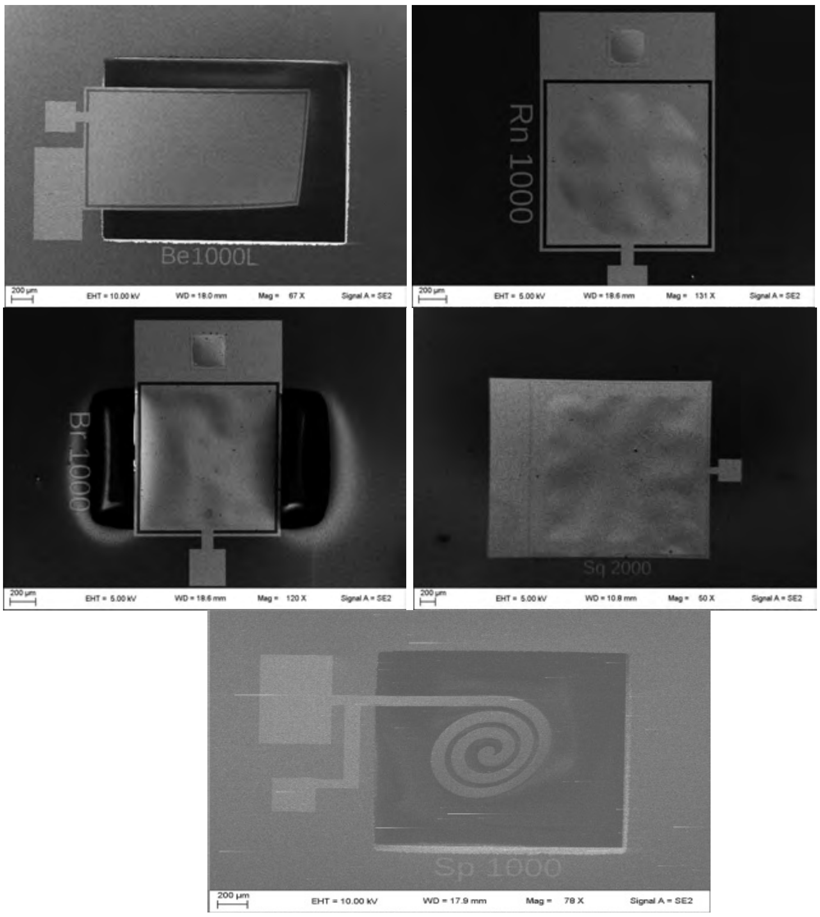


Figure: (Left) 3D map of excitation and response of a membrane with a small mass attached. The frequency range is from 10 Hz to 10 kHz. The excitation is the diagonal ridge and the map shows strong coupling both to higher and lower frequencies. (Right) Power output measured as a function of external load resistor. A maximum output is achieved with an 8 kΩ resistor at excitation frequency of 7 kHz and acceleration of 10 g.

Vibration harvester device design (VTT) is based on the exploitation of multi-stability arising from buckled membranes.



Non-linear energy harvester based on bistable piezoelectric membrane. The non-linearity arises from the remaining compressive stress in the Mo/AlN/Mo stack.



Picture of various piezoelectric nonlinear oscillators made by UNIPG with FE-SEM Leo 1525.

- **Kinetic energy storage at nanoscale.**
  Kinetic energy storage is based on a simple principle: instead of converting kinetic energy from random fluctuation into electric energy and from this to chemical energy for storage, UNIPG proposed to exploit the properties of low losses linear oscillators as kinetic energy temporary storage devices.
  This opens up potential opportunities for applying this concept to micro and nanoscale oscillators with the aim of realizing a nanoscale “dynamic battery”. This activity is currently in the process of patent registration.

- **Energy harvesting based on heat rectification.**
  In the NANOPOWER project we addressed a new class of energy harvesting devices based on heat rectification. ICN proposed two different concepts for devices with functionality of phonon diode with the aim of controlling the directionality of (i) elastic waves and (ii) heat transfer, respectively. The first design is intended as an acoustic waves rectifier based on the breaking of the spatial inversion symmetry. The second design is an extension of the classical thermal rectification approach, which originates in certain cases from the contact of two dissimilar bulk materials with different temperature dependence of the thermal conductivity, to an all silicon structure. The directionality of the in-plane heat flow in an all *Si* plate can be reached when boundary and impurity scattering effects on the thermal conductivity are taken into account. Prototypes, of both elastic waves and heat rectifiers, has been already fabricated (VTT) and measurements are taking place (ICN).

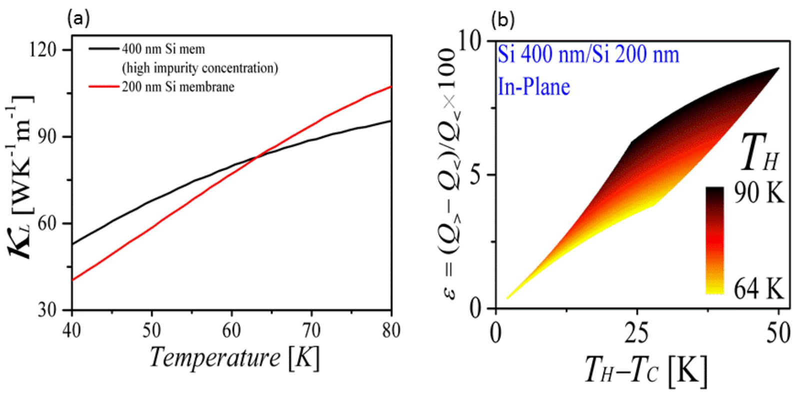


Figure: (a) Temperature dependence of the in-plane thermal conductivity of a highly-doped 400 nm (black curve) and undoped 200 nm (red curve) thick Si membranes. (b) Calculated in-plane thermal rectification factor of the 400-200 nm two-thickness Si membrane.

