NANOENERGY LETTERS number five.

Our newsletter is growing following the growth of the community of scientists involved with the subject of micro and nano energies. In this issue, for the first time, we present some relevant news together with scientific articles that, as previously announced, present original research results. This is an important step toward the future of our publication. Article submission procedure for publication in NANOENERGY LETTERS is indicated at page 5.

On the news side we report on the start of the 7 projects funded by the European Commission under the FET Proactive call “Minimising Energy Consumption of Computing to the Limit” (MINECC). We announce a number of important events for our community, chief among the others, the NANOENERGY2013 international conference to be held in Perugia on July 10-13 2013, just after the annual summer school. Moreover we report on some recent meeting we had, like the Barcelona ZEROPOWER workshop held on October 16-18 2012. (LG)
The aim of Nanoenergy2013 is to bring together researchers, engineers, academicians as well as industrial professionals from all over the world and from different disciplines interested in the subject of micro and nanoscale energies. Energy at small scales is a cross-disciplinary field that covers both theoretical and experimental aspects of fundamental and applied sciences ranging from nanotechnology to statistical physics, from computer science to biomedicine.

**Topics** of the conference include (but are not limited to):
- Energy transformation processes and dissipation at micro and nanoscale
- Non equilibrium thermodynamics of small systems
- Magnetic and Nanomechanical Logic principles and devices
- Bioenergetics and bio-inspired low energy computation
- Energy harvesting for powering micro and nano devices
- ICT-Energy: switch architectures and zero power computing
- Energy aware algorithms and software strategies for low power computing
- Low power distributed sensor networks
- Landauer limit: theory and experiments
- Stochastic Resonance, Noise and fluctuations phenomena in small systems

**Important Dates:**
- Paper Submission (2 pages extended abstract) Before April 1, 2013
- Notification of Acceptance On April 15, 2013
- Early Registration deadline April 25 2013
- Final registration deadline June 1 2013
- Conference Dates July 10-13 2013

contact: info@nanoenergy2013.eu - www.nanoenergy2013.eu

During the conference there will be social events with the International Jazz Festival “Umbria Jazz”

---

**SUMMER SCHOOL: Micro and nanoscale Energy Harvesting - Perugia July 8-10, 2013**

The Noise in Physical System Laboratory is glad to announce the fourth edition of NiPS Summer School and Workshop devoted to “Energy harvesting at micro and nanoscales”.

The school, supported by European Commission under the FET Proactive Coordination and Support Action ZEROPOWER (www.zero-power.eu), 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 nanoscales. As part of the school there is a workshop where the students and external participants can present the result of their research. The workshop covers a wider range of subjects under the title of “Energy harvesting: models and applications” and is open to contributions.

Previous editions of NiPS Summer School have seen in two years the participation of more than 50 students and young researchers from all over the world.

The program of the school and the registration procedure will be soon available at: www.nipslab.org/summerschool.

The participant at the school can attend the international conference Nanoenergy2013 without additional registration fees.
Minimizing Energy Consumption of Computing to the limit (MINECC)

During autumn 2012 the seven projects founded by the European Commission under the call 8 (Objective ICT-2011-.9.8) within the FET-Proactive initiative MINECC have started their activity. These are:

- **ENTRA** - Whole-Systems Energy Transparency
  Project fact sheet (coord. Roskilde University - DK)
- **EXA2GREEN** - Energy-Aware Sustainable Computing on Future Technology – Paving the Road to Exascale Computing
  Project fact sheet (coord. Karlsruhe Inst. of Tech. - Ger)
- **LANDAUER** - Operating ICT basic switches below the Landauer limit
  Project fact sheet (coord. NiPS Lab, Perugia - IT)
- **PARADIME** - Parallel Distributed Infrastructure for Minimization of Energy
  Project fact sheet (coord. Barcelona SuperC. Center - SP)
- **PHIDIAS** - Ultra-Low-Power Holistic Design for Smart Biosignals Computing Platforms
  Project fact sheet (coord. EPFL - CH)
- **SENSATION** - Self Energy-Supporting Autonomous Computation
  Project fact sheet (coord. Aalborg University - DK)
- **TOLOP** - Towards Low Power ICT
  Project fact sheet (coord. Hitachi)


**EACO Workshop Series**

The **Energy Aware COmputing** workshop series was initiated in February 2011 by Dr. Kerstin Eder & Prof. David May of the Microelectronics Research Group. It is supported by the University of Bristol Institute for Advanced Studies and industry sponsorship. Its aim is to bring together researchers and engineers with interests in energy-aware computing for discussions to identify intellectual challenges that can be developed into collaborative research projects.

After the first five workshops in 2011 and 2012 the sixth Energy-Aware Computing (EACO) workshop will take place on 26 and 27 March 2013. The focus of this edition is on Global Engagement. The aim is to find research collaborations beyond the local community and to further develop a research agenda and roadmap in the EACO area.

info: [http://www.cs.bris.ac.uk/Research/Micro/eaco.jsp](http://www.cs.bris.ac.uk/Research/Micro/eaco.jsp)

---

**Energy Harvesting 2013**

Date: Monday **25th March 2013**
Location: Hamilton House, Mabledon Place, **London** (UK)

The Energy Harvesting Network is holding its annual one-day dissemination event. The Network is EPSRC-funded, and is for academia, industry and end-users of energy harvesting technology. The prime sponsors of the event are the EPSRC and Energy Harvesting SIG.

The event will provide a platform for disseminating energy-harvesting advances in the UK, and contain presentations from well-respected speakers in academia and industry, demonstrations from both universities and companies, and posters from postgraduate research students.

