FET Funding Opportunities on Energy Harvesting at the Nano-Scale: "Towards Zero-Power ICT"

Powering all the electronic devices surrounding us in our daily life is still and will remain a challenge. Therefore "Future and Emerging Technologies Proactive (FET)", part of the European Commission, General Directorate Information Society and Media, will launch a new Proactive Initiative in the call FP7-ICT-2009-5. This Proactive Initiative searches for new and disruptive ideas for energy harvesting and storage at the nanometre and molecular scale to power our future information and communication technologies (ICT). The feasibility of proposed approaches should be demonstrated by the construction of nano-scale autonomous devices able to sense, actuate and/or communicate.

To discuss the research challenges and opportunities of this call the Nano-ICT Coordination Action has organized a workshop, which took place on June 23rd, 2009, in Brussels. You will find the summary of this workshop hereafter.

More information on the initiative itself, the call text as well as on the 2zeroP-workshop held in Brussels (June, 23rd 2009) can be found under:

http://cordis.europa.eu/fp7/ict/fet-proactive/2zerop_en.html#news

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Deadline for proposals: October 26th, 2009.

FET Proactive Workshop Towards Zero-Power ICT (2zeroP)
Brussels, 23 June 2009

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1. Overview

Future and Emerging Technologies - Proactive Initiatives (FET - Proactive) is launching a call on a new topic, “Towards Zero-Power ICT” (see also http://cordis.europa.eu/fp7/ict/fet-proactive/2zerop_en.html).
Therefore the Coordination Action "Nano-ICT" has organized together with FET-proactive a workshop to collect opinions on the challenges, the possible solutions, and the research avenues that could be pursued within this topic. The workshop took place in Brussels on June 23rd, 2009. This report summarizes the presentations and the discussion centered around the call, trying to identify and highlight existing challenges and possible solutions.

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2. Contents of the presentations

Presentations addressed a variety of topics connected with the design and implementation of nano-scale systems capable of harvesting energy from environmental sources and making use of such energy for sensing, data processing and mechanical actuation. The topics addressed covered the following broad fields:

- Energy harvesting from mechanical vibrations and thermal fluctuations
- Energy harvesting from the electromagnetic field (RF, light)
- Energy harvesting from thermoelectric conversion
- Energy storage in nanoscale devices
- Actuation by means of magnetic field
- Minimizing the energy consumption

Slides from the presentations are available at http://cordis.europa.eu/fp7/ict/fet-proactive/2zerop-ws-june09_en.html. A summary is reported in the following.

One of the presented lines of research is centered on the development of new materials that should enable scaling down to nanometer dimensions with energy consumption on the order of magnitude of nanowatts. The issue of materials is especially relevant for energy storage, where progress is very slow, with a doubling of energy density only every 10 years. In addition, the charging process of most available types of batteries is slow. Therefore this is a field where improvement would be extremely needed, especially in terms of solutions that are easily applicable at the nanoscale.
Proposed solutions were based on bio-fuel cells, nanoantennas capable of extracting energy from electromagnetic radiation, piezoelectric materials to collect energy from mechanical vibrations.

Then the importance of having, in the future, energetically autonomous nanoscale devices was further stressed and the challenges involved in scavenging energy from mechanical vibrations were addressed. It is intrinsically difficult, due to natural time scales, to make a wide-spectrum harvester at the nano of even micro-scale, and there is still a lack of understanding of the detailed physics of nonequilibrium fluctuations. Another issue that was pointed out is the lack of an agreed upon figure of merit for the performance of energy harvesters.

An important point is represented also by the question about where electronics and energy production meet: reduced power requirements for processing information can alleviate the difficulties in energy scavenging; actually the two problems are tightly connected and should be tackled concurrently, although this call adresses mainly the exploration of new energy harvesting techniques at the nano scale.