- **Energy harvesting based on quantum effects.**
  In the NANOPOWER project we addressed a new class of energy harvesting devices based on mesoscopic systems, where quantum effects play a crucial and relevant role. Examples of such device classes are based on theoretical predictions by the UNIGE group headed by M. Büttiker (M. Büttiker, Z. Phys. B **68**, 161 (1987), R. Sanchez, M. Büttiker, Phys. Rev. B **83**, 085428 (2011)). An ambitious effort of the project was engaged with the experimental realization of several novel device concepts.

  - Quantum harvester based on transport as a consequence of state-dependent diffusion:

A quantum harvester based on a phase difference in the distribution of non linearly excited charge carriers and asymmetric potential profile was realized at UNIWUE in collaboration with other partners of the NANOPOWER consortium. It was predicted by the UNIGE group already in 1987 that Brownian particles moving in a sinusoidal potential which are subject to non-equilibrium noise can contribute to a direct, rectified current. For that purpose a grid was etched into a heterostructure with a two dimensional electron gas which allowed an out of phase electron gas heating by radiation absorption. The collaboration between theoretical and experimental experts in the NANOPOWER consortium enabled a successful proof-of-concept of this quantum harvester class, which also discharged into an exploitation of these concepts by a joint patent application between UNIWUE and UNIGE. The collaboration between the groups from UNIWUE and UNIGE realized a prototype of the quantum harvester referred to as Büttiker-Landauer motors (BLms). In periodically etched low dimensional electron systems current generation was achieved with an out-of-phase electron gas heating by radiation absorption. The concept of this device class is based on state-dependent diffusion, which was first proposed by M. Büttiker in 1987.

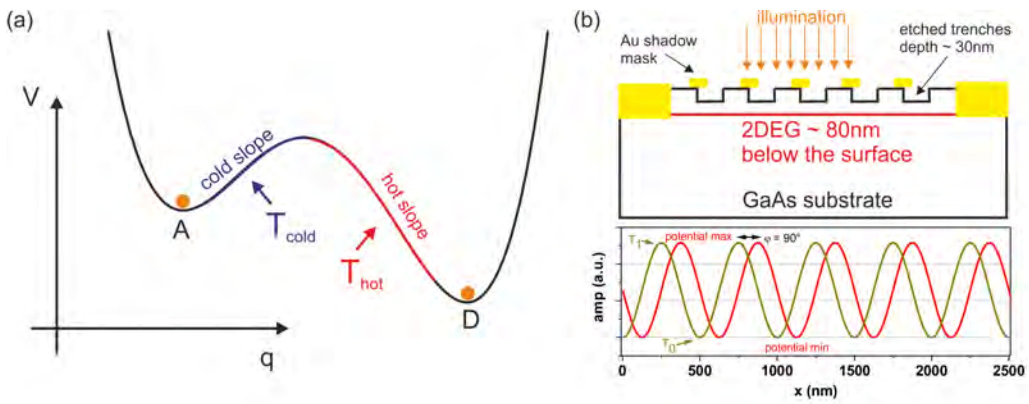


Figure 1:(a) Tilted double well potential with two minima (A and D). D is initially energetic favorable, but may change under non uniform temperatures T_{cold} and T_{hot} (cold and hot slope). Indeed, the particle distribution can be identical for both minima. Particles climb more easily a hot than a cold slope. (b) Top: Sketch of the layer structure and scheme of the proposed devices. The 2DEG is located around 80 nm below the surface and the periodic potential is defined by dry or wet chemical etched trenches. The Au mask serves as phase shifted electron gas heating under optical excitation. Bottom: Periodic potential and temperature modulation under light exposure.

Figure shows a sketch illustrating the operation principle. In a double well potential (see (a)) with two local minima e.g. at A and D and a central potential barrier ΔV, D is energetic favorable for particles since the potential is tilted. If the diffusion is uniform, i.e. the temperature is constant, the particles are preferably located at D compared to A. A different scenario is valid when the diffusion is state dependent for instance when a non-uniform temperature profile exists with a hot and a cold slope and temperatures T_{hot} and T_{cold}, respectively. Particles are more likely to have transitions from D to A than from A to D. Figure 1(b) shows a sketch of the fabricated device layout and the periodic potential with a temperature modulation under light exposure. The BLms were based on a modulation doped GaAs/AlGaAs heterostructures, which were grown by molecular beam epitaxy and further processed at UNIWUE. A high mobility two dimensional electron gas (2DEG) forms at the GaAs/AlGaAs interface located around 80 nm below the surface. The periodic potential was defined by 30 nm deep trenches with period λ by means of electron beam lithography and a soft dry chemical etching technique. On top of the trenches an Au shadow mask was deposited by a second electron beam lithography process and thermal evaporation. The metallic mask has the same period λ but is positioned phase-shifted with respect to the etched trenches. Under light exposure, the 2DEG below the shadow mask becomes thus locally heated (Figure 1(b)). Figure 2(a) shows two views of two devices with different phases of the metallic mask compared to the etched grid, 90° and 180°. It was successfully demonstrated that the out of phase electron gas heating leads to a direct net current with a magnitude and current orientation which depend on the phase difference φ. Figure 2(b) shows an example of the generated output power and efficiency versus the light power of a device with phase difference φ = 270° and the reference device without the periodic potentials.