News from the groups

Physics of Information Group created at Instituto de Telecomunicações in Lisbon, Portugal

The Physics of Information Group has recently been created at Instituto de Telecomunicações (IT), a national research lab in Lisbon, Portugal, rated Excellent in its last international assessment. The group, coordinated by Prof. Yasser Omar, promotes research and advanced training in the physics of information in physical, chemical and biological systems. Namely, the group develops research in quantum Information theory (including entanglement theory, quantum computation and quantum cryptography), in quantum thermodynamics and the understanding of the fundamental limits in energy dissipation and the origins of irreversibility, and in quantum effects in biological systems. The group is involved in several international projects, including FP7 FET project LANDAUER, devoted to Operating ICT basic switches below the Landauer limit. The group is located in the campus of Instituto Superior Técnico (IST, the School of Science and Engineering of the Technical University of Lisbon), in Lisbon, Portugal. Research positions are currently available, namely for Ph.D. students and post-doctoral fellows. For more details, see: http://www.phys-info.org/


Fourth NANO-TEC Workshop

The fourth of the NANO-TEC Workshops, with topic “Summary and Recommendations for the Technology-Design Ecosystem”, took place in Barcelona on 6 and 7 November 2012.

The European Commission ICT theme is funding the Coordination Action project entitled “ECOSYSTEMS TECHNOLOGY and DESIGN for NANOELECTRONICS” (NANO-TEC) to identify the emerging generation of device concepts and technologies for ICT, as well as to build a joint technology-design community in the European research area. The main mechanism to achieve these objectives has been a series of four workshops, the topics of which have ranged from Identifying Technologies and Designs for New Devices to Benchmarking and SWOT analyses of New beyond CMOS device/design concepts. More details of the previous events can be found at https://www.fp7-nanotec.eu/show/events.

The fourth and final workshop dealt with the following topics:
FET Flagships selected

Brussels, 28th January 2013.

The EC has announced the two winners of a multi-billion euro competition of Future and Emerging Technologies (FET). The winning Graphene and Human Brain initiatives are set to receive one billion euros each, to deliver 10 years of world-beating science at the crossroads of science and technology. Each initiative involves researchers from at least 15 EU Member States and nearly 200 research institutes.

"Graphene" will investigate and exploit the unique properties of a revolutionary carbon-based material. Graphene is an extraordinary combination of physical and chemical properties: it is the thinnest material, it conducts electricity much better than copper, it is 100-300 times stronger than steel and it has unique optical properties. The use of graphene was made possible by European scientists in 2004, and the substance is set to become the wonder material of the 21st century, as plastics were to the 20th century, including by replacing silicon in ICT products.

The "Human Brain Project" will create the world's largest experimental facility for developing the most detailed model of the brain, for studying how the human brain works and ultimately to develop personalised treatment of neurological and related diseases. This research lays the scientific and technical foundations for medical progress that has the potential to dramatically improve the quality of life for millions of Europeans.

The European Commission will support "Graphene" and the "Human Brain Project" as FET "flagships" over 10 years through its research and innovation funding programmes. Sustained funding for the full duration of the project will come from the EU's research framework programmes, principally from the Horizon 2020 programme (2014-2020) which is currently negotiated in the European Parliament and Council. European Commission Vice President Neelie Kroes said: "Europe's position as a knowledge superpower depends on thinking the unthinkable and exploiting the best ideas. This multi-billion competition rewards home-grown scientific breakthroughs and shows that when we are ambitious we can develop the best research in Europe. To keep Europe competitive, to keep Europe as the home of scientific excellence, EU governments must agree an ambitious budget for the Horizon 2020 programme in the coming weeks." "Graphene" is led by Prof. Jari Kinaret, from Sweden's Chalmers University. The Flagship involves over 100 research groups, with 136 principal investigators, including four Nobel laureates. "The Human Brain Project" involves scientists from 87 institutions and is led by Prof. Henry Markram of the École Polytechnique Fédérale de Lausanne.

The future of computing and science will be driven by collaboration. The FET flagship programme is a world-leading effort to ride this wave. The flagship race has fostered collaboration on a new scale and duration. Instead of the usual two-to-four year funding cycles, the 10 year duration and the massive financial incentive has driven the level of science in the project proposals to a much higher level, which will deliver greater benefits to Europe over the long-term, including new technologies and faster innovation.

Horizon 2020 is the new EU programme for research and innovation, presented by the Commission as part of its EU budget proposal for 2014 to 2020. In order to give a boost to research and innovation as a driver of growth and jobs, the Commission has proposed an ambitious budget of €80 billion over seven years, including the FET flagship programme itself.

The winners will receive up to €34 million from the European Commission's ICT 2013 Work Programme. Further funding will come from subsequent EU research framework programmes, private partners including universities, Member States and industry.

Experimental demonstration of the MEMSTENNA concept

NANERG LAB (Universitat Autònoma de Barcelona)

NANERG LAB (NOEMS for Energy Laboratory) is progressing well towards the experimental demonstration of the concepts firstly described in the second Issue of Nanoenergy Letters (August 2011). As part of the thesis work of PhD student Jordi Agustí, and with the collaboration of Telecom Engineering student Pau Bramon and PhD student Miquel López-Suárez, first results on the mechanical resonance excitation of a microcantilever by the electrical field generated from a dipole emitting antenna have been obtained. Such a measurements constitute the first experimental demonstration of the MEMSTENNA concept. In particular, a commercial Si3N4 triangular cantilever, with a first mode out of plane resonance at 11.4 kHz, has been chosen to implant charge at its free end, in order to obtain a local micro-electret structure. On the other hand, a 1 m long dipole antenna with an LC feeding circuit has been designed to have a slightly tunable resonance also at 11.4 kHz. The electrical field of the electromagnetic wave radiated by the dipole antenna is able to interact with the permanent charge of the electret and induce a force that will put the MEMSTENNA in resonance.

