NANOENERGY LETTERS is a newsletter created in order to help the circulation of news and thoughts about micro and nano energies. But... what are micro and nano energies? With these terms we intend to address the many different tiny energies present in micro and nanoscale physical systems. The role of micro-energies, indeed is more and more frequently evoked in fields as diverse as nano-electronics, computer science, micro-robotics, wireless telecommunications and it is believed that in general they could play a role in powering the future generations of Information and Communication Technology (ICT) devices. In this newsletter we would like to discuss about these energies, about their role and potential applications together with the physical foundation of this discipline. This newsletter is open to the contribution of all the interested readers and is specially aimed at reaching those readers involved in industry and innovative SMEs as an humble attempt to bridge the gap between Academia and Industry. With your help we will try to keep it twice a year.               LG

Luca Gammaitoni

This newsletter is edited with the help of the NANOENERGY editorial board composed by:

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- J. Ahopelto, VTT (FI)
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FET proactive initiative: Towards Zero-Power ICT

The European Commission, under the Seventh Framework Programme, has launched the initiative designated Toward Zero-Power ICT (FET Proactive) with the specific aim of promoting the research of “new disruptive directions for energy-harvesting technologies at the nanometre and molecular scale, and their integration with low-power ICT into autonomous nano-scale devices for sensing, processing, actuating and communication.”

The target outcome of this initiative is twofold:

a) Foundations of Energy Harvesting at the nano-scale: Demonstration of radically new strategies for energy harvesting and local storage below the micrometer scale. Exploration and harnessing of potential energy sources at that scale including kinetic energy present in the form of random fluctuations, ambient electromagnetic radiation, chemical energy and others.

b) Self-powered autonomous nano-scale electronic devices: Autonomous nano scale electronic devices that harvest energy from the environment, possibly combining multiple sources, and store it locally. These systems would co-ordinate low-power sensing, processing, actuation, communication and energy provision into autonomous wireless nanosystems.

The call for proposal was launched on 30 July 2009, CLOSED on 27 October 09. Seven research proposals were received for evaluation in Call 5. They requested a total EC contribution of €17 million. Three out of four projects above threshold have been funded consuming nearly completely the budget of 7 M€.

SINAPS will employ semiconductor nanowires both for energy harvesting of electromagnetic radiation and for (bio-)chemical sensing. NANOPOWER will investigate the fundamentals of energy harvesting at the nano-scale by using piezoelectric nonlinear vibration, guided phonon transport and Buttiker-Landauer motors. GREEN SILICON will harvest energy from temperature gradients with zero-, one- and two-dimensional silicon silicon-germanium superlattices. The starting date of the project was 1st of August, 2010.

The technological objective of the project is to integrate such technologies into autonomous nanoscale systems to allow new, low-power ICT architectures to find their way into devices. In a joint effort, the nanopower consortium composed by world leading experts in the fabrication of Si and III-V semiconductor nanodevices, fundamental and applied modelling as well as design and integration of ICT architectures will fabricate, test and evaluate new conception devices, addressing applied prototypes and non-equilibrium processes down to the quantum level.

In summary, the ambitious objective of this project is 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.

Information on NANOPOWER activities can be found at the web site: www.nanopwr.eu.
During the European Sustainable Energy week

Since 2010 the NiPS Laboratory (www.nipslab.org) proposes a yearly event to disseminate a new conceptual approach to renewable energies in the field of micro-energies. The First micro-energy day has been then held in Perugia on the 25th of March 2010 during the 2010 European Sustainable Energy Week.

The next Micro-energy day 2011 will take place on the 14th of April 2011, in the framework of the 2011 European Sustainable Energy Week (http://www.eusew.eu).

Why micro energies

With the term "microenergies" we intend all those "small" energies that are often disregarded as unimportant due to their apparently negligible weight 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 you...

Who can participate

The Micro-energyday initiative is open to the participation of individuals, groups, and institutions. It also involves partners from all over Europe such as: research centres, science communication events, media companies and private enterprises or public institutions.

All the stakeholders involved in researching, communicating and taking political actions on renewable energies are invited to join the project and to sustain it through a wide range of actions. A partner is the organiser of a Micro-energy day in its own city or country. Everyone who can sustain the project disseminating information about microenergies and about microenergies events is also a partner.

If you want to know more or what your institution listed as one of the partners please visit the Micro-energy day web site at:

www.microenergyday.eu
The European Future Emerging Technologies (FET) Conference and Exhibition aims to be the European forum for facilitating international cross-disciplinary dialogue and discussion on visions and challenges for frontier research in future and emerging information technologies.

Following the first FET conference held in 2009 in Prague, fet\textsuperscript{11} is designed to be highly interactive and engaging a broad and multi-disciplinary community. It will involve key policy makers, and features a mix of panel discussion, keynote speakers, scientific sessions, and posters sessions. A hands-on exhibition will run throughout, in parallel to the conference, showcasing the latest research developments in future and emerging information technologies.