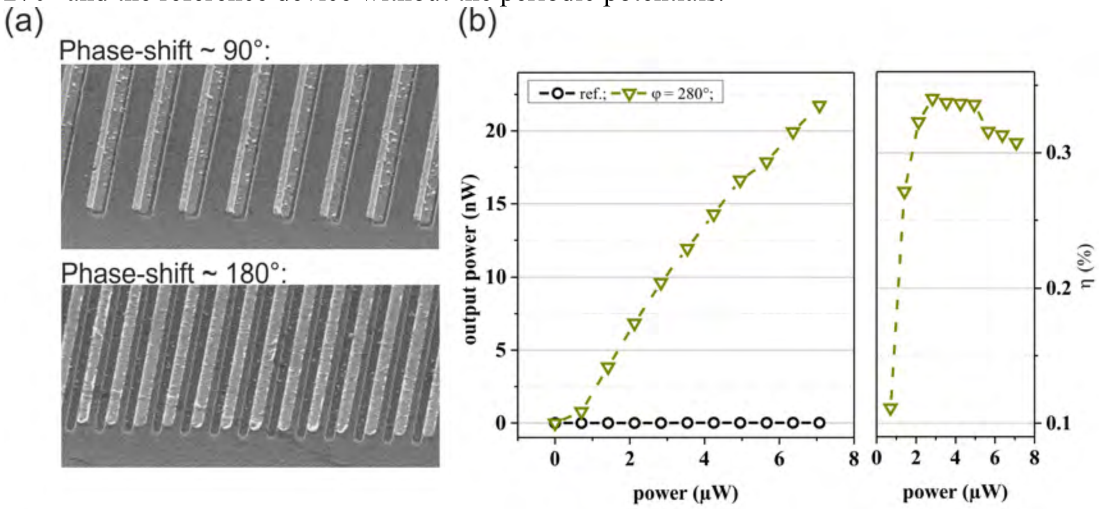


Figure:(a) Electron microscopy image of samples with dry chemical etched trenches, the Au shadow mask (bright) with phase differences φ = 90 (top) and 180° (bottom). (b) Output power and efficiency versus incident light power for a device with φ = 270° and the reference sample (without the periodic potentials).

- *Quantum harvester based on mesoscopic Coulomb drag:*

A second quantum harvester device concept was recently proposed by the UNIGE group and based on Coulomb drag effects in low dimensional systems. They investigated heat-to-current conversion mechanism in low dimensional systems down to the quantum limit[2]. The device concept was also realized successfully at UNIWUE.

Rectification is a non-linear process with large impact for many fields of technologies such as electronics. In the literature exists an ongoing debate if rectifiers could rectify thermal noise of the surrounding system especially those of hot spots. Indeed, with the miniaturization of electric circuits the exploitation of heat and noise becomes a formidable task and excited proposals for heat engines and noise rectifiers capable of converting electronic fluctuations into useful energy. Heat-to-current conversion by quantum dot systems via Coulomb interaction was recently discussed by UNIGE. The group around M. Büttiker showed that two capacitively coupled quantum dots can act as an optimal heat engine in which every energy quantum can be transferred to the motion of single electrons (current quanta). The proposed design allows an operation at maximum efficiency, i.e. Carnot efficiency. UNIGE also investigated a similar design based on open quantum systems and on resonant tunneling systems (B. Sothmann, R. Sanchez, A. N. Jordan, M. Büttiker, Phys. Rev. B **85**, 205301 (2012)). UNIWUE fabricated a prototype of such energy harvester in a modulation doped AlGaAs/GaAs heterostructure with a 2DEG as conductive layer. In Figure 3 there are two electron microscopy (SEM) images of the samples produced at UNIWUE. Etched tranches are reflected by dark contrast in the micrographs. The smallest trenches produced are 50 nm wide. The quantum dots in the finished device have a geometrical diameter of about 400 nm.

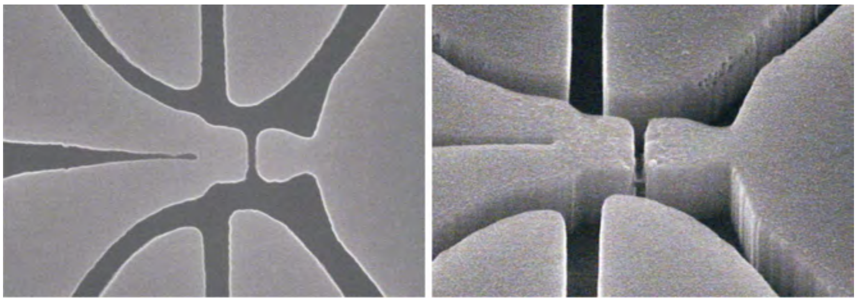


Figure: SEM micrographs of quantum energy harvester prototypes. Dark contrast reflect etched trenches. The quantum dots have a diameter of about 400nm. Due to the soft etching process a high aspect ratio was achieved.