In figure 1, the frequency response of the cantilever based MEMSTENNA mechanical vibration when excited by the dipole antenna (blue curve, CDE), together with the excitation current at the emitting antenna (cyan curve, DA) are shown. The response of the MEMSTENNA when excited with a piezo (red curve, CPE), as well as the mathematical product of the curves CDE by DA are also plotted. As it can be appreciated by comparing two different tuning conditions, the MEMSTENNA response is the result of the convolution of both resonances, the one of the microcantilever and the one of the dipole antenna.

A big progress has been also achieved by Miquel López-Suárez and Dr. Francesc Torres in the challenging route towards the physical implementation of the graphene NEMS based energy harvester, also described in Issue#2 (M. López-Suárez et al., PRB 84, 161401(R), 2011). A very simple method to fabricate suspended graphene nanoribbons, which is based on using PMMA as a sacrificial layer, has been successfully tested. The SEM and AFM images of figure 2 show one of the 600nm long and 800nm wide suspended graphene nanoribbons that was obtained using this method. Note that convolution effects produced by lack of sharpness of the AFM probe tip are present in the AFM image. Thus, the double steps in the graphene bottom edge and in the left PMMA anchor are just apparent, as it is evidenced by the corresponding SEM image.

Figure 1: Frequency response of the mechanical vibration of a MEMSTENNA when excited by a piezo (red curve) or by the dipole antenna (blue curve), and of the current at the exciting dipole antenna in the tuned (a) and out-of-tune (b) conditions. Cantilever vibrations are measured by means of an AFM-like optical readout system.

Figure 2: Tilted SEM (a) and top-view AFM (b) images of a suspended graphene nanoribbon. A 60 degree tilt on the SEM image is used in order to show that the NEMS structure is released and not collapsed.
Abstract — A micro-power energy harvesting system based on miniaturised solar cells together with a nanowire-modified CMOS platform for sensing hydrogen gas have been developed as components of dust-sized autonomous chemical sensor nodes. The possibility of low-power miniaturised chemical sensors of liquid analytes through microfluidic delivery to surface functionalised silicon nanowires is also pursued. This contribution highlights the activities in each of the four major activities within SiNAPS[1].

High Efficiency Silicon Nanowire Solar Cells are prepared for harvesting the energy that supplies the autonomous sensors. The nanowires are based on core-shell structures, with a crystalline silicon core surrounded by an amorphous silicon shell. It is essential to improve the performance of nanowire solar cells by suppressing surface recombination.

To this end, an ultrathin passivating Al2O3 tunnel layer was deposited on the highly doped p-type a-Si:H emitter prior to a transparent conducting oxide by atomic layer deposition (ALD). Both open circuit voltage and current density increase significantly due to the insertion of the ultrathin Al2O3 layer. An efficiency of 10.0% has been reached by using this multiple core–shell structure.

Minimodules with 8 or 6 cells connected in series by wire bonding have been fabricated and these have been successfully tested for integration with the electronics for battery charging.

Another aspect of the work involves the development of 1 mm x 1 mm footprint sensing devices, combining high surface area silicon nanowire (NW) sensors with a microfluidic liquid delivery system.

SiNW devices using nanowires of diameters down to 10 nm have been fabricated using electron beam lithography and reactive ion etching techniques. Current work is now focused on functionalising the SiNWs to infer specificity in the chemical detection, using biotin-streptavidin as a model system.

The aqueous sample is delivered directly to the NW sensors by use of microfluidic channels fabricated in polydimethylsiloxane. The channel surface chemistry has been engineered such that the fluid can be delivered passively by capillary action, removing the need for extraneous pumps or other forms of active injection, with a view to creating fully self-contained devices for point-of-care diagnostics.

Our energy-efficient solar energy harvesting and sensing microsystem harvests solar energy from a micro-power photovoltaic module for autonomous operation of a hydrogen gas sensor.

Hydrogen concentration and temperature are measured using an integrated sensor interface circuit and a wireless data transceiver transmits the measurement results to a base station. A fully integrated solar energy harvester stores the harvested energy in a rechargeable NiMH microbattery. As the harvested solar energy varies depending on lighting conditions, the proposed area and energy efficient circuit scales the power consumption and performance of the sensor to guarantee autonomous operation of the sensor.

The operating frequency of digital circuits and bias currents of analog circuits are reconfigured according to the harvested solar energy. To measure H2 concentration, conductance changes in a miniaturized palladium nanowire gas sensor is measured and converted to a digital value.

The microsystem has been implemented in a 0.18µm CMOS process occupying a core area of 0.25mm^2. The circuit features a low power consumption of 1.7µW when operating at its highest performance. It operates with low power supply voltage in the 0.8V to 1.6V range.
The final activity is integration of the solar cell, microfluidics/sensor and the electronics into a single miniaturised device.

A thermoplastic bonding process has been developed to support high density placement of Si dies at the substrate, with activity focussing on placement tests that show promising results.

Equipment for hot due placement has been designed, built and tested, with software developed to support semi-automated die placement. Preliminary shear tests to measure bond strength show good results, with minimal intrusion depth on the substrate. Low deformation of the dies enables close positioning of the dies, which is a key issue for final minimisation, as a minimal gap size is required.

The process is feasible for integrating the individual components, with reliable bonding. While placement is still semi-automated, a computer vision system will be added to eliminate any still existing small errors.

REFERENCES

[1] SiNAPS is one of the projects funded under the FET call TOWARD ZERO-POWER ICT.

[2] From the SiNAPS web site:

The aim of the SiNAPS project is to develop standalone dust-sized chemical sensing platforms that harvest energy from ambient electromagnetic radiation (light) and will enable miniaturisation below the current mm^3 barrier.