There is no forum in Europe for facilitating cross-disciplinary dialogue on frontier research in information technologies. The FET Conference aims to remedy this, by becoming the periodic 'rendez-vous' for stakeholders to discuss the scientific, societal and policy challenges in this domain. While there are a large number of scientific conferences targeted at specific scientific domains, the FET Conference focusses on bridging disparate disciplines and communities, and fostering the interplay between science, policy and society.

Jan 19th 2011: the ZEROPOWER kick-off

The ZEROPOWER consortium held the first (kick-off) meeting in London on Jan 19 2011. The ZEROPOWER project (Co-ordinating Research Efforts Towards Zero-Power ICT) is a Coordination and Support Action funded by the Future and Emerging Technologies (FET) programme within the ICT theme of the Seventh Framework Programme for Research of the European Commission. The Consortium, led by NiPS, is composed by 4 laboratories:

- NiPS, University of Perugia, Italy (UNIPG)
- Tyndall National Institute, University College Cork, Ireland (Tyndall-UCC)
- Universitat Autònoma de Barcelona, Spain (UAB)
- University of Glasgow, United Kingdom (UG)

The Consortium met in London for the first time since the official start of the project on Jan 1st 2011.
For more information please visit: www.zero-power.eu
Micro and nanoscale Energy Harvesting

The Noise in Physical System Laboratory (NiPS Lab) organizes the 2011 NiPS Summer School devoted to Energy Harvesting at micro and nano scale. The school, supported by the EC Fet Proactive project NANOPOWER, and the Coordination and Support Action ZEROPOWER, is open to graduate students, post-docs, young researchers, and in general to all scientists interested in the physical foundations and practical applications of energy harvesting at micro and nanoscale.

Some of the topics covered at the school:
- Introduction to Energy Harvesting (EH)
- Linear and non-linear vibration H.
- Thermoelectric efficiency
- Noise rectification
- Phonon engineering for EH
- MEMS/NEMS design and realization
- Micro/Nano devices for EH
- ICT applications of EH
- Future technological trends: Beyond CMOS technology and Energy Efficiency.

TO REMEMBER
School location: Perugia, IT

Important dates:
- August 1-4 2011: SUMMER SCHOOL
- March 1 2011: Student registration opens
- July 1 2011: Student registration closes

web site:
www.nipslab.org/summerschool

Images from 2010 NiPS Summer School held in Avigliano Umbro (IT).

The Noise in Physical System Laboratory organized the 2010 NiPS Summer School devoted to Energy Harvesting at micro and nanoscale. The school, supported by the EC Fet Proactive project NANOPOWER, has seen the participation of more than 35 graduate students, post-docs, young researchers, all scientists interested in the physical foundations of energy harvesting at micro and nanoscale. Attached to the school there was a two days workshop where the students and external participants presented the result of their research. The workshop covered a wider range of subjects under the title of “Noise in dynamical systems at the micro and nanoscale”.

Slides from the lectures are available at: http://www.nipslab.org/summerschool/abstracts

Lukas Worschech lecturing at NiPS Summer School 2010
Energy harvesting via noise rectification?

The possibility of extracting useful work out of unbiased random fluctuations (also called noise rectification) by means of a device where all applied forces and temperature gradients average out to zero, can be considered an educated guess, for a rigorous proof can hardly be given. P. Curie postulated that if such a venue is not explicitly ruled out by the dynamical symmetries of the underlying microscopic processes, then it will generically occur.

The most obvious asymmetry one can try to advocate is spatial asymmetry (say, under mirror reflection, or chiral). Yet, despite the broken spatial symmetry, equilibrium fluctuations alone cannot power a device in a preferential direction of motion, lest it operates as a Maxwell demon, or perpetuum mobile of the second kind, in apparent conflict with the Second Law of thermodynamics. This objection, however, can be reconciled with Curie’s criterion: Indeed, a necessary (but not sufficient!) condition for a system to be at thermal equilibrium can also be expressed in the form of a dynamical symmetry, namely reversibility, or time inversion symmetry (detailed balance). Time asymmetry is thus a second crucial ingredient one advocates in the quest for noise rectification. Note, however, that detailed balance is a subtle probabilistic concept, which, in certain situations, is at odds with one’s intuition. For instance, as reversibility is not a sufficient equilibrium condition, rectification may be suppressed also in the presence of time asymmetry. On the other hand, a device surely operates under nonequilibrium conditions when stationary external perturbations act directly on it or on its environment.

In conclusion, the extraction of mechanical work from an equilibrium heat bath by means of an artificial device cannot be ruled out a priori, as long as the spatial and time symmetry of the dynamics that controls the device operation and its coupling to the environment, are simultaneously broken.

Fabio Marchesoni
for UNICAM group in NANOPOWER

Nanoscale membranes for vibration harvesting

The VTT group is working on the realization of nanoscale membranes to be used in nonlinear vibration energy harvesters. 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 VTT focuses 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 such bistable/multistable nonlinear oscillators have been demonstrated to have noise-activated switching with an increased energy conversion efficiency (see e.g. F. Cottone et al. Phys. Rev. Lett. 102, 080601 2009).

Membranes realized by VTT for the NANOPOWER project benefits from a new realization process that significantly improve the flatness of the membrane. As it is well apparent in the figures, the thermal SiO2 with compressive stress too high, leads to corrugation. It has been replaced by LPCVD SiN with low tensile stress that keeps membrane flat.