- **<u>ICT integration at nanoscale.</u>**
  Under the leading role of UWUERZ, we designed autonomous ICT devices composed by nanoscale power generator and a powered, fully integrated sensors. The device is capable of temperature measurement and light detection and includes data communication capability.
  Most impressing the integration is obtained by integration of a quantum harvester and the RTD (Resonant Tunneling Diode) sensor as shown in figure below. The power and voltage is supplied by the quantum harvester based on radiation absorption. Its leads are connected to a capacitor in parallel, which is directly implemented in the GaAs system of the device. Additionally, a rectifier composed of rectangular shaped structure can be implemented within the power source and the RTD sensor. The main part of the emitter and sensor consist of an RTD. This structure can be grown on top of the quantum harvester.

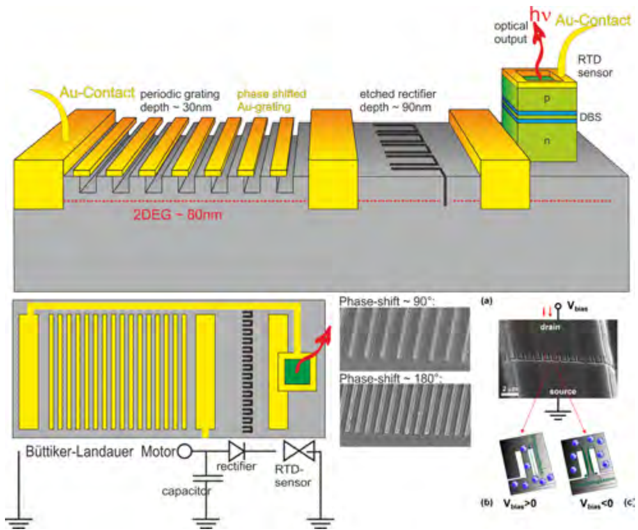


Figure: Integrated layout for the autonomous ICT device composed by an energy harvester (BLm), a rectifier, a capacitor and the RTD temperature and light sensor with the optical read out of the device.

0.4 Potential impact, dissemination and exploitation of results.

The NANOPOWER project was conceived to address the nanoscale energy management issue. We were and are convinced that this is a new, exciting field that is gaining increasing importance with the realization that a new generation of micro-to-nanoscale devices aimed at sensing, processing, actuating and communication will not be possible without solving the powering issue. The powering of such tiny devices is in-fact the bottle neck that need to be addressed in order to move from the laboratory prototype to the mass market.
We believe that with the results obtained in this project we made a significant step in this direction. For this reason we foreseen that the future impact of these results will be significant both in the scientific community and in the technology application by the companies that we have already started to involve.

In the following we discuss how the results obtained in the project have already impacted (and can further do it) on the scientific and industrial environment, what are the dissemination activities that we have realized in order to make such an impact and, finally, how do we plan to exploit these results.

We start we briefly summarising the most relevant results distinguishing among different target groups:
a) Scientific community
b) Industry / technology community
c) Policy makers
d) General public

a) Regarding the **scientific community** the most relevant results are associated with advancements in the scientific knowledge. We have already listed in the previous chapter the most relevant scientific and technological results.

Exploitation actions.
We have disseminated the scientific results through a number of channels:
- We have carried on an intensive publication activity on high-impact factor scientific journals with specific attention to open source publications.
- We have presented these scientific results at a number of high-level scientific conference.
- We have set up and maintained a web site devoted to the project.
- We have created and distributed a newsletter "Nanoenergy Letters".
- We have supervised a number of graduation and PhD Thesis on these topics.

b) Regarding the Industry / technology community, we believe we have reached significant advances with respect to the following topics (among others):
- An unprecedented database for vibration data.
- Software code for numerical simulation of nonlinear stochastic dynamics in energy harvesting.
- A novel realization technique for thin membranes of piezo material.
- A nanoscale prototype for vibration harvesting with high efficiency (world record).

- A set of novel concept-devices for quantum harvesting.
- A new kinetic energy storage system at nanoscale.

Exploitation actions.
With attention to a proper intellectual property protection strategy (see below) we have disseminated the technological results through a number of channels:

- We have carried on an intensive publication activity on high-impact factor scientific and technological journals.
- We have presented these scientific results at a number of high-level technology conference.
- We have set up and maintained a web site devoted to the project.
- We have created and distributed a newsletter “Nanoenergy Letters”. We now plan to transform it into a regular scientific publication.
- We have disseminated the results through networks of sme and industries (see e.g. the energy harvesting network at www.eh-network.org).
- We have disseminated the results through activities associated with the Coordinated Action ZEROPOWER (see www.zero-power.eu).

c) Regarding the policy makers, we believe we have reached significant advances with respect to the following topics (among others):

- Focussed the funding agencies attention on the Toward-zero-power topics.
- Realized that energy harvesting and energy dissipation at nanoscale are connected.
- Brought together the pre-existing community for energy harvesting with the novel community funded under *Toward-zero-power* call.