Current solutions in nano-electronics are enabled by new materials at the nano-scale. It is proposed to use high-density semiconductor nano-wire arrays, such as Si and Ge, as efficient photovoltaic units and low-power chemical sensing elements on small volume modules to be integrated, via 3D system in a chip, in a miniaturised platform that transmits the acquired information wirelessly for further processing. To demonstrate the proof-of-concept without committing huge resources in optimization the SiNAPS project has set a pragmatic but ambitious, miniaturisation target ~10^8 µm^3, beyond the state-of-the-art. With further development of the energy harvesting and sensing technology, 10^6 µm^3 and below can be possible.

SiNAPS brings together a consortium to address the two topics of the ICT-Proactive call (TOWARD ZERO-POWER ICT), namely: (a) fundamentals of ambient energy harvesting at the nano-scale and (b) development of self powered autonomous sensor devices, with target dimensions of 1 mm^3. These topics are of great interest in the areas of energy supply, energy use in ICT, smart(er) buildings, medical diagnostics, e-health and integrated smart systems. SiNAPS involves the development of the capacity of nano-wires for use as a nano-scale energy harvester and a (bio-)chemical sensor for the prototype biotin-streptavidin system via fundamental studies. Miniaturised CMOS electronics will be developed for efficient power management and sensor interface. Existing IP for wireless communication will be used to avoid costly development. The integrated modules will be used to demonstrate the SiNAPS mote concept. Concluding SiNAPS, a set of new technologies for self powered autonomous devices and beyond will be available for further development towards commercialisation.
Abstract — Strong efforts are nowadays directed towards the search of nanoscale devices able to control heat flows or convert them into electric power. Thermoelectric properties such as the conversion efficiency are expected to be enhanced in quantum dot systems and are currently under experimental test. Unfortunately, in nanosystems, there is no direct way to measure the essential quantity to be measured: the heat current.

Recently, nanoscale devices working as energy harvesters have been proposed based on three terminal configurations [1,2,3], see figure 1. Two quantum dots are capacitively coupled such that their electrons exchange energy via Coulomb interaction. Importantly, discretization of the energy levels fixes the amount of energy that can be transferred via electron-electron interaction between the different dots. One of them supports a charge current I between two terminals. The second one is connected to only one terminal through which heat but no net charge currents flow. The heat current flowing through the third terminal, J, is converted to electrical power in the conductor. It has been shown that the device can be tuned to achieve a thermoelectric efficiency close to the Carnot limit [1]. The advantage of three terminal systems is the strict separation of the current carrying channel and the heat conduction path.

In a recent manuscript published in Europhysics Letters [4], a mechanism that allows for the detection of heat flows in quantum dot systems is proposed. This is done by relating the heat current to a state-resolved charge detection. For the heat current transferred from the heat source to the conductor, of most importance, this is possible because it depends solely on electron-electron interaction. The two conductors exchange a quantum of heat by well defined sequences of charge fluctuations involving the different charge occupations of the system. A nearby quantum point contact which is asymmetrically coupled to the two dots is able to monitor such sequences. Thus, not only average currents but the statistics of heat fluctuations can be measured.

The latest is important for the investigation of nonlinear fluctuation relations. The fluctuation theorem relates reversed trajectories in a non-equilibrium situation. In this respect, mesoscale conductors have been demonstrated to be an ideal playground due to their high degree of tunability, detection and the importance of fluctuations in the transference of the electric charge. In the presence of a heat source, the fluctuation theorem for charge currents deviates from that expected for a voltage driven structure. The deviation is shown to be related to the absorbed heat [4]. A universal fluctuation theorem holds when formulated in terms of heat currents. The heat detection mechanism proposed in reference [4] is therefore essential for the investigation of universal fluctuation relations.

REFERENCES

Computing with uncertainty can help lowering the minimum energy required?

Luca Gammaitoni
NiPS Laboratory, Università di Perugia and INFN Perugia, Via A. Pascoli 1 - 06123 Perugia (IT)

Abstract — In the last forty years the semiconductor industry has been driven by its ability to scale down the size of the CMOS-FET switches, the building block of present computing devices, and to increase computing capability density up to a point where the power dissipated in heat during computation has become a serious limitation. According to the ITRS the limits imposed by the physics of switch operation will be the roadblock for future scaling in the next 10-15 years. The theoretical limit on the minimum energy per switching is set at $k_B T \ln(2)$ (approx $10^{-21}$ J at room temperature) identified with the so-called Shannon–von Neumann–Landauer limit when information is erased in the process. Here we discuss the possibility of reducing such limit by trading the minimum energy with uncertainty in the distinguishability of switch logic states.

I. INTRODUCTION

The concept of minimum computing energy was popularized by Ralph Landauer[1] in the sixties and it has been often invoked in the framework of the so-called reversible computing[2]. In recent years this concept has been revisited due to a number of experimental attempts to reach the minimum energy dissipation limit.

On the other hand, power dissipated versus switching speed of devices have been characterized since the seventies[3,4] by a linear scaling rule where micro-fabrication capabilities, through the replacement of bipolar transistors with CMOS, allowed the continuation of the exponential increase trend in information processing capability which has been known as Moore’s law. However, since 2004 the Nanoelectronics Research Initiative[5], a US based consortium of Semiconductor Industry Association companies, has launched a grand challenge to address the fundamental limits of the physics of switches. Such limits are mainly represented by the minimum energy and minimum time, required to operate a switch and are estimated by assuming that a two-well, one-barrier model is a valid abstraction for electron transport switching devices[6]. In this approach the FET transistor can be thought of as consisting of two wells (source and drain) located at a distance $a$ and separated by a potential energy barrier height $E_b$ (see Fig.1). The two logic states “0” and “1” are here represented by an electron (or the equivalent information carrier) sitting in the left and right well, respectively. The switching event is obtained by making the electron energetic enough to overcome the potential barrier separating the two states or, what is equivalent, by lowering the potential barrier on the electron side. Notwithstanding the simplicity of this model it has been often applied[5] in order to estimate the relevant aspects of the physics of switches. Specifically, the minimum operational energy of the switch is computed by assuming that the barrier height $E_b$ is chosen in order to enable the distinguishability of the two logic states. Such a condition is threaten in fact by unwanted crossings of the potential barriers due to thermally induced jumps (classical) or tunneling (quantum) effects. The larger $E_b$ and the distance $a$ between the two wells, the lower the threat to the distinguishability of the two states.