Then an evaluation of the existing state of the art in the field was presented, focusing in particular on the “smart dust” concept that has been driving several research projects in the US. The current size of a “smart-dust” autonomous device is of the order of 1 mm^3: it was proposed that reasonable targets for the present call should be sizes of 10^3 μm^3, energy usage of less than 1 nJ and power below 1 mW. To achieve such results, three-dimensional packaging could be helpful, as well the implementation of parallel 2-D arrays of harvesters based on Nano ElectroMechanical Systems (NEMS). It was suggested that micromachined cantilevers could be instrumental in collecting energy form sources as disparate as mechanical fluctuations or radio-frequency signals, especially if operated in the nonlinear regime where efficiency appears to be increased.

One presentation was specifically aimed at introducing some concepts of reversible computing: reversible computing can in principle overcome typical thermodynamical limitations such as those associated with the erasure of information, which costs at least $kT \ln 2$ per bit; however it has to retain all data of the computation and to operate sufficiently slowly to be in the adiabatic regime. It was also pointed out that “adiabatic” at the nanoscale may indeed not be so slow, because natural time constants can be as low as a few femtoseconds.

A possible solution for actuation (which is also within the scope of the call) at the nanoscale was mentioned in one of the presentations, specifically consisting in the usage of controlled magnetic fields to propel and direct motion of nanoscale probes in the human body (for example in the blood stream). The results of experiments in which such concepts have successfully been tested were presented. This would be a relatively simple solution in which the energy needed for motion would be supplied wirelessly from the environment.

Then a different aspect was addressed: improving our understanding of heat transport at the nanoscale, both in homogeneous materials and at interfaces or grain boundaries and at reduced dimensionalities. This is directly connected, at the microscopic level, with phonon-electron, phonon-phonon interactions, and, by careful engineering of material properties, it should be possible to exploit quasi-particle interactions, including also photon-electron, photon-plasmon, and phonon-electron events, to harvest and to store energy.

Another issue deserving attention is represented by an optimization of energy consumption in terms of circuit design and software approaches. This leads to the need of careful hardware-software codesign. Some lessons in terms of extremely low power consumption can be drawn from the experience with single-electron circuits, in particular those based on the QCA (Quantum Cellular Automaton) paradigm, which, although not of practical applicability, due to its excessive sensitivity to fabrication tolerances, has represented a testbed for computation with energy consumption of the order of kT per operation.
It was also noted that maximizing energy collection and downscaling devices are unfortunately two conflicting requirements and optimal trade-offs must be sought for.

An interesting approach to improve the efficiency of energy harvesting was proposed, based on the cooperative action of quantum dots and of a particular protein, the bacteriorhodopsin (bR), which is capable of photovoltaic conversion. In particular, the quantum dots can adsorb electromagnetic energy in a broad spectrum and reemit by photoluminescence in a narrow band where the bR protein has the best conversion performance.

Finally the remarkable technological advances in the fabrication of semiconductor nanowires have been pointed out. It is currently possible to manufacture, at a relatively low-cost, high-quality semiconductor nanowires, which can be further downscaled and which are suitable for many applications of interest for the present call: high-efficiency transistors based on a wrap-around gate (which improves channel control) and with improved subthreshold slope (nanowire tunnel FET), as well as devices for high-yield photovoltaic energy conversion and nanothermoelectronics.

3. Topics of discussion

A part of the session was devoted to discussions amongst those in attendance. The following topics were discussed:

- Highly interdisciplinary nature of the effort required for developing nanoscale energy harvesters and interacting autonomous systems

- Presence of issues of a fundamental nature, such as the behaviour and exploitability for our purposes of non-equilibrium fluctuations, energetic limits of computation, understanding and mimicking of biological processes
- Possibility of achieving adiabatic evolution, and time scale that would correspond to adiabatic evolution
- Significance of the $kT \ln 2$ limit per elementary logic operation
- Do problems of leakage current become more severe at the nanoscale for all types of devices?

4. Synthesis of discussions

There was ample consensus about the need for the participation of consortia including expertises in diverse fields and the need for the definition of agreed upon common criteria to benchmark the different approaches to energy scavenging.