Exploitation actions.
Our activity is aimed to promote the research in the “Toward-zero-power” topics by involving both academia and industries. This activity has been covered mostly under the two Coordinated Actions that we promoted: ZEROPOWER (C.A. FET 2011-2013); ICT-Energy (C.A. FET 2013-2016).

d) Regarding the general public, we believe we have reached significant advances with respect to the following topics (among others):

- Raised awareness on the role of micro energies.
- Brought to the public attention the need for energy efficiency in ICT.

Exploitation actions.
The activity with respect to the general public is associated with the more general dissemination activity. With specific reference to the this point we notice that the dissemination of scientific results, e.g. scientific breakthroughs within the NANOPOWER project, is mandatory, requested by the shareholder, e.g. the European Commission, and eligible for the consortium. Especially it is demanded that scientific results of the project address a broad and multi-disciplinary audience, i.e. the general public, the scientific community, shareholders and possible industrial partners. A dissemination activity should thus cover the needs for the whole and not only a fraction of the multi-disciplinary audience. Otherwise significant opportunities would leave open and potentially lower the impact of the project. The exploitation plan has to address and take into account the needs as well as the scientific background of the aimed audience. Thus quiet substantially, it should be designed and address precisely the aimed audience. E.g. the general public might be overstrained with fancy equations and therefore the dissemination has to be translated from a scientific to a comprehensive “language”. One has to highlight the intention of the research and

how it interferes with the audiences' needs. On the other hand, dissemination to the scientific community is highly demanded as well. Science is interdisciplinary and it is desired to expand the community with on and off topic experts, because future problems might only be solved by an interdisciplinary work among various experts with different academic background.

Among the various activities that we have briefly mentioned there are some that deserves a deeper description.

The publication of scientific results on high-impact factor journals.

We have published the following papers:

N	Title	First author	Journal	Issue	Year
1	Drift in Diffusion Gradients	Marchesoni F.	Materials	8/2013 Vol. 6 Issue 8	2013
2	Self-Propelled Janus Particles in a Ratchet: Numerical Simulations	Ghosh P. K.	Physical Review Letters	6/2013 Vol. 110 Issue 26	2013
3	Periodically driven Brownian motion with dry friction and ultrarelativistic Langevin equations	Pototsky A.	Physical Review E	3/2013 Vol. 87 Issue 3	2013
4	Non Local Corrections to the Electronic Structure of Non Ideal Electron Gases: The Case of Graphene and Tyrosine	Garcia Y.	Journal of Modern Physics	Vol. 04 Issue 04	2013
5	Ultra-thin free-standing single crystalline silicon membranes with strain control	Shchepetov A.	Applied Physics Letters	Vol. 102 Issue 19	2013
6	Lifetimes of Confined Acoustic Phonons in Ultrathin Silicon Membranes	Cuffe J.	Physical Review Letters	2/2013 Vol. 110 Issue 9	2013
7	Powerful and efficient energy harvester with resonant-tunneling quantum dots	Jordan A. N.	Physical Review B	2/2013 Vol. 87 Issue 7	2013
8	Direct Measurement of Room-Temperature Nondiffusive Thermal Transport Over Micron Distances in a Silicon Membrane	Johnson J. A.	Physical Review Letters	1/2013 Vol. 110 Issue 2	2013
9	Sorting with uncertainty: Trading accuracy with energy saving	Neri I.	Nanoenergy Letters	08/2013 Vol. 6	2013
10	Hybrid Microwave Cavity Heat Engine	Bergenfeldt C.	arXiv:1307.4833v1	07/2013	2013
11	Nonlinear bi-stable vibration energy harvester at work	Orfei F.	Journal of Wireless Sensor Network	07/2013 Vol. 1	
12	Correlations of heat and charge currents in quantum-dot thermoelectric engines	Sanchez R.	arXiv:1307:0598	07/2013	