Jouni Ahopelto
for VTT group in NANOPOWER
In the frame of NANOPOWER, the ICN team leads research in design, fabrication and characterization of phonon rectifiers. The principle of phonon rectification is presented in Figure 1. Briefly stated, rectification is a phenomenon that appears when the net flux flowing from left to right (case 1) is different from the net flux flowing from right to left (case 2). The source and detector locations have to be reversed in order to detect it. The phenomenon is based on the interplay between the asymmetric geometry, here schematically represented by triangles, and the nonlinearity of the acoustic properties of the medium. The goal of such work is to show the ability of controlling the directionality of the phonon propagation and therefore to improve the efficiency of a number of devices involving acoustic and/or heat dissipations. Phonons are indeed the main source of losses in many devices and they are very often difficult to control. A dream would be the fabrication of kind of phonon valve. The goal of this line of research in NANOPOWER is to see if nano-structuration can help to go further on the way to this aim.

Modelling and simulation

In order to predict accurately the phonon propagation in the nanostructures that will be fabricated, we firstly need to master a suite of methods that aim at simulating the media phononic, electronic and optical properties. Two types of methods are being used:

• Classical continuum elasticity-based models, that are known for allowing the calculation of the phonon transmission
• First-principle methods, required when the quantum limit is approached, in our case for carbon-based molecular systems and at interfaces.

We show in Figure 2 the acoustic dispersion of the first phonon modes in nanometer-thin silicon membranes, and compare with the measurements made thanks to Brillouin inelastic light scattering spectroscopy. Knowing which modes can be transmitted in such a medium is a first step toward the optimization of the rectification coefficient $\phi_1/\phi_2$. At a given frequency, the phonon flux can indeed be written similarly to

$$\phi(\omega) = \hbar \omega v_g(\omega) t_{LR}(\omega)$$

where $\hbar \omega$ is the energy carried by a phonon mode, $v_g$ the group velocity of this mode also calculated thanks to the dispersion curves and $t_{LR}$ the transmission coefficient. Here LR (left to right) underlines the importance of the directionality in such calculations.

**Figure 1.** Concept of a device that undergoes phonon rectification: The flux is larger when the source is at right and the detector at left than in the reversed case presented here.

**Figure 2.** a) Dispersion curves of a 30 nm thick free-standing silicon membrane showing flexural and dilational modes, calculated with the elastic continuum model.

b) Comparison of the simulated results (solid lines) with the experimental data squares, circles and triangles obtained by Brillouin inelastic light scattering spectroscopy for the flexural mode of free-standing membranes fabricated by the partner VTT.

c) Group velocities associated with the dispersion curves. The definition of the dispersion relations is needed for the calculation of thermal fluxes.
Fabrication and characterization of samples

We have started preliminary tests prior to the fabrication of the nanodevices and their further characterization. Based on our first predictions, we know that the fabrication of our systems requires the use of advanced nanofabrication techniques such as electron beam lithography (EBL) and reactive ion etching (RIE). We have already used such techniques for the fabrication of test samples such as those shown in Figures 3 (a) and (b). Phononic crystals, i.e. large arrays of periodic structures allowing the transmission of certain frequencies but forbidding other ones, are presented, in particular when asymmetry can be obtained like in Figure 3 (a). The studies aiming at achieving the highest hole-to-substrate surface ratios allow to find the limit before the contact between the elements (here circles), that destroy the acoustic propagation on top of the sample, see Figure 3 (b).

The characterizations of the samples will be done thanks to optical techniques, such as Raman and Brillouin light scattering spectroscopy, and electrical ones based on the 3-omega method, represented on Figure 3 (c). This method aims at measuring the heat flux dissipated by a heated metal stripe deposited on top of the sample. On the Figure 3 (c), one can see 4 tips in contact between the pads connected to the stripe. This allow for a rapid and efficient measurement of the heat flux. This type of measurements is targeted for the analysis of thermal rectification.

All the techniques mentioned here will be soon applied to rectifying samples based on the principle shown in Figure 1.

Clivia Sotomayor Torres
for ICN Group in NANOPOWER

Figure 3. (a) Top-view SEM images of 250 nm thick PMMA resist after EBL exposure and development of the honeycomb lattice. Distortion of the pattern is seen at higher doses due to the enhanced proximity of the exposures. The honeycomb lattice is chosen, as it has been demonstrated to exhibit large and simultaneous photon and phonon band gaps. (b) Top-view SEM images of silicon RIE-etched honeycomb lattice structures patterned using the 150nm polymer resist. The arrow indicates increasing r/a-ratio for holes of the unit cell etched into silicon. (c) Optical microscopy image of 3ω method based setup used for the determination of the thermal conductivities. The test sample was fabricated at VTT. 4 probing tips are in contact with the device deposited onto the glass sample.


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NANOENERGY LETTERS is realized with the contribution of NANOPower project, funded under the Future and Emerging Technologies (FET) programme within the ICT theme of the Seventh Framework Programme for Research of the European Commission.