Additionally the Heisemberg energy-time indetermination relation is invoked in this context to set a further limit to the barrier height $E_b$. Based on these arguments the authors in [6] have been able to estimate a minimum energy per switching event of the order of few $k_B T \ln(2)$.

II. THE ROLE OF FLUCTUATIONS

In a recent paper[7] we have observed that in order to better highlight the extent of the validity of the arguments used in this estimate we should consider that in a nanoscale switch in contact with a thermal bath at temperature $T$, the role of fluctuations (thermal or quantum) on the system dynamics can be relevant and it is better accounted by introducing a statistical description of the carrier position in terms of a probability density function $p(x)$. In this condition the switch assumes the logic state “0” with probability $p_0$ measured by the area under $p(x)$ when $x<0$. 

Fig. 1. Schematic representation of a bistable switch. The switch dynamics can be described in terms of the motion of a particle in a double well potential energy. Each well represents a single logic state (left well, $x<0$, logic state “0”; right well, $x>0$, logic state “1”). The two wells are located at a distance $a$ and separated by a potential energy barrier height $E_b$. 

Computing with uncertainty can help lowering the minimum energy required?
and assumes the logic state “1” with probability \( p_1 \) measured by the area under \( p(x) \) when \( x=0 \). When the potential is symmetric the equilibrium probability distribution dictates: \( p_0 = p_1 = 1/2 \) (Fig 2a).

According to Landauer[1], the switching operation associated with the erasure of one bit of information (a logically irreversible operation) produces a decrease of the system entropy equal to \( k_B \ln(2) \) and thus, if the system is operated at temperature \( T \), the potential energy dissipated during the erasure operation is:

\[
S = S_i - T \ln(2)
\]

where \( S_i \) is the initial entropy of the system. According to Landauer's principle, the energy dissipated during the erasure operation is:

\[
Q(P_e) = T S(P_e)
\]

where \( Q(P_e) \) is the energy dissipated during the erasure operation, and \( S(P_e) \) is the entropy of the system after the erasure. According to Landauer, the energy dissipated during the erasure operation is:

\[
Q(P_e) = k_B T \ln(2)
\]

and this is the minimum energy dissipation that is required to perform the erasure operation. The energy dissipation is a function of the error probability \( P_e \):

\[
\frac{dQ(P_e)}{dP_e} = k_B T
\]

We can define the energy ratio \( \eta_e = Q(P_e)/Q_L \) as a function of the error probability \( P_e \). As it is well apparent, for \( P_e = 0 \) we have \( \eta_e < 1 \), implying that if we are willing to accept a larger-than-zero error probability, we can beat the Landauer's limit and perform the resetting operation with an energy toll smaller than \( k_B T \ln(2) \).

Consistently the zero limit for energy dissipation is reached when \( P_e = 0.5 \), corresponding to the maximum uncertainty (complete indistinguishability according to [1]), i.e. no reset. In the \( P_e = 0 \) limit we regain the Landauer's prediction \( Q(P_e) = Q_L \).

We point out that the analysis presented here is completely general and does not depend on the switching error mechanism nor on the specific potential landscape typical of different switches.

REFERENCES

[5] The Nanoelectronics Research Initiative (nri.src.org) was formed in 2004 as a consortium of Semiconductor Industry Association (SIA) (www.sianline.org) companies to manage a university-based research program as part of the Semiconductor Research Corporation (SRC) (www.src.org).
Abstract — The concept to harvest energy from the environment to power small electronic devices has become increasingly important. Nowadays, various types of energy harvesters have been proposed that are powered by random vibrations, phonons or electromagnetic radiation. Nanoscale solid-state devices can be used to recover waste heat from electronic circuits on a chip, thereby helping to face the energy crisis.

Recently, a particular interest in energy harvesters realized in quantum dot structures arose. On the one hand, quantum dots are appealing because they provide simple model systems that can be investigated analytically. On the other hand, quantum dots are promising because their electronic properties like level positions can be easily tuned experimentally by applying gate voltages. Their small size allows to combine many such harvesters in parallel to generate large output powers. Finally, they offer sharp spectral features which are beneficial for thermoelectric purposes.

A specific proposal for such a quantum-dot harvester was made some time ago in the group of Markus Büttiker [1,2]. It consists of two capacitively coupled quantum dots connected to hot and cold baths, respectively. In the Coulomb-blockade regime, these devices turn out to be efficient heat-to-charge converters that can reach Carnot efficiency.

Now, we have come up with the proposal for a new type of quantum dot harvester that is powered by magnetic fluctuations [3]. It consists of a quantum dot coupled to two ferromagnetic metals and one ferromagnetic insulator held at different temperatures. Magnons hosted in the insulator are absorbed by the quantum dot and drive an electronic current between the two metals. Depending on the magnetic configuration, the magnons either drive a spin-polarized current or even a pure spin current. In the limit of completely polarized electrodes, the device can be shown to work as an optimal converter that transfers one electron for each magnon absorbed. In consequence, the system reaches Carnot efficiency. Finally, our setup is interesting as it allows to investigate Onsager relations in a system with broken time-reversal symmetry.