13	Flexural mode dispersion in ultra-thin Ge membranes	Chavez E.	14th International Conference on Ultimate Integration on Silicon (ULIS) Proceedings		2013
14	Brownian transport in corrugated channels with inertia	Ghosh P.	Physical Review E	8/2012 Vol. 86 Issue 2	2012
15	Rectification of thermal fluctuations in a chaotic cavity heat engine	Sothmann B.	Physical Review B	5/2012 Vol. 85 Issue 20	2012
16	Analytical estimates of free Brownian diffusion times in corrugated narrow channels	Bosi L.	The Journal of Chemical Physics	2012 Vol. 137 Issue 17	2012
17	Note: Particle transport through deformable pore geometries	Ghosh P. K.	The Journal of Chemical Physics	2012 Vol. 136 Issue 11	2012
18	Energy dissipation in small-scale shape-change dynamics	Gammaitoni L.	Physical Review E	2/2012 Vol. 85 Issue 2	2012
19	Rectification of Spatial Disorder	Um J.	Physical Review Letters	2/2012 Vol. 108 Issue 6	2012
20	Calculation of the specific heat in ultra-thin free-standing silicon membranes	Chavez E.	Journal of Physics: Conference Series	11/2012 Vol. 395	2012
21	Detection of single-electron heat transfer statistics	Sanchez R.	EPL (Europhysics Letters)	11/2012 Vol. 100 Issue 4	2012
22	Onsager relations in coupled electric, thermoelectric, and spin transport: The tenfold way	Jacquod P.	Physical Review B	10/2012 Vol. 86 Issue 15	2012
23	Relativistic Brownian motion on a graphene chip	Pototsky A.	The European Physical Journal B	10/2012 Vol. 85 Issue 10	2012
24	Driven Brownian transport through arrays of symmetric obstacles	Ghosh P.	Physical Review E	1/2012 Vol. 85 Issue 1	2012
25	Kinetic energy harvesting with bistable oscillators	Vocca H.	Applied Energy	1/2012	2012
26	Magnon-driven quantum-dot heat engine	Sothmann B.	EPL (Europhysics Letters)	07/2012 Vol. 99 Issue 2	2012
27	Phonons in Slow Motion: Dispersion Relations in Ultrathin Si Membranes	Cuffe J.	Nano Letters	07/2012 Vol. 12 Issue 7	2012
28	Detectable inertial effects on Brownian transport through narrow pores	Kumar Ghosh P.	EPL (Europhysics Letters)	06/2012 Vol. 98 Issue 5	2012
29	There's plenty of energy at the bottom (micro and nano scale nonlinear noise harvesting)	Gammaitoni L.	Contemporary Physics	01/2012	2012
30	Energetics of stochastic resonance	Jung P.	Chaos: An Interdisciplinary Journal of Nonlinear Science	Vol. 21 Issue 4	2011
31	Nanostructured graphene for energy harvesting	Lopez-Suarez M.	Phys. Rev. B	10/2011 Vol. 84	2011

32	Heat dissipation in nanometer-scale ridges	Chapuis P. O.	E-nanoNewsLetter	08/2011 Issue 22	2011
33	Geometric stochastic resonance in a double cavity	Ghosh P. K.	Phys. Rev. E	07/2011 Vol. 84 Number 1	2011
34	Temperature-resonant cyclotron spectra in confined geometries	Pototsky A.	Phys. Rev. E	07/2011 Vol. 84 Number 1	2011
35	Light-induced stochastic resonance in a nanoscale resonant-tunneling diode	Hartmann F.	Applied Physics Letters	06/2011 Vol. 98 Issue 24	2011
36	Ratcheting of driven attracting colloidal particles: Temporal density oscillations and current multiplicity	Pototsky A.	Phys. Rev. E	06/2011 Vol. 83 Number 6	2011
37	Strain dependence of electron-phonon energy loss rate in many-valley semiconductors	Muhonen J. T.	Appl. Phys. Lett. 98	05/2011 Vol. 98 Issue 18	2011
38	Optimal energy quanta to current conversion	Sanchez R.	Physical Review B	02/2011 Vol. 83 Issue 8	2011
39	Nanowatt logic stochastic resonance in branched resonant tunneling diodes	Hartmann F.	Applied Physics Letters	Vol. 98	2011
40	Nonlinear Kinetic Energy Harvesting	Cottone F.	Procedia Computer Science	Vol. 7	2011
41	Nonlinear noise harvesters for nanosensors	Neri I.	Nano Communication Networks	Vol. 2 Number 4	2011
42	Sustainable ICT: Micro and Nanoscale Energy Management	Gammaitoni L.	Procedia Computer Science	Vol. 7	2011
43	Vibration Energy Harvesting: Linear and Non Linear Oscillator Approaches	Gammaitoni L.	Sustainable Energy Harvesting Technologies - Past, Present and Future		2011
44	Acoustic Phonon Tunneling and Heat Transport due to Evanescent Electric Fields	Prunnila M.	Physical Review Letters	09/2010 Vol. 105 Issue 12	2010
45	Mesoscopic Coulomb Drag, Broken Detailed Balance, and Fluctuation Relations	Sanchez R.	Physical Review Letters	02/2010 Vol. 104 Number 7	2010

The dissemination through participation to conferences.

We have presented the project results at 98 scientific meetings. Here we list only the conferences from 2013 (the complete list is available at the project web site: www.nanopwr.eu):