The issue of how energy dissipation of less than $kT \ln 2$per logic operation was debated. There was agreement on the fact that erasure of a bit involves an energy cost of $kT \ln 2$ as a result of fundamental entropy considerations, but the issue whether or not the operation itself uses up such an amount of energy even if performed reversibly remained open. On the other hand, it was discussed whether it might be difficult to perform useful reversible computation, because of the memory size required to store intermediate information. An interdisciplinary research (reversible hardware, reversible software, and reversible memory) would be necessary.

It was clear to all participants that to achieve convincing proof of concept both target outcomes (energy harvesting and the creation of nanoscale interacting autonomous systems) should be addressed at the same time and in a coherent fashion. Indeed, the energy harvesting part must be tailored to the power supply requirements of the autonomous interacting systems.

5. Challenges

A few outstanding challenges were recognized, which need to be addressed to achieve results with a real technological and societal impact.

- **Challenge of identifying the energy sources that we can tap into and of establishing yardsticks to evaluate performance**

The first identified challenge is about where to harvest energy from and how to benchmark the different possible approaches. Besides those already mentioned, all other energy sources available to the system can be pursued, such as chemical energy from organic compounds, mechanical energy from fluid motion, or others.

- **Challenge of finding novel materials, techniques and approaches to store energy in nanoscale devices**

This challenge arises from the need of improved energy storage, since all “free” energy sources are in general not constant.

- **Challenge of actuation performed by nanoscale devices, in terms of motion, navigation, and energy supply**

One more challenge consists in having autonomous nanoscale entities that can also mechanically interact with the environment. Whatever the approach, we need to find the way of supplying to them also the energy for actuation.

- **Challenge of achieving an energy balance by optimizing the systems in terms of energy consumption**

In order to ease the requirements on energy harvesters, it is also important to minimize the energy requirements of the autonomous systems, by means of new materials, new device technologies, new software approaches, new architectures (from this point of view, the final challenge, in a very-long-term perspective, is that of achieving close to zero energy consumption with approaches such as reversible computing).

- **Challenge of the efficient exploitation of highly distributed systems made up of autonomous units**

In a longer-term perspective a challenge is also that of finding the best applications for networks of autonomous nanosystems.

- **The challenge of system integration**

This challenge is meant to search for the necessary elements in order to achieve the integration of different devices into a system being able to communicate at the inter- and intra-device level as well as with the external world.

- **The challenge of bio-inspired devices**

As far as we know Nature has managed to build-up truly miniaturized devices working far down to the nanoscale level and making use of stable external energy sources in the shape of the energy stored in the atomic and molecular bonds. A good example could be the mitochondria. This challenge will certainly address the question of letting us be inspired by this type of solutions and maybe therefore determine new ways of integration, miniaturization fabrication, etc.

6. Conclusions

During the workshop some clear challenges facing the still forming zero-power community have been highlighted, which have to be tackled in order to obtain

nanoscale systems that can operate autonomously collecting the energy they need from the environment.
Envisaged solutions have been proposed for some of the challenges, but it is clear that the objective is long-term, because many technological hurdles have to be overcome before actual autonomous nanosystems can be successfully produced.
Therefore this initiative does not include solution of short-term industrial problems that may take advantage from, for example, nanostructured materials.

The potentially very wide research horizon that is related to efficient energy collection has therefore to be narrowed, in order to define the actual scope of the call, which specifically looks for approaches to the improvement of energy harvesting at the nanoscale and their application to nanoscale autonomous systems. This means, for example, that nanostructured materials for increasing the conversion efficiency of photovoltaic cells are outside the scope of the call, since photovoltaic cells are not nanoscale autonomous systems. On the other hand, an approach to photovoltaic conversion based on nanoscale devices applied to a network of interacting nanoscale sensors would be admissible.

It is however to be recognized that, although the objective of the call is clearly aimed at the nanoscale, initial efforts to achieve proof of concept will most probably have to rely on a platform at the micro scale.

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