Compared to similar proposal that rely on a quantum dot harvesting phonons [4] our device offers a number of advantages. First, magnons are easier to control than phonons as they are confined to the ferromagnetic insulator whereas phonons exist in any material. Second, magnons can be electrically injected via the spin Hall effect thus allowing operation at very low temperatures where magnons and parasitic phonons are not thermally excited.

Furthermore, the magnon-driven quantum-dot heat engine provides a bridge between the fields of energy harvesting and spin caloritronics. The latter deals with how to generate and manipulate spin currents by heat. Pure spin currents offer interesting prospects for future electronics as they are dissipationless. In addition, they can be used in information processing to switch magnetically stored bits.

References

Effect of temperature and pH level on the hydrothermal growth of ZnO fine wires

O. G. Súchil, G. Abadal, F. Torres
Departament d’ Enginyeria Electrònica. Universitat Autònoma de Barcelona. 08193 – Bellaterra. SP

Abstract — The synthesis of ZnO fine wires has been made, on a solution of zinc hexahydrate and hexamine, using the Hydrothermal Method (HTT). By varying the temperature level of the furnace and pH level, with a constant heating time, the influence of each separated parameter was observed, revealing important changes on the morphology and the length of the fine wires. The obtained fine wires were observed by optical microscopy and scanning electron microscopy (SEM). The I-V curves measured on individual fine wires show a non-linear rectifying behavior, which confirm the semiconductor nature of the growth material.

INTRODUCTION

Micro and nanostructures based on ZnO have received significant interest because of their high performance in optoelectronics and photonics. The absence of a center of symmetry in its wurtzite structure and a large electromechanical coupling, give rise to piezoelectric and pyroelectric properties [1].

Focusing on the piezoelectricity of the ZnO, significant studies were made, based on the principle of applying a stress to a ZnO nanowire that produces a piezoelectric field along the length, causing a transient charge flow [2-3]. This property has been used, for instance, with the purpose of designing a flexible high output nano generator (HONG) [4]. On the other hand, other studies suggest carbon nano-tubes (CNTs), as the basic element of purely mechanical elastic energy storage batteries [5].

Previous studies successfully synthesized fine wires by using the hydrothermal method (HTT), because its implementation is easy and low cost. The technique consists in the thermal degradation of hexamine and zinc nitrate [6]. In this paper, a systematic study was conducted to control the growth behavior, in terms of lateral and longitudinal dimensions of the fine wires, as well as their verticality and density, by analyzing two main parameters: the temperature and the pH level. This work will be the basis for future experiments addressed to produce a demonstrator of a mechanical energy storage device, based on a compact array of fine wires.

EXPERIMENTAL PROCEDURE

As part of the analysis the experiments were separated in two groups. For the first group the temperature was varied, while the heating time and the concentration of the solution were constant. For the second group the pH level was varied, while the temperature and the heating time were kept constant.

The solution had an initial pH level of 6.6, that was changed in order to obtain the levels for each test, by using HCl and NaOH. For the two group of experiments, an aqueous solution was used, by mixing zinc nitrate hexahydrate Zn(NO)₃ at a concentration of 0.00505 M, as a source of Zn²⁺ ions, with hexamine at a concentration of 0.00502 M.

Each of the samples had a heating time of 5 hours, causing a thermal degradation, for releasing the OH⁻ ions that react with the Zn²⁺ ions, and form the ZnO. The process is summarized by the following reactions [7-9].

(\text{CH}_2\text{N}_4 + 6\text{H}_2\text{O} \leftrightarrow 6\text{HCHO} + 4\text{NH}_3, \quad (1) \\
\text{NH}_3 + \text{H}_2\text{O} \leftrightarrow \text{NH}_4^+ + \text{OH}^-, \quad (2) \\
2\text{OH}^- + \text{Zn}^{2+} \rightarrow \text{ZnO(s)} + \text{H}_2\text{O}. \quad (3)

For each test, the growth reaction was made in a 1 cm² sample 500 μm thick of Si, with 20 nm of Cr and 100 nm of Au, deposited on top by the electron beam deposition method. This sample was placed face down with the gold face touching the solution, without overcoming the surface tension.

Description of temperature variation experiments

In order to find the optimum temperature of growth, three samples were heated, using the same initial pH level of 6.6. The temperatures of each test were: 90°C, 70°C and 50°C. For the first test (TA-90°C), the effects of the high temperature in the growth were analyzed, in the second test (TB-70°C), the density of fine wires and the hexagonal rod structures were analyzed. The last test (TC-50°C) was done in order to analyze the minimum temperature for the crystallization.

Description of pH variation experiments

To analyze the pH level as an independent parameter, the temperature was kept constant at 80°C.

The variation of the pH levels was adjusted at the beginning of each test, by using NaOH, at a concentration of 3 M and HCl at a concentration of 2 M. The pH levels for these experiments were: 6.68 (pHA), 7.08 (pHB), 7.74 (pHC). In order to analyze the limits of pH level, these last tests were studied: 11.72 (pHD) and 5.7 (pHE).

Having these pH levels, the effect on the morphology of the ZnO fine wires was analyzed, to determine if the growth of hexagonal rod structures was pH dependent. After the heating process, each sample was washed 3 times using deionized water, and dried with nitrogen.
RESULTS

Temperature variation results

In the Fig.1 we can see the results of the first group of tests. On test TA, the growth population was more uniform throughout the sample, but the needle shape was more predominant than the hexagonal rod structure. At test TB, the growth population was lower than in test TA, but the hexagonal rod formations appeared with a perpendicular angle of growth. In test TC, the growth population was null, the formations were amorphous forming granules. For experimental purposes, the resulting granules of test TC were reheated to 90°C, in order to verify if they can be used as seeds. This last test had the same effects of random morphology as the test TA, having no reaction of growth for some granules.