N	Type of activities	Participant	Type of contribution	Title	Date	Place	Type of audience
1	Conference	F. Marchesoni	Invited talk	Phononics and Thermal Science	2013-09-02 - 2013-09-04	Shangai - China	Scientific Community
2	Conference	UNIPG, F. Hartmann, B. Sothmann	Poster Talk Organizer	NANOENERGY 2013	2013-07-10 - 2013-07-13	Perugia - Italy	Scientific Community
3	Workshop	B. Graczykowski	Talk	QMNTIA 2013	2013-07-10 - 2013-07-12	Reims - France	Scientific Community
4	School	L. Gammaitoni, L. Worschech, H. Vocca, F. Cottone, S. Lombardi	Lecture Organizer	NiPS Summer School 2013	2013-07-08 - 2013-07-10	Perugia - Italy	Scientific Community
5	Conference	L. Gammaitoni	Invited talk	JETC 2013 - 12th Joint European Thermodynamics Conference	2013-07-01 - 2013-07-05	Brescia - Italy	Scientific Community
6	Outreach	UNIPG	Talk Organizer	Micro-Energy Day 2013	2013-06-27	Perugia - Italy	Civil Society
7	Conference	M. Buttiker, B. Sothmann	Talk	International Conference on Noise anf Fluctuations (ICNF) 2013	2013-06-24 - 2013-06-28	Montpellier - France	Scientific Community
8	Conference	L. Gammaitoni	Invited talk	CHIST-ERA Conference 2013	2013-06-13 - 2013-06-14	Brussels - Belgium	Scientific Community
9	Conference	F. Marchesoni	Invited talk	Engineering of Chemical Complexity	2013-06-10 - 2013-06-13	Rostock-Warnemunde - Germany	Scientific Community
10	Conference	M. Buttiker	Invited talk	Colloquium: „Energy harvesting: Converting waste heat into electricity at the nanoscale“	2013-06-10	FRIAS, Freiburg - Germany	Scientific Community
11	Conference	C. M. Sotomayor Torres, J. S. Reparaz	Invited talk Poster	Phononics 2013	2013-06-02 - 2013-06-07	Sharm El-Sheikh - Egypt	Scientific Community
12	Conference	J. S. Reparaz	Talk	E-MRS Spring Meeting	2013-05-27 - 2013-05-31	Strasbourg - France	Scientific Community
13	Conference	F. Orfei	Invited talk	IEEE International Symposium on Circuits and Systems (ISCAS)	2013-05-19 - 2013-05-23	Beijing - China	Scientific Community
14	Conference	F. Hartmann	Talk	16th Brazilian workshop on semiconductor	2013-05-05 - 2013-05-10	Sao Carlos - Brazil	Scientific Community

				physics			
15	Conference	C. M. Sotomayor Torres, J. Ahopelto, L. Gammaitoni, F. Hartmann, B. Sothmann, H. Vocca, E. Chávez, A. Shchepetov	Invited talk Organizer	Trends in NanoApplications Conference (TNA) - IMAGINENANO 2013	2013-04-23 - 2013-04-24	Bilbao - Spain	Scientific Community
16	Conference	P.O. Chapuis, E. Chavez, S. Reparaz	Invited talk Poster Talk	MRS Spring meeting 2013	2013-04-01 - 2013-04-05	San Francisco – USA	Scientific Community
17	Conference	L. Gammaitoni	Invited talk	EACO Workshop 6	2013-03-26 - 2013-03-27	Bristol - United Kingdom	Scientific Community
18	Conference	L. Gammaitoni	Invited talk	Energy Harvesting 2013	2013-03-25	London - United Kingdom	Scientific Community
19	Conference	E. Chávez	Poster	ULIS 2013 Conference	2013-03-19 - 2013-03-21	Warwick - United Kingdom	Scientific Community
20	Conference	A. Pfenning, B. Sothmann	Talk	DPG Spring meeting	2013-03-10 - 2013-03-15	Regensburg - Germany	Scientific Community
21	Conference	F. Marchesoni	Invited talk	Workshop on "Microenergetics and fluctuation theorems"	2013-01-10	Seoul - Corea	Scientific Community

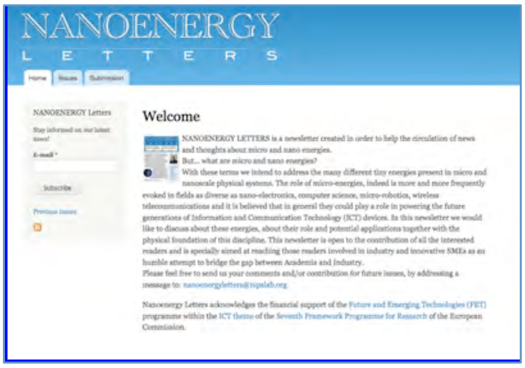
The creation of a scientific publication: NANOENERGY LETTERS.

At the beginning of the project in 2010, we have created a scientific newsletter entitled NANOENERGY LETTERS. The idea was to a way to communicate twice a year the main results obtained in the NANOPOWER project. After the first issue we realized that this newsletter was of interest to a larger community involved in the ICT-Energy issue. Since 2010 we have now published 6 issues and the newsletter has widen its public and the broadened its ambition in order to become a truly scientific journal that publishes news and papers from the wide scientific and industrial community.

The editorial board is composed by:

- *L. Gammaitoni, NiPS Laboratory, University of Perugia (IT)*
- *L. Worshech, University of Wuerzburg (Ger)*
- *J. Ahopelto, VTT (FI)*
- *C. Sotomayor Torres, ICN and ICREA Barcellona (SP)*
- *M. Buttiker, University of Geneva (CH)*
- *F. Marchesoni, University of Camerino (IT)*
- *G. Abadal Berini, Universitat Autònoma de Barcelona (SP)*
- *P. Douglas, University of Glasgow (UK)*
- *G. Fagas, Tyndall National Institute University College Cork (IR)*
- *S. Lombardi, NiPS Laboratory, University of Perugia (IT)*

NANOENERGY LETTERS can be freely downloaded as a digital journal at www.nanoenergyletters.eu.

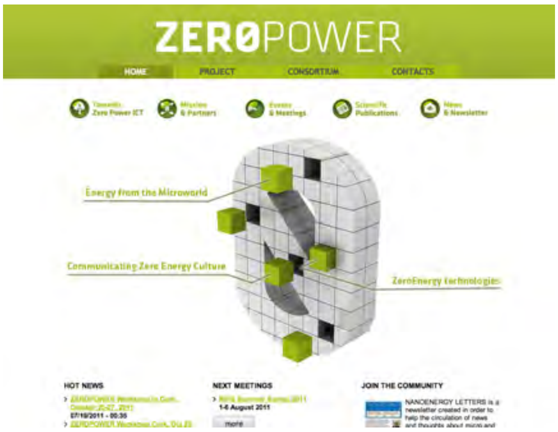


www.nanoenergyletters.eu web site

The creation of a scientific community interested in zero-power ICT

During the lifetime of the NANOPOWER project we have worked hard to bring together the wide community of scientist from academia and industry interested in the ICT-Energy issue. This work has produced an initiative denominated ZEROPOWER Coordinated Action that has been funded by the European Commission under FET (C.A. ZEROPOWER, 2011-2013) and it will be continued under the new activity denominated "ICT-Energy" (C.A. FET 2013-2016). This coordination activity has brought together eleven European groups (more that 80 scientists) that shares information and plan common research activities. More information on this coordination can be found at www.zero-power.eu.

www.zero-



The ZEROPOWER Coordination Action web site

Special attention has been also devoted to the utilization of the new media in order to exchange information and to disseminate results to the public with a FACEBOOK page and a TWITTER account.

During July 2013 we have also organized the first international scientific conference devoted to nanoenergies (NANOENERGY2013 – Perugia 10-13 July 2013).

The proceedings of the conference (www.nanoenergy2013.eu) have been published as a special issue of NANOENERGY LETTERS.

The creation of an annual summer school

We have created an annual summer school devoted to micro and nano energies.

Four edition of the school have been realized with an average participation of 40 students each, coming from 18 different countries. More information on the summer school can be found at http://www.nipslab.org/summerschool2013.

The creation of a European energy day: MICRO-ENERGY DAY.

We have created a micro-energy awareness initiative that we have called “micro-energy day”.

www.microenergyday.eu

This is a yearly event to disseminate a new conceptual approach to renewable energies in the field of microenergies. Microenergies are all those energies that are often disregarded as unimportant but instead play a significant role in our daily life. As an example… when you run out of battery in your mobile phone and really need to make that call !!! The amount of energy involved in this case is really very small compared to the energy that makes your car going but its absence appears to be very important to the public. In 2013 this was June 27th where different groups in different cities in Europe have organized events to meet people and discuss about microenergies.

The intellectual property protection activity.

Based on our analysis of the most relevant results obtained during the project, we decided to proceed with actions aimed at protecting the intellectual property of the following findings that are potentially interesting for industrial exploitation:

- A set of novel concept-devices for quantum harvesting.
- A new kinetic energy storage system at nanoscale.

Specifically, we have selected three candidate devices for potential patent registrations:

- Kinetic energy storage.
- Quantum harvester from radiation absorption.
- Quantum device temperature sensor

In the following we briefly describe these three devices. Being the patent registration process not yet completed we cannot provide here much detail.

Kinetic energy storage

FIELD OF THE INVENTION

Kinetic energy storage is based on a simple principle: instead of converting kinetic energy from random fluctuation into electric energy and from this to chemical energy for storage, we proposed to exploit the properties of low losses linear oscillators as kinetic energy temporary storage devices.

This opens up potential opportunities for applying this concept to micro and nanoscale oscillators with the aim of realizing a nanoscale “dynamic battery”. UNIPG is currently involved in this activity.

Quantum harvester from radiation absorption

FIELD OF THE INVENTION

The present invention relates on energy harvesting from radiation absorption. Two partners from NANOPOWER (UNIWUE and UNIGE) have declared their intention in proceeding with the deposit of a patent on an “integrated quantum harvester device” with an energy harvesting mechanism based on radiation absorption at nanoscale. The device consists of a Landauer-Büttiker motor (LBm) and an integrated resonant tunneling diode (RTD). Herby, the LBm generates an electrical current by a periodic and spatially symmetric electronic potential subject to an out of phase, but also periodic heating of the electron gas (or more general nonlinear noise).

Quantum device temperature sensor

FIELD OF THE INVENTION

The present invention provides a high sensitive and wide temperature sensor suitable for temperature sensing from cryogenic to above room temperature with an electrical and optical readout. The patent process is ongoing and at this time no further detail can be provided.

Consortium

No	Participating Institution	Short Name	Country
1	Dipartimento di Fisica Universita degli Studi Perugia	UNIPG	Italy
2	Julius Maximilians Universität Würzburg	UNI WUE	Germany
3	Technical Research Centre Finland	VTT	Finland
4	Istituto Catalano de Nanotecnologia	ICN	Spain
5	University of Geneva	UNIGE	Switzerland
6	Università degli Studi di Camerino	UNICAM	Italy

Contact Information

Coordinator: Prof. Luca Gammaitoni
Institution: Dipartimento di Fisica, Università di Perugia
Email: luca.gammaitoni@nipslab.org
Phone: +39-075-5852733, (Fax +39-075-5848458)

Mailing address: NiPS Laboratory, Dipartimento di Fisica
Università di Perugia
Via A. Pascoli, 1 - 06123, Perugia, Italy

Project Web-site: www.nanopwr.eu

Project Logo: NANOPOWER