By the observations made on each test, it can be supposed that the temperature level works as a reaction catalyst. With higher temperature the general population of the finewires increases, but at the same time the angle of growth decreases. At an average temperature, as shown in the second test (TB), the finewires were formed more separated, but with a higher growth angle, causing more perpendicular formations. Also at this temperature level, the hexagonal rod formations were more frequent than in any other test. For the last test (TC), the beginning of the growth reaction was observed, showing the formation of granules, without enough energy to create a successful crystallization.

At the optimal temperature conditions (Fig.1-TB), the morphology of the finewires was found to be conical, with average diameters of 1.4 μm at the base and 0.6 μm at the top.

For test TC, the formation of granules without structure was observed, with sizes ranging from 5 μm to 16 μm, and the growth population of finewires was null. For the central region of the sample, small formations were observed as fuzz. Having identified the average temperature, at which finewires can grow stably, an average temperature was taken between the test TA and test TB, therefore the value of 80°C was fixed for the pH experiments that are shown below.

pH variation results

The pH and the temperature levels were measured by using a Crison pH-Meter Basic 20, with an electrode and thermocouple, to analyze both parameters at the same time. The levels of pH were measured in 4 instants: i) Initially, before HTT process (T0), ii) after 5 hours of the HTT (T1), iii) after the solution was cooled to room temperature (T2) and after 12 hours of natural cooling (T3). The results are shown in Fig. 2.

In good agreement with previous studies on the pH behavior, it can be supposed that the pH level drops for the 2 first hours because of two main effects. The first is related to zinc ions: the two first hours are critical and concentration drops rapidly. After this period, the concentration decreases in a linear proportion. The second effect is related to hexamine: during the first two hours, which are critical too, the concentration drops faster, but after this period the decay of the concentration remains approximately constant [10-12].

If the HMT remains constant in the degradation process, ammonium and formaldehyde ions are added to the zinc complexes of the initial reaction [13]. Some of these consequences are observed in Fig.3.

The obtained rectifying characteristic is consistent with the Schottky barriers created at the metal-semiconductor contacts, which are defined by the finewire/substrate and finewire/probe interfaces.
CONCLUSIONS

The ZnO fine wires were grown with average diameters of 0.6 µm, and average lengths of 6 µm for some of the samples measured. By analyzing the different tests, it seems to be that the temperature influences the growth, by accelerating the formation of fine wires when it is increased. Moreover if the temperature decreases, the reaction is inhibited and no crystallization starts (Fig1-TC). The hexagonal rod structures were more common, in the test TA (Fig1-TA). The structures that were found in the test HB varied widely, without a tendency to a particular structure, length and thickness (Fig1-TC). On the other hand the pH tests, offered a better structure formation [14], when the initial pH level was low (Fig4). In the Fig.4-pHE it can be seen, that with a pH level lower than 6, the hexagonal rod structure, changes in thickness abruptly resulting in a stepped structure. Moreover with a pH level about 7.7, the structure was compromised, and the crystallization did not begin, even with a temperature of 80°C as it can be seen in Fig.3-pHC. But with a pH level about 11, particular formations were found, with flowers and stars shape, without hexagonal structure (Fig.3-pHD).

ACKNOWLEDGEMENTS

This work was financed by EXPLORA project TEC2010-10459-E, NEMS Based Mechanical Energy Storage funded by “Ministerio de Ciencia e Innovación”, and with a collaboration of “Consejo Nacional de Ciencia y Tecnología (CONACYT)” coordinated by the Mexican government.

REFERENCES

Abstract — Amorphous silicon (a-Si) and hydrogenated amorphous silicon (a-Si:H) are the model amorphous systems, while heterojunctions of amorphous and crystalline (c-Si) are used in solar cells, offering tuned light absorption and reasonable efficiency. There remain fundamental questions regarding: (1) the effect of hydrogen on the optical properties of a-Si:H, (2) the structure of the a-Si:H/c-Si interface and (3) the electronic and optical properties of the a-Si:H/c-Si heterojunction. In this contribution, we use large-scale atomistic simulations of a-Si, a-Si:H and a-Si:H/c-Si heterojunctions models to show that: (1) the hydrogen concentration has no effect on the optical and mobility gaps of a-Si:H, so long as the H concentration is at saturation and (2) the formation of the a-Si:H/c-Si heterojunction can show effects on the optical properties due to the surface orientation and the relative thickness of the a-Si:H and c-Si regions.

INTRODUCTION

Amorphous silicon (a-Si) and hydrogenated amorphous silicon (a-Si:H) are the paradigm amorphous materials, in which there is short range order, but no long range order. A-Si is technologically important as a cheap semiconductor for large-area electronics and photovoltaic applications.1,2 In a-Si there are many defects, primarily the dangling bonds from undercoordinated silicon atoms that introduce charge trap states acting as recombination centres.1 Hydrogenation improves the properties of a-Si by passivating dangling bonds and a-Si:H is a much more efficient visible light absorber compared to c-Si.3 Amorphous-crystalline Si heterojunctions are used in solar cells. A detailed understanding on the role of hydrogen incorporation remains a challenge.

Of particular importance is its effect on the optical properties of a-Si, which will determine light absorption in a solar cell. Despite a significant amount of work, this as yet unresolved question has led to conflicting interpretations regarding the effect of hydrogen on the optical band gap.4,5,6 Cody et al.4 showed that two samples with a saturated hydrogen content, but different H concentration in each sample, have the same optical gap. However, more recent work tends to state that the optical gap depends on H concentration,5,6 even where the published data appear to indicate a constant optical gap at saturation.

In order to study this question, we have used large-scale density functional theory (DFT) simulations to prepare a-Si:H samples in a controlled way to determine the optical and mobility gaps in bulk a-Si:H and their dependence on H concentration. In addition, we present some results on the amorphous-crystalline interface examining the effect of Si surface orientation on the structural and optical properties.

METHODOLOGY

Heat and Quench Simulations — We use a heat and quench approach to generate a-Si and a-Si:H models (within the classical molecular dynamics code GULP), using the Tersoff Si interatomic potential. In heat and quench, c-Si is melted and quickly quenched, giving model structures with coordination defects including three and five fold coordinated Si - that is the dangling bond and the floating bond and a non-vanishing density of states in the band gap, consistent with undercoordinated Si atoms. We run a “melting” simulation at 3500 K (bulk) and 3000 K (interface) for 250 ps and 10 ps, respectively in the NVT ensemble, with an integration timestep of 0.1 fs using Verlet leapfrog integration. We quench to 300 K at a quench rate of: 1x1012 K/s for bulk and 6x1012 K/s for interface and anneal for 100 ps at 600 K and relax with DFT, giving model structures of a-Si. Incorporating hydrogen in a-Si passivates undercoordinated Si, and generates models of a-Si:H. For bulk, the saturation hydrogen concentration is 14% (with an unsaturated model having 12 % H). The amorphous-crystalline interface model has a 17% H concentration.

DFT Modelling — Structural, electronic and optical properties are calculated from structural models of a-Si:H bulk and interfaces relaxed with density functional theory (DFT),
implemented in VASP. The generalized gradient approximation (PW91) and the screened exchange HSE06 functional are used. Interactions between ion cores and valence electrons are described with the projector-augmented wave method (PAW), with 4 electrons on Si and 1 electron on H. The electron wavefunctions are described in a plane wave basis set with a kinetic-energy cutoff of 400 eV. Brillouin zone integration for the 512 atom supercell is at the Γ point.

RESULTS AND DISCUSSION

Bulk amorphous silicon – Figure 1 (a) shows a Tauc plot to determine the optical gap of a-Si:H with 14 % saturation H concentration. The optical gap is 1.25 eV. The optical gap for the same a-Si:H system, but with 12 % H concentration, is 1.16 eV; the increase in the optical gap with an increase in hydrogen concentration is consistent with experiment4-6. Despite the underestimation of the optical gap with GGA-DFT, the qualitative behaviour is correctly described. The optical gap for other saturation H concentrations, 15% and 16.5% is also 1.25 eV, so that the optical gap is invariant to H concentration, where saturation H concentration is reached.

In figure 1 (b) we show the Si-Si radial distribution function (RDF) for a-Si and the corresponding hydrogenated a-Si:H with 14 % H. Both structures display an RDF typical of amorphous silicon, with a peak at the bulk Si-Si distance and no sharp peaks for longer Si-Si distances.

Amorphous silicon is also characterised by the so-called mobility gap, which we calculate from the inverse participation ratio (IPR) of the wavefunction of each energy eigenstate, calculated from

\[ IPR_i = \frac{\int |\Psi_i(r)|^4 \, dr}{\left( \int |\Psi_i(r)|^2 \, dr \right)^2} \]

(V is the volume)

A large IPR indicates a localised state and a small value indicates a delocalised state and from the IPR we determine the positions of the valence and conduction band mobility edges, giving the mobility gap. Figure 1 (c) and (d) show the IPR (as a histogram) for a-Si:H with 14 % H and with 12 % H and the semi-log density of states (DOS), which displays the band tails around the mobility edges, arising from the amorphous nature of a-Si:H. For a-Si:H with 14 % H, there are no states in the band gap, while with 12 % H (undersaturation), there are localised states in the gap, arising from dangling silicon bonds. The valence and conduction band mobility edges are indicated in figure 1(c) and (d) and we compute mobility gaps of 1.27 eV and 1.20 eV from GGA-DFT with 14 % and 12 % H, respectively; with the more accurate hybrid DFT method, we obtain a mobility gap of 1.83 eV, consistent with the range of 1.88 – 1.90 eV in experiment. Continuing this analysis for the H contents of 15 and 16.5%, we find mobility gaps of 1.25 and 1.26 eV (hybrid DFT 1.84 eV), confirming that the mobility gap of bulk a-Si:H does not depend on H concentration, once the saturation concentration is reached.

The Amorphous-Crystalline Interface – Figure 2 shows the atomic structure of a-Si:H/c-Si generated from heat and quench of the Si (100) surface. In this case a a relatively thick amorphous region is obtained compared to the (110) and (111) surfaces. This is consistent with the known stability of the crystalline unreconstructed surfaces - (110) and (111) are more stable than the (100) surface. In Figure 2 we show the computed RDF and DOS for a single crystalline layer (indicated by the label B) and in the interface and amorphous layers. In the RDF layers H and I show deviations from the c-Si RDF; consistent with the obvious disorder present in the structure and in layer M, the RDF is consistent with an amorphous layer.

In the electronic density of states (EDOS), the crystalline layers show a c-Si EDOS, with a clear valence-conduction band energy gap. In the amorphous region, there are no states around the Fermi level so that incorporation of H has passivated the dangling silicon bonds. Going from the crystalline to amorphous regions, band tails form consistent with disorder, e.g. in layer I where the RDF shows a crystalline structure. The EDOS is thus more sensitive to small perturbations in the atomic positions than the RDF, so that from the perspective of the electronic structure, the interface spreads over a larger region.
ACKNOWLEDGEMENTS

We acknowledge support from The European Commission, through the 7th Framework ICT-FET-Proactive program, Project: SiNAPS (contract no 257856).

REFERENCES

## SAVE THE DATE

<table>
<thead>
<tr>
<th>DATE</th>
<th>EVENT</th>
<th>WEBSITE</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 1–5, 2012 - San Francisco</td>
<td>MRS Spring Meeting &amp; Exhibit</td>
<td><a href="http://www.mrs.org/spring2013/">http://www.mrs.org/spring2013/</a></td>
</tr>
</tbody>
</table>

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